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Sex and height estimation using percutaneous ulna and tibia length in a Ghanaian population: New data and a test of published equations

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ABSTRACT

Whether one population-specific model for sex and height estimation can be extrapolated to another population has been a source of controversy. This study sought to develop and compare models for sex and height estimation from the percutaneous lengths of the ulna and tibia in a Ghanaian population. The study was cross-sectional from January to June 2021 at the University for Development Studies, Tamale. There were 191 (male=89, female=102) participants between 18 and 30 years of age. The standing height, ulna length (UL) and tibial length (TL) were measured following recommended anthropometric techniques. The sample was randomly assigned to training (60%) and holdout (40%) samples. Discriminant models for sex and linear regression models for height estimations were formulated using the training sample. The new models and other population-specific models were tested on the holdout sample for reliability using the Bland-Altmann method, Cohen's *d* for height and cross-validation for sex estimations. The observed and the estimated height of males and females using UL (bias, *d*: male=2.75, 0.46; female= 0.73, 0.13), TL (bias, *d*: male= 2.74, 0.42; female= 1.50, 0.28) or UL+TL (bias, *d*: male= 2.76, 0.42; female= 0.86, 0.14) were not statistically different. The average sex estimation accuracy from the holdout sample was better in the multivariable UL+TL (82.9%) than in the univariable UL (76.3%) or TL (55.3%). Models based on UL [bias: 0.50 (95%CI: −8.10 to 9.09), *d*: 0.07] from Kumasi-Ghana and TL [bias: − 0.01 (95%CI: −10.37 to 10.34), *d*: 0.00] from the Amhara Region-Ethiopia were most reliable for estimating male's height. For female height estimation, models based on UL [bias: − 0.62 (95%CI: −12.08 to 10.83), *d*: 01.2] from Tamale-Ghana and TL [bias: − 3.72 (95%CI: −16.81 to 9.37), *d*: 0.76] from the Amhara Region-Ethiopia were most reliable. However, the other models deviated in the range of − 17.09 cm [Khasi tribe-India (UL)] to 0.54 cm [Kumasi-Ghana (UL)] in male height estimation and − 9.86 cm [Barcelona-Spain (TL)] to 1.05 cm [Kumasi-Ghana (UL)] in estimating female height. Cohen's *d* was more precise than the Bland-Altmann method in assessing the reliability of height estimation models. Height can be estimated using UL, TL or UL+TL, however, it is recommended to use UL+TL for sex estimation in a Ghanaian population. Although the use of population-specific models (UL and TL) for sex and height estimations is recommended, other models outside the target population may be applicable. Additionally, when measuring the reliability of height estimation models (UL and TL), Cohen's *d* should be preferred to the Bland-Altmann method.

Introduction

The estimation of sex is routine for most medico-legal investigations [1,2]. Traditionally, the pelvic and cranial bones are preferred to other bones for sex attribution due to their being more sexually dimorphic [2]. However, pelvic and cranial bones may not be available if the sample is not skeletal or may be damaged due to environmental effects arising from taphonomic and anthropic processes. Where a living population, fragmented bodily parts or cadaveric samples are involved, percutaneous measurement of long bones such as the ulna and tibia may serve as suitable alternatives [3–5]. Sexual dimorphism in the ulna and tibia lengths has been demonstrated in the literature with evidence of

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reliability in sex estimation [6,7]. The differences between the male and female ulna may be due to hormonal effects during puberty as androgens in males tend to promote and prolong bone growth and maturation while estrogens may cause the early maturation of female bones resulting in shorter lengths [2,8]. The ulna and tibia may also exhibit sex-specific adaptations for reproduction and task allocations.

Similarly, height is also routinely estimated for purposes of human identification. The lower limb bones have allometric while the upper limb bones have an isometric relationship with height i.e. as height increases the lengths of the lower limb bones also increase but not so for the upper limb bones [9]. Height estimation can be performed using either anatomical or mathematical methods. The former is applicable in living samples while the latter is preferred where the sample consists of only body parts or cadavers [10]. There is a linear relationship between height and the lengths of the ulna and tibia allowing for the height of an individual to be estimated with reliability [10]. However, there are differences in the relationship between body proportions given to genetic and environmental factors [1,10,11]. Although height estimation from lower limb bones such as the tibia is said to be more precise, the use of the upper limb bones such as the ulna is also reliable [12]. The ulna is the most preferred bone for height estimation in living subjects due to the ease of getting accurate measurements [12]. Previous studies have shown that estimating height using the mathematical method may be fraught with errors, particularly for shorter or taller people [10].

It is required by the Daubert Standards to subject Forensic methods to empirical testing, the calculation of error rates, external validity and peer-review. The application of a sex estimation model depends on the degree of sexual dimorphism of both the study and target populations [6]. Previous studies have shown that there are similarities as well as variations in the reliabilities and accuracies of height and sex estimation based on the ulna and tibia lengths between populations [6,13]. The application of population-specific equations may over-estimate or under-estimate stature in different populations, or individuals may be misclassified according to sex when equations are applied to different populations. Variabilities in sex and height estimation models may be attributed to variabilities in genetics, intrauterine or childhood malnutrition and socioeconomic factors as the developing world is disproportionately affected by poverty, malnutrition and the global burden of diseases [13,14]. Sex and height estimation may also be affected by secular changes or trends [15–17]. Secular trends are biological changes in skeletal morphology over time in a given population that can lead to changes in body size and structures and their relationship with each other. Previous studies have shown that allometric secular changes in long bones were stronger in males versus females; stronger in lower vs upper limbs and stronger in distal vs proximal bones [9]. Secular trends may be due to genetic or environmental factors which are usually difficult to tease apart [17]. Different parts of the body may respond differently or at different rates to environmental factors. It may also mean that different body parts reach their genetically determined potential or maturity at different rates in response to environmental factors. Although the effect of secular trends is sexually dimorphic, nutrition and disease are the two most common environmental factors that influence secular changes in long bones [9,15,17]. A model that was formulated in one century may not be applicable in another. Although global models for sex and height estimations have been proposed and may be applied, the use of population-specific models has been recommended [6].

Previous studies have indicated that some sex and height estimation models may apply to populations that are different from the population from which they were formulated, while other models from the same population but different localities may not be comparable [6,13,18]. It has been argued that there is no need for population-specific models as global models from pooled data are more precise for height and sex estimations [18]. Although sex and height estimation models based on the ulna and tibial lengths exist in Ghana, new models are still needed because Ghana is not a homogeneous nation. Different cultural groups show variabilities in the average standing height. This also means there may be differences in body proportions and their relationship with standing height [2,19,20]. Also, similar models from other populations have not been tested in the Ghanaian population. This study, therefore, sought to develop new sex and height estimation models from the length of the ulna and tibia and also to determine whether similar models from other populations can be extrapolated to the Ghanaian population with reliability.

Materials and methods

Study design and setting

The study was cross-sectional from January to June 2021 at the Tamale campus of the University for Development Studies (UDS). The university (UDS) is a multi-campus institution, located in the largest metropolis in the northern zone of Ghana. The university offers both undergraduate and postgraduate programs in Education as well as Social, Agricultural, Natural and Medical Sciences.

Study population and sampling

The study population comprised males ($n = 89$) and females ($n = 102$) who were between the ages of 18–30 years. The study population was healthy without a history of previous fractures that could markedly affect the ulna and tibia length. All participants could stand on their own without support and were devoid of any condition that could substantially affect standing height. Participation in the study was voluntary and was not restricted by religion, the program of study or cultural group.

Measurements

The standing height, percutaneous ulna and tibia length (left side) were measured following standard anthropometric techniques. The standing height was measured using the stadiometer. Each participant stood bare-footed with the hills, buttocks, back and the back of the head touching the scale. The hands were on the side and the head positioned in the Frankfort plane. The stadiometer plate was then lowered gently to touch the head and the height was then recorded. The tibial length was measured using a sliding caliper with the participant seated with the left ankle resting on the right knee. The distance between the most proximal medial condylar margin and that of the most distal one of the medial malleolus margin was then measured [21]. To measure the ulna length, participants laid their uncovered left arm over their chest, touching the right shoulder. The ulna length was measured from the tip of the olecranon process to the midpoint of the styloid process using a sliding calliper [2]. All measurements were made twice by one observer to the nearest 0.1 cm and the two values were then averaged. The intraclass correlation coefficient (ICC) was then calculated using the two-way-mixed, single measures, absolute agreement model [22]. The ICC was found to be 0.989, 0.977 and 0.969 for the height, ulna length and tibia length respectively.

Statistical analysis

The data was collected and then sorted on an Excel Spreadsheet before statistical analysis in GraphPad Prism (v8) and SPSS (v23) statistical packages. The assumptions of discriminant function and linear regression analysis were tested. The Shapiro-Wilk test was used to test the normality of the data while the variance inflation factor (VIF) was used to assess multicollinearity between the variables. The homogeneity of variance and the homogeneity of covariance were tested using Levene's test and Box's M test respectively. Descriptive statistics were then performed separately for males and females and were then presented as mean (standard deviation-SD). The differences between the male and female mean values were tested using the student t-test (unpaired, 2-tailed) and effect sizes were estimated using standardized mean differences (Hedge's) since the sample size for males and females were different. The total sample was then randomly assigned to training (60%) and holdout (40%) samples. The training sample was used to formulate discriminant models for sex estimation and linear regression models for height estimation. The standing height and sex were the dependent variables in the linear regression and discriminant analysis respectively while UL and TL were the predictor variables. The reliability of the discriminant models was then tested by cross-validation on the training sample using the leave-one-out method and also on the holdout sample. The reliability of the linear regression models was assessed on the holdout sample using the Bland-Altman method as well as standardized mean difference (Cohen's *d*). Cohen's *d* was used because the sample size was the same for the observed and the estimated height (holdout sample). The Bland-Altman analysis may indicate a reduced bias between the observed and the estimated height, however, the limits of agreement may be too wide, making the results less reliable. Also, the limits of agreement may be narrow and no significant difference may exist between the methods but the bias may be large [23]. To reduce interpretation challenges, the bias and limits of agreement of the Bland-Altman method were compared to the effect size from the standardized mean difference (Cohen's *d*). A Cohen's *d* that is negligible ($d<$ 0.20) or small (0.20 $<d<$0.50) almost always indicates a better agreement between the methods [24]. Other published model equations from different populations including Ghana, Ethiopia, Nigeria, India, South Africa, Nepal, Britain, The Caribbean, Mexico, Italy and Spain were tested on the holdout sample for their reliability in estimating the sex and height of the study population [1,2,11,13,19,21,25–31]. All statistical analyses were 2-tailed at $P < 0.050$.

Ethical declarations

The study complied with the guidelines of the Declaration of Helsinki (1964) and its later amendments regarding human subject studies. The study received the approval of the institutional review board of the University for Development Studies (N#: UDS/RB/003/21). Written informed consent was obtained from each participant before data collection.

Results

Test of assumptions

The Shapiro-Wilk test showed that the dataset for Height (W:0.993, $P = 0.466$) and TL (W:998, $P = 0.102$) were normally distributed. The dataset for UL (W:983, $P = 0.019$) was skewed but no extreme values were detected. There was no multicollinearity between UL and TL per their variance inflation factors (VIF=1.292, both). The hypotheses that there was a lack of homogeneity of variance and/or covariance in the male and female datasets were rejected by the results of the Levene's and Box's M tests respectively ($P \geq 0.050$).

Table 1
The mean and standard deviations of the male and female variables.

Variable	Male (n = 89) Mean (SD)	Female (n = 102) Mean (SD)	P-value	*g*
Height (cm)	171.7(7.94)	162.6(6.30)	< 0.001	1.28
UL (cm)	29.8(2.24)	27.4(1.75)	< 0.001	1.21
TL (cm)	41.4(3.71)	41.2(2.17)	0.542	0.07

The standardized mean difference was expressed as Hedge's *g*: negligible ($d<0.20$), small ($0.20 \leq d<0.50$), medium ($0.50 \leq d \leq 0.80$) and large ($d>0.80$).

Descriptive statistics

The general attributes of the study population are summarized in Table 1. Male participants were significantly taller with longer ulnae than females ($P < 0.001$) with large effect sizes. No significant differences were observed in the length of the tibia between males and females.

Height estimation models

The univariable and multivariable linear regression models for height estimation were all significant ($P < 0.001$). However, a combination of UL and TL in a multivariable model accounted for the most variability (47.1%) in males (adjR^2 =0.471) and also in females (adjR^2 =0.538). The ulna length accounted for more variability in height than the tibial length in both males and females (Table 2).

Reliability of the height estimation models

There were no significant differences between the observed and the model-estimated height for all models in both males and females (Fig. 1). However, the tibial length produced the least biased model in males [bias= 2.64 (95%CI: −7.57 to 12.85)] while in females, it was the ulna length [bias= 0.72 (95%CI: −10.73 to 12.17)]. In general, the female height estimation models were less biased than the males.

Sex estimation models

The discriminant function models for sex estimation are shown in Table 3. The univariable model based on ulna length and the multivariable model based on both the ulna and tibial lengths were significant ($P < 0.001$). The multivariable model (UL+TL) was the best as it had the highest Eigenvalue (0.451) and the least Wilk's Lambda (0.689) when compared to the univariable models.

Reliability of the sex estimation models

The ulna length was a better attributor of sex than the tibial length, on average. However, when combined (UL+TL), the sex estimation accuracy improved (82.9%) over the univariable UL (76.3%) and TL (55.3%) in the holdout sample. In general, females were better classified than males using the ulna length while males were better classified than females using the tibia length, although their accuracy were generally poor (Table 4).

Table 2
Height estimation models based on the ulna and tibia lengths in males and females.

Variable	r	R^2	adjR^2	SEE	F-value	P-value
Male (n = 48)						
$y = 2.094 *UL+ 108.028$	0.614	0.377	0.364	6.560	27.893	< 0.001
$y = 1.288 *TL+ 117.165$	0.561	0.315	0.300	6.880	21.166	< 0.001
$y = 1.530 *UL+ 0.798 *TL+ 91.783$	0.686	0.471	0.471	6.114	20.030	< 0.001
Female (n = 65)						
$y = 2.258 *UL+ 100.385$	0.705	0.497	0.490	4.200	64.301	< 0.001
$y = 1.458 *TL+ 102.011$	0.560	0.314	0.303	4.906	29.753	< 0.001
$y = 1.815 *UL+ 0.709 *TL+ 83.308$	0.743	0.552	0.538	3.994	39.480	< 0.001

The models were formulated using univariate and multivariate linear regression. UL=ulna length, TL=tibia length, r = correlation coefficient, R=coefficient of determination, adj=adjusted, SEE=standard error of estimation.

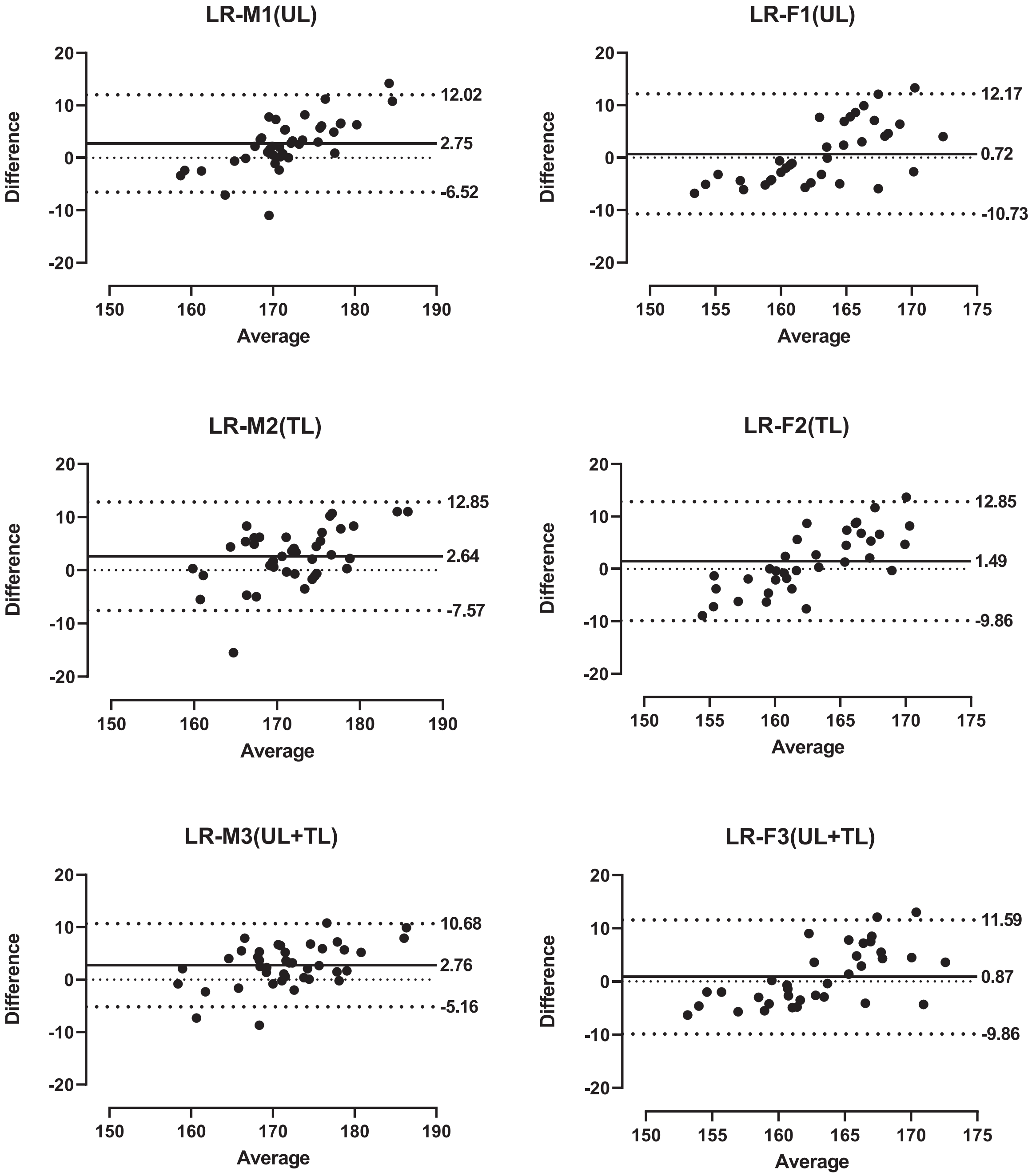

Fig. 1. Scatter plots showing the agreement between the observed height and the estimated height using the Bland-Altmann method. LR=linear regression, UL=ulna length, TL=tibial length, M=male, F=female.

Test of published sex and height estimation equations

Regarding male height (Table 5), a previous ulna-based height estimation model from Tamale-Ghana and the current model were similar in their reliabilities. While both did not differ in the standardized mean difference (d=0.46), the former over-estimated while the latter under-estimated male height by about 3.0 cm. Better still, two ulna-based height estimation models from Kumasi-Ghana performed similarly but outperformed the current model as their over-estimation of male height was < 1.0 cm and their standardized mean differences were also negligible (d< 0.20). However, an ulna-based height estimation model from the Amhara region of Ethiopia had reliability comparable to the current study as the over-estimation in male height was just about 3.0 cm and had a medium size standardized mean difference (d=0.47). Using the tibial length, the current model and height estimations from both urban and rural Mayan populations were comparable. However, the current model under-estimated while the Mayan models over-estimated male height by about 3.0 cm but all the models had medium-sized standardized mean differences (0.20 <d<0.50). Interestingly, a tibial-based height estimation model from the Amhara region of Ethiopia outperformed the current model [bias= −0.01 (95%CI: −10.37 to 10.34), d= 0.00]. On the contrary, other models based on the ulna or tibial length either under- or over-estimated male height in the range of 7.0–17.0 cm. In estimating female height (Table 6), two ulna-based models from Ghana and one among Black-Caribbean were comparable to the current model (d: 0.12 to o.37). However, while the current model underestimated female height by < 1.0 cm the Black-Caribbean model over-estimated female height by about 2 cm. A previous sex estimation

Table 3
Sex estimation models based on the length of the ulna and tibia.

Variable	Unstandardized coefficient (n = 115)		
	DF1 (UL)	DF2 (TL)	DF3 (UL+TL)
UL (cm)	0.477		0.544
TL (cm)		0.346	-0.163
Constant	-13.546	-14.315	-8.735
Group centroids			
Male	0.717	0.068	0.786
female	-0.514	-0.049	-0.563
Sectioning point (S.P)	0.203	0.019	0.223
Eigenvalue	0.375	0.003	0.451
Canonical correlation coefficient	0.522	0.058	0.557
Wilk’s Lambda	0.727	0.997	0.689
Chi-square	37.831	0.376	41.672
P-value	< 0.001	0.540	< 0.001

The models were created using discriminant function analysis with assumption testing. UL=ulna length, TL=tibial length, DF=discriminant function.

model based on ulna length from Tamale-Ghana was compared to the current study for their sex attribution accuracies on the holdout sample (Table 7). The sex classification accuracy was comparable for males but in females, the sex estimation accuracy was markedly higher in the present study than in the previous study.

Cohen’s d method vs the Bland-Altman method

From Table 5, an ulna-based model from India-Marathwada Region overstated the height of Ghanaian males by about 8 cm [bias= −7.62 (95%CI: −16.22 to 0.98)]. Meanwhile, per the Bland-Altman analysis, no significant differences existed between the observed and the estimated height even though the standardized mean difference was large (*d*=1.10). Also, the limit of agreement in the Bland-Altman analysis ranged from about − 16 cm to –1 cm. Similar results can be seen using the tibial length in males particularly the population-specific model from Italy-Ferrara [bias= −7.10 (95%CI: −17.53 to 3.32), *d*= 1.00]. Similarly, an ulna-based model from a population of mixed ethnicity from South Africa-Bloemfontein over-estimated the height of female Ghanaians by about 9 cm [bias= −8.64 (95%CI: −20.12 to 2.85)]. Even though no statistical difference existed between the observed and estimated height, the limit of agreement was wide and the standardized mean difference was large (*d*=1.49). The same can be said of the multivariable ulna and tibia-based model from the Amhara region of Ethiopia used in estimating the height of female Ghanaians [bias= −8.57 (95%CI: −21.36 to 4.23), *d*= 1.72] as shown in Table 6. On the other hand, where the standardized mean difference was negligible or small, the bias was also small and the limit of the agreement were relatively narrow (Tables 5 and 6).

Discussion

The study aimed to formulate sex and height estimation model equations using the percutaneous ulna and tibial lengths and to test their reliability as well as the reliability of other published model equations when used in the Ghanaian population. The ulna and tibial lengths were found to be reliable in the estimation of standing height and sex. Although there were population variabilities in height estimation models based on the ulna and tibial lengths, some models may be extrapolated to the Ghanaian population. The Bland-Altman method may have wider limits of agreement and caution should be observed when when assessing the reliability of height estimation models based on long bones.

The ulna length was better than tibial length in sex estimation, but their combination improved the average sex prediction accuracy to over 80%. Moreover, females were better classified by the ulna length while males were better classified by the tibial length. Although there were no significant sex difference in tibial length in this study, previous studies have observed that the lengths of the ulna and tibia are sexually dimorphic [6,7]. The sex differences in the ulna and tibial lengths may be due to differences in the effects of hormones as androgens in males tend to prolong bone growth, increases bone size, and delays its maturation as opposed to estrogens in females which do the reverse [2]. Sexual dimorphism may also arise due to sex-specific adaptations for reproduction, carriage and tasks [19,35]. For females to be better classified than males using the ulna length may indicate that there are more males in the Ghanaian population with more female-like ulna length such that more males are misclassified as females. Similarly, there may be more females with male-like tibia length leading to more females being misclassified as males. This may have led to the reduced prediction accuracies because while the female ulna lengths are clustered, that of males are spread widely, overlapping with that of females. Similarly, female tibia length had overlapped substantially with male values in the study population [36]. Although some authors have argued that the decision to use multivariable models for height or sex estimation should be at the discretion of the investigator because multivariable models do not always lead to better models [37,38], it has been shown in the current study that using multivariable models for sex estimation in anthropometric modeling is worth the effort.

The percutaneous ulna and tibia length are good estimators of height in the study population although the female models were less biased. Previous population-specific studies have also reported similar findings [1,27,33]. There is a linear relationship between the ulna and tibia length and that of height in both males and females. However, there may be sexual dimorphism in the relationship between long bones and height. This may be due to the differences in sex hormone activity, particularly during the pubertal period as pubertal testosterone in males is pro-chondrocyte proliferative while estrogen retards chondrocyte growth [2,39]. Different parts of the body may respond differently or at different rates to environmental factors. It may also mean that different body parts reach their genetically determined potential or maturity at different rates in response to environmental factors. Although genetics may play a major role, nutrition and disease are the two most common environmental factors that influence changes in long bones and their relationship with height [9,15,17].

Models from estimating sex and height, based on the length of the ulna and tibia showed variabilities by ethnicity or population and sex. Ethnicity here refers to a group of people with common descent,

Table 4
The sex estimation accuracies of the discriminant function models.

DF	Tested on the training sample (n = 115)						Tested on the holdout sample (n = 76) (%)		
	Original (%)			Cross-validation (%)					
	Male	Female	Average	Male	Female	Average	Male	Female	Average
1 (UL)	64.6	77.6	72.2	64.6	77.6	72.2	73.2	80.0	76.3
2 (TL)	56.3	49.3	52.2	56.3	49.3	52.2	51.2	60.0	55.3
3 (UL+TL)	66.7	76.1	72.2	66.7	76.1	72.2	82.9	82.9	82.9

The validity of the discriminant models was tested in the training sample by cross-validation using the leave-one-out method and also in the holdout sample. UL=ulna length, TL=tibial length, DF=discriminant function.

Table 5

Testing published height estimation models on the male holdout sample.

Study	Country/Location/ Population	n	age	LR Equation	SEE	Observed height (cm) Mean ± SD (173.1 ± 7.472), n = 41		
						Estimated Height (cm)	d	Bias (95%CI)
UL (cm)								
This study	Ghana-Tamale	89	18–30	y = 2.094 *UL+ 108.028	6.56	170.3 ± 4.292	**0.46**	2.75 (−6.52 to 12.02)
Amidu, Banyeh [25]	Ghana-Tamale	52	19–30	y = 2.640 *UL+ 97.611	4.634	176.1 ± 5.411	**0.46**	-3.08 (−11.76 to 5.61)
Ansah, Abaidoo [2]	Ghana-Kumasi	55	19–33	y = 3.360 *UL+ 72.58	–	172.5 ± 6.887	0.08	0.54 (−8.21 to 9.29)
Okai, Pianim [19]	Ghana-Kumasi	160	18–33	y = 2.970 *UL+ 84.22	0.22	172.6 ± 6.088	0.07	0.50 (−8.10 to 9.09)
Wube, Seyoum [1]	Ethiopia-Amhara Region	286	18–26	y = 1.890 *UL+ 119.68	5.12	175.9 ± 3.874	**0.47**	-2.84 (−12.43 to 6.76)
Emmanuel [11]	Nigeria-Delta State	74	19–30	y = 5.020 *UL+ 28.48	16.85	177.8 ± 10.29	***0.52***	-7.47 (−16.69 to 7.22)
Van den Berg, Nel [26]	South Africa-Bloemfontein (mixed ethnicity)	104	19–60	y = 3.600 *UL+ 79.20	–	186.3 ± 7.379	1.78	-13.22 (−22.20 to −4.24) *
Sarma, Das [27]	India-Khasi Tribe	118	25–45	y = 5.495 *UL+ 26.71	–	190.2 ± 11.26	**1.79**	-17.09 (−30.45 to −3.74) *
Inamdar and Sultan [28]	India-Marathwada Region	150	18–24	y = 3.044 *UL+ 90.14	–	180.7 ± 6.239	**1.10**	-7.62 (−16.22 to 0.98)
Sah, Rana [29]	Nepal-Birgunj	150	20–45	y = 2.540 *UL+ 94.23	7.18	169.8 ± 5.206	***0.51***	3.28 (−5.47 to 12.03)
Madden, Mashanova [13]	British-White	38	≥ 21	y = 3.260 *UL+ 87.66	–	184.6 ± 6.682	**1.62**	-11.57 (−20.25 to −2.88) *
	Caribbean-Black	59	≥ 21	y = 3.260 *UL+ 81.63	–	178.6 ± 6.682	***0.78***	-5.54 (−14.22 to 3.15)
TL (cm)								
This study	Ghana-Tamale	89	18–30	y = 1.288 *TL+ 117.165	6.88	170.4 ± 5.014	**0.42**	2.74 (−7.57 to 12.85)
Wube, Seyoum [1]	Ethiopia- Amhara Region	286	18–26	y = 1.140 *TL+ 125.93	4.57	173.1 ± 4.438	0.00	-0.01 (−10.37 to 10.34)
Chay, Batún [30]$^{\#}$	Mexico-Rural Maya	37	21–45	y = 2.5133 *TL+ 711.658	3.76	175.1 ± 9.784	**0.23**	-2.04 (−15.42 to 11.34)
	Mexico-Urban Maya	45	21–45	y = 2.6557 *TL+ 663.57	2.63	176.2 ± 10.34	**0.34**	-3.12 (−17.23 to 10.99)
Gualdi-Russo, Bramanti [21]	Italy- Ferrara	219	20–35	y = 1.663 *TL+ 111.39	5.01	180.2 ± 6.747	**1.00**	-7.10 (−17.53 to 3.32)
Saco-Ledo, Porta [32]	Spain- Barcelona	495	18–55	y = 3.29 *TL+ 48.00	3.29	157.9 ± 0.000	**1.00**	16.14 (0.49–29.78) *
UL+TL (cm)								
This study	Ghana-Tamale	89	18–30	y = 1.530 *UL+ 0.798 *TL+ 91.783	6.114	170.3 ± 5.636	**0.42**	2.76 (−5.16 to 10.68)
Wube, Seyoum [1]	Ethiopia-Amhara region	286	18–26	y = 0.900 *UL+ 0.920 *TL+ 110.760	4.42	175.6 ± 4.956	**0.39**	-2.52 (−11.21 to 6.17)

The observed and the estimated height were compared using the Bland-Altmann method while the effect size of their mean difference was estimated using Cohens d: negligible ($d<0.20$), **small** ($0.20 \le d<0.50$), ***medium*** ($0.50 \le d \le 0.80$) and **large** ($d>0.80$). $^{\#}$Height was estimated in millimeters (mm) and then converted to centimetres (cm). *Significant at P < 0.050.

homeland and history while population may refer to a group of people with shared characteristics. Ethnicity and population may therefore overlap and sometimes interchangeable [40]. It was observed that height-estimation models from populations in Kumasi-Ghana, as well as those from Tamale-Ghana, were similar to the current study in reliability. In general, models that were formulated outside the study populations either over-estimated or under-estimated the observed height with medium to large effect size. However, this was not a universal observation since population-specific models from the Amhara region of Ethiopia and Mexican Maya out-performed the current models in estimating the height of Ghanaian males [30,41]. When published ulna- and tibia-based height estimating equations were applied in a Turkish healthy male adults population, it was observed that the study population-specific model equation was more precise, however, a model for a Mongoloid population was as well comparable (bias: ulna= −1.92 cm, tibia= −0.01 cm) to the population-specific model [12]. However, a White population-based equation was less precise compared to the Mongoloid's. Other Turkish-based models for height estimation using the ulna and tibia lengths fared well but were better than non-Turkish models [12]. In one study where recent ulna-based height estimation models for women from West Bengal and Vietnam were tested on adult Asians based in the United Kingdom, it was observed that there were significant differences between the actual and the estimated height. This was because there was more heterogeneity in the UK-based Asian population than in the Vietnamese or West Bengal sample from which the models were derived [13]. It was observed that recent height estimation models from a combined sample of Black Caribbean, Indians and other Asians performed well in estimating height in a historically Black sample. Similarly, recent models from other Asians (except Indians) could estimate the height of a historically Asian sample including Indians [14].

The similarities, as well as the variabilities in sex and height estimation models based on the ulna and tibia length may be attributed to several factors. Height and the length of long bones such as the ulna and tibia are influenced by population, socioeconomic factors, intrauterine and childhood nutrition as well as diseases during the window of growth [13]. There are substantial global inequalities in disease burden, socioeconomic variables as well as nutrition which may confound sex and

Table 6
Testing published height estimation models on the female holdout sample.

Study	Country/Location/ Population	n	Age (years)	LR Equation	SEE	Observed height (cm) Mean ± SD (163.5 ± 7.031), n = 35		
						Estimated Height (cm)	*d*	Bias (95%CI)
UL (cm)								
This study	Ghana-Tamale	102	18–29	y = 2.258 *UL+ 100.385	4.20	162.8 ± 3.545	0.13	0.73 (−10.74 to 12.20)
Amidu, Banyeh [25]	Ghana-Tamale	47	19–30	y = 2.598 *UL+ 92.341	3.747	164.2 ± 4.078	0.12	-0.62 (−12.08 to 10.83)
Ansah, Abaidoo [2]	Ghana-Kumasi	45	18–45	y = 1.400 *UL+ 123.78	–	162.5 ± 2.198	0.19	1.05 (−10.88 to 12.99)
Okai, Pianim [19]	Ghana-Kumasi	140	18–22	y = 2.980 *UL+ 84.22	0.23	166.6 ± 4.678	***0.52***	-3.06 (−14.61 to 8.49)
Wube, Seyoum [1]	Ethiopia-Amhara Region	286	18–26	y = 0.390 *UL+ 155.60	3.98	166.4 ± 0.612	***0.58***	-2.85 (−16.00 to 10.30)
Emmanuel [11]	Nigeria-Delta State	76	19–30	y = 4.030 *UL+ 55.71	5.02	167.1 ± 6.326	***0.54***	-3.58 (−15.97 to 8.91)
Van den Berg, Nel [26]	South Africa-Bloemfontein (mixed ethnicity)	96	19–60	y = 2.770 *UL+ 95.60	–	172.2 ± 4.348	**1.49**	-8.64 (−20.12 to 2.85)
Sarma, Das [27]	India-Khasi tribe	46	25–45	y = 5.777 *UL+ 19.09	–	178.8 ± 9.069	**1.89**	-15.25 (−30.52 to 0.02)
Inamdar and Sultan [28]	India-Marathwada region	150	18–24	y = 2.455 *UL+ 112.1	–	180.0 ± 3.854	**2.91**	-16.43 (−27.88 to −4.98) *
Sah and Bhaskar [33]	Nepal-Birgunj	150	20–45	y = 2.370 *UL+ 94.11	4.72	159.6 ± 3.720	***0.69***	3.91 (−7.55 to 15.37)
Madden, Mashanova [13]	British-White	17	≥ 21	y = 3.260 *UL+ 81.70	–	171.8 ± 5.118	**1.35**	-8.28 (−19.97 to 3.41)
	Caribbean-Black	5	≥ 21	y = 3.260 *UL+ 75.67	–	165.8 ± 5.118	**0.37**	-2.25 (−13.94 to 9.44)
TL (cm)								
This study	Ghana-Tamale	102	18–29	y = 1.458 *TL+ 102.011	4.906	162.0 ± 2.942	**0.28**	1.50 (−9.85 to 12.84)
Wube, Seyoum[1]	Ethiopia- Amhara Region	286	18–26	y = 0.310 *TL+ 154.49	3.89	167.3 ± 0.626	***0.76***	-3.72 (−16.81 to 9.37)
Chay, Batún[30]#	Mexico-Rural Maya	63	21–45	y = 2.558 *TL+ 631.96	29.35	168.5 ± 5.162	**0.81**	-4.98 (−16.22 to 6.26)
	Mexico-Urban Maya	26	21–45	y = 2.849 *TL+ 557.162	28.70	173.0 ± 5.749	**1.48**	-9.48 (−20.97 to 2.02)
Gualdi-Russo, Bramanti [21]	Italy- Ferrara	155	20–29	y = 1.899 *TL+ 94.45	4.62	172.6 ± 3.832	**1.61**	-9.10 (−20.20 to 1.997)
Saco-Ledo, Porta [31]	Spain- Barcelona	351	18–55	y = 2.210 *TL+ 82.40	3.46	173.4 ± 4.460	**1.68**	-9.86 (−20.94 to 1.24)
UL+TL (cm)								
This study	Ghana-Tamale	102	18–29	y = 1.815 *UL+ 0.709 *TL+ 83.308	3.994	162.7 ± 3.844	0.14	0.86 (−9.86 to 11.59)
Wube, Seyoum [1]	Ethiopia-Amhara region	286	18–26	y = 0.020 *UL+ 0.300 *TL+ 154.22	3.89	172.1 ± 0.825	**1.72**	-8.57 (−21.36 to 4.23)

The observed and the estimated height were compared using the Bland-Altmann method while the effect size of their mean difference was estimated using Cohens *d*: negligible (*d*<0.20), **small** (0.20 ≤*d*<0.50), ***medium*** (0.50 ≤*d*≤0.80) and **large** (*d*>0.80). # Height was estimated in millimeters (mm) and then converted to centimeters (cm). *Significant at P < 0.050.

Table 7
Test of sex estimation accuracies of discriminant models on the holdout sample.

Study	Country/ Location	n	Age (years)	DF Equation		Tested on the holdout sample (n = 76)		
						Male	Female	Average
UL (cm)								
This study	Ghana-Tamale	191	18–30	y = 0.477 *UL-13.546	0.203	73.2	80.0	76.3
Banyeh, Bani [34]	Ghana-Tamale	99	19–32	y = 0.623 *UL-17.734	0.000	75.6	68.6	72.4

DF=discriminant function, UL=ulna length, S. P = sectioning point.

height estimation models. Populations in the developing world have a disproportionately poor socioeconomic status leading to a higher disease burden, coupled with under- and malnutrition which may affect sexual dimorphism in bone development and also prevent the attainment of a person's genetically determined height [14]. Moreover, there is a general loss of height with age, although there is no evidence of change in ulna length with age. The accuracies of sex estimation models have also been found to vary within populations due to heterogeneity in ethnic distribution [13]. There are also changes in secular trends and socioeconomic factors even within populations which have short-term effects on sexual dimorphism [6]. Therefore, extrapolating an aged height-estimation model onto a younger population and vice-versa may introduce errors. Some previous studies have recommended the use of age-specific formulae derived from the ulna and tibia for height estimation in a given population [10,14,31,32]. Some authors have even advised against the use of height estimation models that are based on the ulna length because the models were found to have an over-estimated height of about 6.2 cm in males and 8.1 cm in females [42].

The choice of statistical method for model validation is vital in height estimation using the ulna and tibia length. It was observed that although the Bland-Altman method may have indicated that there was little bias and that there was no significant difference between the observed and the estimated height, the standardized mean differences (Cohen's *d*) may be large ($d > 0.80$). This arose from the observation that the Bland-Altman analysis produced wider limits of agreement (95%CI) which reduced the reliability of the models [43,44]. Similar findings were observed in a previous study making the authors not recommend the use of ulna length in the estimation of height [23]. A smaller mean difference (not bias), between the observed and the estimated height, is a better indicator of a more reliable model [13]. However, it is argued that the acceptability of the limits of the agreement should be set priori since the Bland-Altman method does not state whether the limits of the agreement are acceptable or not [45,46].

The current study is among a few studies in Ghana to formulate new models for sex and height estimation using percutaneous lengths of the ulna and tibia and to test their validity along with other population-specific models. The study has indicated that population-specific models may be extrapolated despite the popular opinion that such models are specific to a given population. Also, the statistical methods used were appropriate because there was assumption testing before their selection. The reliability of the Bland-Altman method for model validation was cross-checked with the standardized mean difference (Cohen's *d*). However, the authors acknowledge that the Ghanaian population is not homogeneous. There are different cultural groups in Ghana with phenotypic variabilities. We, therefore, recommend that future studies should focus on specific cultural groups for sex and height estimation models based on the percutaneous lengths of the ulna and tibia.

Conclusion

The sex and height of the study population can be estimated with a high degree of reliability using the ulna and tibia lengths for height and their combination for sex. Height estimation models from one population may be extrapolated to another population although variabilities exist. In testing the reliabilities of height estimation models based on the ulna or tibial lengths, the standardized mean difference (Cohen's *d*) should be preferred to the Bland-Altman method.

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Competing interest statement

The authors declare no competing interest.

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