International Journal of Science and Research (IJSR)
ISSN (Online): 2319-7064
Index Copernicus Value (2013): 6.14 | Impact Factor (2013): 4.438

Foot Anthropometry: A Forensic and Prosthetic Application

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Abstract: ***Foot dimensions/measurements are important in prosthetic designs, fabrication and fittings and its application in height estimation is continually being investigated. Objectives: The present study examines the relationship between height and foot dimensions in the Igbos, Nigeria, for forensic and prosthetic application. Materials and Methods: Height (Y), Foot length (FL), foot height (FH) foot breath (FB), and bimalleolar breadth (BMB) of 211subjects comprising of 123 females and 88 males were measured after obtaining an informed consent. The data obtained were analyzed using SPSS 17.0. Results: Sex differences were found to be highly significant (P < 0.0001) for all the measurements with males having higher values than the females. The multiple linear regression generated using BMB, FB, and FL provide the highest reliability and accuracy (R= 0 .616) in both genders together than the simple linear regression generated using FL, (R= 0.555). For the females, the highest reliability and accuracy was obtained using FL, (R= 0.481) only, while the multiple linear regression generated using BMB and FL provide that of the male's (R= 0.500). Conclusion: The foot dimensions obtained here would be useful in the design and fabrication of foot prosthesis and orthosis for the Igbos, Nigeria, which would help to approximate the normal gait in cases of amputation of lower extremity. The generated linear and multiple regressions models are of utmost importance in height reconstruction for the study population in cases of mass/man-made disaster or crime investigation.***

Keywords: Anthropometer, foot dimensions, sliding caliper, height, prosthetics.

1. Introduction

Anatomically and functionally the zones of the foot are: the hind-foot (calcaneus and talus), the mid-foot (navicular, cuboid, and three cuneiforms), and the forefoot (five metatarsals and fourteen phalanges [1] [2] . The characteristics of these bones and its landmarks are necessary for understanding the structure of the foot [1] and foot anthropometry. The foot provides a platform for supporting the body when standing and has an important role in locomotion/propulsion [1] [2] .Its dimensions/measurements are important tool in prosthetic designs, fabrications and fittings and its application in height estimation is continually being investigated.

Its reliability on the prediction of height has been reported to be as high as that from long bones [3] [4] [5] [6] [7] . Ossification and maturation in the foot bones begins earlier than that of the long bones of the body because of that, age and height could be more accurately predicted from foot measurements as compared to that of long bones [6] .

Due to the strong correlation between one's stature and foot size, forensic experts have been able to reconstruct height from foot prints and also the measurement of foot has helped the prosthetist to construct a missing foot from the available one (contralateral foot) and the orthotist in the construction of orthotic device for the management of foot deformities like club foot and sprain ankle etc.

The morphology of human feet is greatly influenced by combined effects of heredity and living style. These determine the size and shape of the feet and footprints and thereby making those unique data to establish human identity [8] . This study tries to establish the foot anthropometry of the Igbos in Nigeria which would be useful in height reconstruction in cases of mass / manmade disaster or criminal activity and in prosthetic and Orthotic designs of the foot.

2. Materials and Methods

This study was based on a random sampling of 211 subjects (females, *n* = 123, and males, *n* = 88) aged 16 - 45 years of the Igbo extraction of Nigeria, and attention was paid to height prediction using foot anthropometry and its application in prosthetics and orthotics. Subjects gave their informed consent before data were collected.

3. Study Location and Duration

The present study was carried out in Imo State, Nigeria and it covered a period of ten months as follows:

(i) Eight months for field work. (ii) Two month for data analysis and interpretations.

Demographics: The subjects gave information on their age, sex, and state of origin.

Exclusion criteria: Subjects who were not of Igbo extraction and pregnant women were not included in the study. Individuals with musculoskeletal disorder affecting height and foot were also excluded in this study.

Anthropometrics: Height was measured and the following foot measurements were taken (see figure 1 and 2) in centimeters using a sliding caliper:

Height (Y) was measured to the nearest 0.1 cm from the vertex using an Anthropometry with subjects standing without shoes with the heels held together, toes apart, and the head held in the Frankfort plane [9].

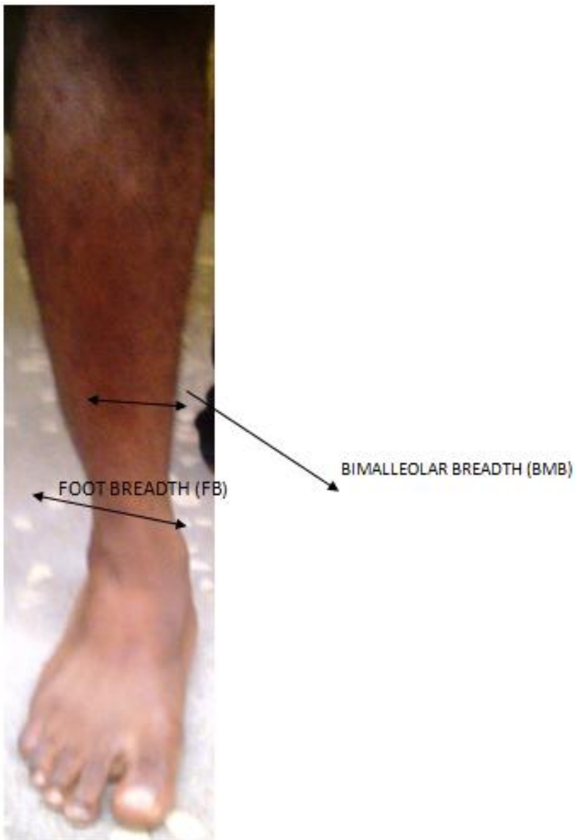
Foot height (FH) was calculated as the distance between the distal part of the lateral malleolus and the floor.

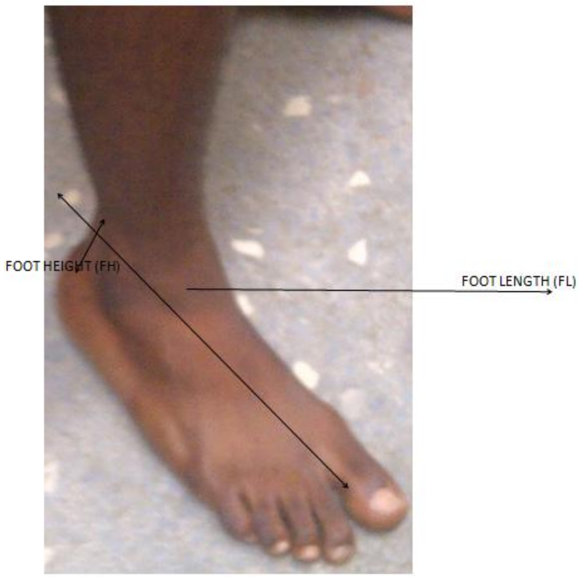
Foot Breadth (FB) is measured as the distance between the lateral and medial sides at the metataso-phalanygeal region using a sling caliper.

Foot length (FL) is the maximum distance between the most anterior and the most posterior projecting part of the foot, measured with a sliding caliper.

BiMalleolar Breadth (BMB) the right ankle bimalleolar breath was taken at the maximum projection on the medial and lateral malleoli using a sliding caliper [10].

All measurements were taken percutaneous.





4. Result

Table 1 shows the descriptive statistics of both genders for foot anthropometry. The mean value for the dependent variable (height) of the population under study was 167.55 ± .9.10 while those of the explanatory variables (X) are as in the table. The mean value for the female's stature was 163.17 ± 7.64 while that of the males was 173.66 ± 7.30; the mean value for female's foot length (FL) was 25.25cm; that of the males was 27.50cm; the values for the rest of the variables are as in tables (Tables 2 and 3).

Table 1: Descriptive statistics of both genders put together, foot anthropometry (cm)

Variables	*N*	*Minimum*	*Maximum*	*Mean*	*Standard Deviation*
AGE (years)	211	16	45	23.58	4.95
Y (cm)	211	149.00	190.00	167.55	9.10
FH	203	3.30	8.00	5.31	1.03
FL	207	22.00	40.00	26.19	2.07
FB	207	5.90	12.40	8.58	1.47
BMB	206	5.20	11.60	6.90	0.91

Y= Height, FH= Foot Height, FL= Foot Lenght, FB= Foot Breath, BMB= Bimalleolar Breadth

Table 2: Descriptive statistics of females

Variables	*N*	*Minimum*	*Maximum*	*Mean*	*Standard Deviation*
AGE (years)	123	16	45	23.74	5.356
Y (cm)	123	149.00	190.00	163.1715	7.64279
FH	118	3.30	7.40	5.0419	.89836
FL	121	22.00	29.30	25.2537	1.45063
FB	121	5.90	11.00	8.2299	1.31076
BMB	121	5.20	8.80	6.5421	.60686

Y= Height, FH= Foot Height, FL= Foot Length, FB= Foot Breath, BMB= Bimalleolar Breadth

Table 3: Descriptive statistics of males

Variables	*N*	*Minimum*	*Maximum*	*Mean*	*Std. Deviation*
AGE (years)	88	18	43	23.35	4.337
Y (cm)	88	156.00	190.00	173.6602	7.29561
FH	85	3.90	8.00	5.6894	1.08197
FL	86	24.00	40.00	27.5012	2.10811
FB	86	6.20	12.40	9.0635	1.54321
BMB	85	5.90	11.60	7.4100	1.02689

Y= Height, FH= Foot Height, FL= Foot Length, FB= Foot Breath, BMB= Bimalleolar Breadth

Table 4 represents a comparison of variables between females and males in foot anthropometry. It reveals that FH, FL, FB, BMB are highly significant in males than females as $P < 0.0001$.

Table 4: Comparison of variables between females and males in foot anthropometry

VARIABLES (CM)	Paired Differences					T	Df	Sig. (2-tailed)
				95% Confidence Interval of the Difference				
	Mean	SD	Std. Error Mean	Lower	Upper			
Y (F) - Y (M)	-14.00682	3.77036	.40192	-14.80568	-13.20796	-34.850	87	.000
FH (F) - FH(M)	-.65964	1.35472	.14870	-.95545	-.36383	-4.436	82	.000
FL(F) - FL(M)	-2.56471	2.44247	.26492	-3.09153	-2.03788	-9.681	84	.000
FB(F) - FB(M)	-.86541	2.07111	.22464	-1.31214	-.41868	-3.852	84	.000
BMB(F) - BMB(M)	-.94417	1.18125	.12888	-1.20051	-.68782	-7.326	83	.000

Y= Height, FH= Foot Height, FL= Foot Length, FB= Foot Breath, BMB= Bimalleolar Breadth, (F)= Female, (M)= Male

The Pearson correlations (r) between the dependent variable and the explanatory variables for both genders, females and males are given in tables 5, 6 and 7 respectively. In both genders all the four explanatory variables were significantly correlated with stature. The correlation between height (Y) and foot length (X_{FL}) i.e. r = 0.555 was better than that between Y and bimalleolar breath (X_{BMB}) i.e. r = 0 .405 in both genders. The least significant correlation was noted in FB (r = 0.150) in both genders.

In females, there were no significant correlations between FH, FB, BMB and Y. As such FH, FB and BMB could not be used to construct regression equations for the females; while the correlation between female's height (Y_F) and female's foot length (X_{FFL}) was 0.26.

In males, the correlation between male's height (Y_M) and males foot length (X_{MFL}) i.e. r = 0.481, was better than that between Y_M and male's bimalloli breadth (X_{MBMB}) i.e. r = 0.220. There was no significant correlation between Y_M and $X_{M FH}$ as well as with $X_{M FB}$.

Table 5: Correlation coefficients between height (Dependent variable) and foot variables (Explanatory variables) in both genders

Variables	*N*	*Pearson Correlation*	*Sig. (2-tailed)*
FH	203	.224**	.001
FL	207	.555**	.000
FB	207	.150*	.030
BMB	206	.405**	.000

*. Correlation is significant at the 0.05 level (2-tailed).
**. Correlation is significant at the 0.01 level (2-tailed).

Table 6: Correlation coefficients between height (Dependent variable) and foot variables (Explanatory variables) in females

Variables	*N*	*Pearson Correlation*	*Sig. (2-tailed)*
FH	118	.027	.772
FL	121	.264**	.003
FB	121	-.123	.178
BMB	121	.170	.062

FH= Foot Height, FL= Foot Length, FB= Foot Breath, BMB= Bimalleolar Breadth
*. Correlation is significant at the 0.05 level (2-tailed).
**. Correlation is significant at the 0.01 level (2-tailed).

Table 7: Correlation coefficients between height (Dependent variable) and foot variables (Explanatory variables) in males

Variables	*N*	*Pearson Correlation*	*Sig. (2-tailed)*
FH	85	.099	.369
FL	86	.481**	.000
FB	86	.134	.220
BMB	85	.220*	.043

*. Correlation is significant at the 0.05 level (2-tailed).
**. Correlation is significant at the 0.01 level (2-tailed).

Table 8 shows the constant, regression coefficient and the variation explained of foot variables with the dependent variable (Y) in both genders. The combination of BMB, FB, and FL contributed 38% to the variation in the dependent variable.

The computed values of the multiple correlation coefficients R, of the coefficients of determinations R^2 and $R^2_{adjusted}$, and the standard errors of the estimates (SEE), [11] of all possible and multiple linear regression equations for each of the variables were tested for the best model (Table 9). The multiple linear regression models was found to be the best model with the highest values for multiple correlation coefficient R as 0.616, coefficient of determination R^2 as 0.380 and $R^2_{adjusted}$ as 0.370 and with 7.201 SEE.

According to all possible simple and multiple linear regression analysis, the best multiple linear equation to estimation Y from foot dimensions in both genders together is Y= 95.785 + 2.363 (BMB) - 0.827(FB) + 2.454 (FL).

When the explanatory variables were considered one after the other, the best linear equation used to regress height is Y= 103.654 + 2.436 (FL); however Y could also be estimated from any segment of the foot as in table 10.

Table 8: Constant, Regression coefficient and Variation explained (r2) of foot variables with Y (dependent) variable in both genders

	Constant	*Regression Coefficient*	*r2*	*p value*
FH	156.999	1.989	.050	.001
FL	103.654	2.436	.308	.000
FB	159.467	.932	.023	.030
BMB	139.664	4.036	.164	.000
BMB, FB, FL	95.785	2.363 -.827 2.454	.380	.000 .036 .000

FH= Foot Height, FL= Foot Length, FB= Foot Breath, BMB= Bimalleolar Breadth

Table 9: R, R^2, Adjusted R^2, and SEE of both genders in foot anthropometry

Variables	*R*	*R^2*	*Adjusted R^2*	*SEE*
FH	.224	.050	.045	8.91880
FL	.555	.308	.305	7.57598
FB	.150	.023	.018	9.00671
BMB	.405	.164	.160	8.31582
BMB, FB, FL	.616	.380	.370	7.20119

FH= Foot Height, FL= Foot Length, FB= Foot Breath, BMB= Bimalleolar Breadth

Table 10: Regression Equations for estimation of Y in both genders from foot measurements

Regression equation	*SEE*
Y =156.999+1.989 (FH)	8.91880
Y =103.654+2.436 (FL)	7.57598
Y=159.467+.932 (FB)	9.00671
Y =139.664+4.036 (BMB)	8.31582
Y =95.785+2.363 (BMB) -.827(FB) + 2.454 (FL)	7.20119

(FH)= Foot Height, (FL)= Foot Length, (FB)= Foot Breath, (BMB)= Bimalleolar Breadth, SEE= Standard error of estimate, Y= Height

The mean predicted value of height through the regression function was similar to the mean observed value; however the minimum and maximum value indicated that there were differences in the predicted and observed value. (Table 11)

Table 11: Minimum, Maximum, Mean and standard deviations of the predicted Values of Y by regression functions using foot parameters in both genders

Observed value		*Minimum*	*Maximum*	*Mean*	*Std. Deviation*	*N*
		149.00	190.00	167.5460	9.1027	211
Predicted value from:	FH	163.5618	172.9084	167.5650	2.04432	203
	FL	157.2572	201.1141	167.4599	5.04782	207
	FB	164.9656	171.0238	167.4599	1.36760	207
	BMB	160.6530	186.4856	167.5155	3.67981	206
	BMB, FB, FL	156.5243	199.5272	167.5155	5.59090	206

FH= Foot Height, FL= Foot Length, FB= Foot Breath, BMB= Bimalleolar Breadth

In the females only one linear regression equation was derived for the foot measurement using FL and this indicates that the constant was 127.78 and the regression coefficient was 1.40 (Table 12).

For the males the constant ranged from 123.608 – 162.475; while the coefficient of regression was around 1.118-1.667 (Table 12). The regression coefficients were significant indicating that they are contributing for the prediction of height in females as well as in the males. The variation explained (r2 x 100) showed that it was 7.0% in the females while it ranged from 4.8% to 25.00% in the males.

Table 12: Constant, Regression coefficient and Variation explained (R^2) of foot anthropometry with Stature (dependent) variables in females and males

Variables	*Females*				*Males*			
	Constant	*Regression Coefficient*	*R^2*	*p value*	*Constant*	*Regression Coefficient*	*R^2*	*p value*
FL	127.775	1.401	.070	.003	127.687	1.667	.232	.000
BMB					162.475	1.518	.048	.043
BMB, FL					123.608	1.520 1.118	.250	.000 .097

FH= Foot Height, FL= Foot Lenght, FB= Foot Breath, BMB= Bimalleolar Breadth

The multiple linear regression model was found to be the best model with the highest values for multiple correlation coefficient R as 0.500, coefficient of determination R^2 as 0.250 and $R^2_{adjusted}$ as 0.232 and with a lower SEE as 6.21064 for themale's explanatory variables than either the simple linear regression models obtained in the females or males (Tables 13 and 14).

Table 13: R, R^2, Adjusted R^2, and SEE of foot anthropometry in females and males

Variables	Females				Males			
	R	R^2	Adjusted R^2	SEE	R	R^2	Adjusted R^2	SEE
FL	0.264	0.070	0.062	7.443	0.481	0.232	0.223	6.434
BMB					.0220	0.048	0.037	6.953
BMB, FL					0.500	0.250	0.232	6.214

FL= Foot Length, BMB= Bimalleolar Breadth

Table 14: Regression Equations for estimation of height in females of foot anthropometry in females and males

Females		*Males*	
Regression equation	*SEE*	*Regression equation*	*SEE*
Y = 127.775 + 1.401 (FL)	7.44290	Y =127.687+ 1.667 (FL)	6.43420
		Y =162.475 + 1.518 (BMB)	6.95245
		Y = 123.608 +1.520 (BMB) +1.118 (FL)	6.21064

(FL)= Foot Length, (BMB) = Bimalleolar Breadth SEE= Standard error of estimate, Y= Height

Table 15: Minimum, Maximum, Mean and standard deviations of the predicted Values of height by regression functions with the foot parameters in the females and males

Observed value		*Females*					*Males*				
		Min	*Max*	*Mean*	*SD*	*N*	*Min*	*Max*	*Mean*	*SD*	*N*
		149.00	190.00	163.18	7.64	123	156.00	190.00	173.66	7.30	88
Predicted value from:	FL	158.60	168.82	163.15	2.03	121	167.68	194.35	173.52	3.51	86
	BMB						171.43	180.07	173.72	1.56	85
	BMB, FL						167.31	192.79	173.72	3.54	85

FL= Foot Length, BMB= Bimalleolar Breadth, SD= Standard deviation

The mean predicted value of Y through the regression function was similar to the mean observed value; however the minimum and maximum value indicated that there were differences in the predicted and observed value. The minimum predicted value overestimates the minimum observed value in the two sexes; the maximum predicted value using BMB in males and FL in the females underestimate the maximum observed value. The rest of the parameter (BMB and FL combined) overestimate the maximum predicted value in the males (Table 15).

5. Discussion

Four dimensions of the foot including height of the subjects were taken. The prediction function was derived through linear regression and multiple regressions for each of the measurement with height, for both gender and for the males and females separately.

In this study, the mean height for the population under study is 167.55± 9.00cm, while that of the female and male are163.17 ± 7.64cm, and173.66 ±7.30cm respectively.

In sexing the foot parameters, all the variables were highly significant (P< 0.0001). These values were higher in the males than in the females. In support of this is the report by [12] that males had significantly higher values of foot length and foot breadth than females, p <0.001. Male's and female's feet dimensions in this present study has higher mean value than that of Caucasians. This observation must be put into consideration while constructing prosthetic feet and foot orthosis for the Igbos, Nigeria.

The findings of the present study indicate that the correlation 'r' between height and foot measurements were significant for FH, FL, FB and BMB in both genders put together; the highest correlation between the dependent variable and the independent variable (FL) in both gender was 0.555 (P< 0.0001). In the females the correlation 'r' between the dependent variable and the explanatory variables was significant for FL, only. In the males the study revealed that the correlation 'r' between the dependent variable and the explanatory variable was significant for FL and BMB. The highest correlation 'r' between the dependent variable and the explanatory variable (FL) was 0.41 (P< 0.0001). This implies that foot dimensions are proportionate to Y. Therefore an individual with a missing lower extremity should go for foot prostheses or orthoses who's FL is proportionate to Y in other to approximate his/her normal gait.

[13] in their study noted that the correlation 'r' between stature and FL, in males, females and both genders together was 0.716, 0.699 and 0.873 respectively. The highest correlation between stature and the explanatory variables was recorded in both genders together, and this agrees with our findings but our 'r' value (0.555) is lower but highly significant (P< 0.0001).

[6] estimated height from measurements of foot length in Gujarat region of India. The mean height and foot length (FL) of the male and female in their study were 170.96cm and 24.44 cm, 156.14 cm and 22.34cm respectively. These values are lower than that gotten in this study. This observation may be due to environmental factors and racial variation.

The value of coefficient of determination R^2 for the multiple linear regression equations with height as the dependent variable and BMB, FB and FL as explanatory variables in both genders together was 0.380. This means that 38% of the total variation in height is explained by the explanatory variables BMB, FB and FL in both genders together.

The values of multiple correlation coefficient R for the multiple linear regression equations for both genders together and males were 0.616 and 0.500 respectively, while the SEE were 7.201 and 6.21. This means that the multiple linear regression models for both genders together as well as for the males fits very well to the observed data (tables 9 and 13) unlike the linear regression model.

The correlation coefficient between height and FH, FL, FB, and BMB were strong in both genders together. It was also significant between height and FL in both males and females and significant for BMB in females only. This means there is a strong bond between height and FH, FL, FB, and BMB and if either of the dimensions is known, the other can be calculated and this would be of utmost important to Anthropologist, Forensic experts, Prosthetist and Orthotist.

[14] in his study to estimate stature from dimensions of hands and feet in North Indian population observed that the correlation between stature and all the measurements of hand and feet were positive and statistically significant. The highest correlation coefficient between stature and foot length and the lowest SEE indicated that the foot length provides the highest reliability and accuracy in estimating stature of unknown individuals. This is in agreement with our finding where the FL in males provided a low SEE; however the multiple regression analysis yielded a much lower SEE using FL and BMB in both genders.

In support of our findings also is the report by [5] that FL displays a biological correlation with height (Y). Y can be estimated from foot when such evidence provides an investigator the best or only opportunity to gauge that aspect of a suspect's physical description. Their study was intended to determine percentages and linear regressions for determining Y from FL for young adult males and females based upon very large U.S Army Anthropometric database.

[6] estimated height from measurements of foot length in Gujarat rejoin of India. Measurement of foot length and body height of 502 students aged 17-22 was taken. The data obtained was analysed and they made attempt to find out correlation and to derive a regression formula between foot length and height. Their result showed a strong correlation between Y and FL; if one of the measurements (FL or total Y) is known, the other could be calculated. Our findings in this present study is congrant with above since FL has significant correlation with Y.

The estimation of stature and determination of gender through foot measurement has been performed [15] . Anthropometric measurements used include: length, width, malleolar height, navicular height measurements of the right and left feet as well as the stature from 249 subjects. From the research, it was observed that while stature estimation dependent on the gender yielded 9 – 10cm errors, those that are independent on gender yielded less than 4cm errors. The study hence concluded by suggesting that stature estimation can be obtained using foot measurements. Our study agrees with this conclusion, in addition, we also regressY with FH and BMB in both genders.

The foot dimension/measurement used in stature estimation has also been found to vary according to gender. In their study, [16] examined the relationship between stature and foot dimensions among Gujjars in India. Stature, foot length and breadth of 200 subjects comprising of 100 males and 100 females were measured. The study showed that bilateral variation for all measurements except for the foot breadth in males were insignificant. The study also showed that sex differences were highly significant for all the measurement and that the correlation coefficient between stature and the foot measurements were highly significant. More importantly, the study stipulated that the foot length provides the highest reliability and accuracy in stature estimation in males while the foot breadth provides the highest reliability and accuracy in stature estimation in females. Comparing the above with our findings, we noted a highly significant sex differences in FH, FB and FL with males having a high value. The multiple linear regression generated using BMB, FB, and FL provided the highest reliability and accuracy (R= 0 .616) in both genders together than the simple linear regression generated using FL, (R= 0.555).

For the females, the highest reliability and accuracy was obtained using FL, (R= 0.481) only, while multiple linear regression generated using BMB and FL provided that of the male's (R= 0.500).

Many factors have been documented to influence changes in the size and morphology of foot. Such factors include sex, weight, pregnancy, nutrition, age, genetics, disease, and even environmental conditions [17] [18] [19] [20] .In many of the published works males have significantly high foot length than females. [21] in their study aimed to determine whether proportionate foot length is sexually dimorphic and if so the nature of that dimorphism. They surveyed genetically disparate populations using data from three previous anthropometric studies [10] [22] [23] and foot tracing from the Steggerda Collections at US National Museum of Health and Medicine. Their analyses explored sex differences in the ratio between FL and stature, and tested for nonlinearity. Results although varying in degree across populations, proportionate to stature, female's FL is consistently smaller than male FL; this is in accordance with our findings. However, [24] examined 60 individuals aged 17-18 years and noted proportionate foot length as the same in males and females.

Since the estimation of Y is a very important step in developing a biological profile for forensic identification [25] ; the regression equations obtained in this very study were checked for their accuracy by comparing the predicted Y and actual/observe Y. The results obtained here were comparable and has utmost application in forensic investigation, design and production of foot prosthesis and orthoses since the foot anthropometry of the study population has been established and regression equations generated.

Conclusively, if the Y of the subject or any of the foot dimensions (FL, FB, FH, and BMB) is known the other could be generated from the regression equations constructed by applying simple substitution.

Acknowledgment

I sincerely use this space to express my gratitude to the subjects who participated in this study.

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