Taylor & Francis
Taylor & Francis Group

Australian Journal of Forensic Sciences

ISSN: 0045-0618 (Print) 1834-562X (Online) Journal homepage: https://www.tandfonline.com/loi/tajf20

Estimation of sex from metatarsals using discriminant function and logistic regression analyses

M. A. Bidmos, A. A. Adebesin, P. Mazengenya, O. I. Olateju & O. Adegboye

To cite this article: M. A. Bidmos, A. A. Adebesin, P. Mazengenya, O. I. Olateju & O. Adegboye (2020): Estimation of sex from metatarsals using discriminant function and logistic regression analyses, Australian Journal of Forensic Sciences, DOI: 10.1080/00450618.2019.1711180

To link to this article: https://doi.org/10.1080/00450618.2019.1711180

AUSTRALIAN JOURNAL OF FORENSIC SCIENCES
https://doi.org/10.1080/00450618.2019.1711180

Estimation of sex from metatarsals using discriminant function and logistic regression analyses

M. A. Bidmos[a], A. A. Adebesin[b], P. Mazengenya[c,d], O. I. Olateju[c] and O. Adegboye[e,f]

[a]College of Medicine, QU Health, Qatar University, Doha, Qatar; [b]Department of Human Anatomy, Sefako Makgatho Health Sciences University, Ga-Rankuwa, South Africa; [c]School of Anatomical Sciences, Faculty of Health Sciences, University of the Witwatersrand, Johannesburg, South Africa; [d]College of Medicine, Ajman University, Ajman, United Arab Emirates; [e]Department for Management of Science and Technology Development, Ton Duc Thang University, Ho Chi Minh City, Vietnam; [f]Faculty of Mathematics and Statistics, Ton Duc Thang University, Ho Chi Minh City, Vietnam

ABSTRACT

South Africa has one of the highest crime rates in the world and the discovery of dismembered bodies for human identification process poses a greater challenge. The South African Africans (also known as South African blacks) population group is often the victims of crimes as they are the largest group. While measurements of several bones of the human skeleton have been used for sex estimation, the potential of metatarsals have not been explored in this population group. Metatarsal bones are usually well-preserved since they are recovered in shoes protected from scavengers and they are able to withstand environmental degradation and taphonomy. This study investigated the potential of measurements of metatarsals in sex estimate amongst South African Africans using logistic and discriminant function analysis. Six measurements of metatarsals from 100 individuals of known sex and population affinity from the Raymond Dart Collection of Human skeletons were analysed. Various combinations of measurements of metatarsal bones yielded suitably high average accuracies (79% to 84%) for sex estimation and are comparable to functions derived from other skeletal elements of South African Africans. Metatarsals of South African Africans are therefore useful as alternatives to highly sexual dimorphic bones in the forensic estimation of sex.

ARTICLE HISTORY
Received 14 October 2019
Accepted 15 December 2019

KEYWORDS
Estimation of sex; metatarsals; discriminant function analysis; logistic regression analysis; South Africa; forensic anthropology

Introduction

Estimation of the sex of an individual from recovered bones forms an essential part of human identification. Two methods are used in the estimation of sex from recovered skeletons, namely, non-metric and metric methods. The non-metric method involves using morphological traits on bones such as the skull and pelvis, which exhibit high sexual dimorphism [1]. These traits include the presence of occipital hook, large mastoid process and pronounced muscle attachments in male skulls while wide subpubic angle, short and broad sacrum, laterally deviated ischial spines and wide pelvic inlet are usually associated with the

CONTACT M. A. Bidmos mbidmos@qu.edu.qa
Supplemental data for this article can be accessed here.

female pelvis[1]. The main drawbacks of the non-metric method are its subjectivity as it depends on the expertise of the examiner[2] and it is considered a complex method[3]. The metric method on the other hand involves measuring a variable or taking a suite of measurements on a bone and it is reliable and reproducible[2].

The metrical method is widely used because of its objectivity as the measurement technique can be assessed and validated using a variety of statistical methods[2]. The measurements from the metric method can be subjected to a variety of statistical techniques including and not limited to use of indices, student's *t-test*, demarking and identification points, logistic regression and discriminant function analyses. Thus, continuous efforts are being made by forensic and physical anthropologists to generate new logistic regression and discriminant function equations from a variety of measurements of bones that display sexual dimorphism while at the same time revising old equations to monitor secular trends.

Population-specific discriminant function and logistic regression equations for estimation of sex have been formulated from measurements of the skull[4–9], pectoral girdle[10–15], sternum[16–21], pelvis[22–24], hand and foot bones[25–30] with various degrees of accuracies. In addition, several studies have shown the usefulness of intact long bones of upper and lower limbs[13,30–40] for sex prediction in different parts of the world. In South Africa, local osteometric standards for sex estimation from skeletons have also been formulated from measurements of the skull[41–43], long bones of the limbs[44–52], sternum[53], pelvis[54] and patella[55,56]. Similarly, measurements from the largest bones of the foot such as the talus[57,58] and calcaneus[59,60] have also been used for sex estimation.

The calcaneus being the largest tarsal bone was evaluated for its sexing potential in South Africans[59,60]. Nine measurements of the calcaneus were subjected to discriminant function analysis. The range of average accuracy in correct sex classification in South African whites ranged from 81 to 92%[59] while that in South African blacks[60] was from 79 to 86%. The function derived from a combination of all measurements produced the highest average accuracy in both population groups[59,60]. Since the calcaneus articulates directly with the talus to form the subtalar joint, the potential of the talus in sex estimation was also investigated. In a previous study by Steele[25], the talus was shown to exhibit greater sexual dimorphism compared to the calcaneus. Consequently, nine measurements of the talus of South Africans were subjected to discriminant function analysis[57,58]. The range of average accuracy in South African whites was 78 to 88%[57]. A similar range of average accuracy (80–89%) was also obtained for the South African black sample studied[58]. In addition to been sexually dimorphic, morphologic features of the calcaneus such as the number of talar articular facets[61,62] exhibit population variability. Discriminant function equations derived from measurements of both the talus and calcaneus can also be used in the assessment of population affinity[62,63] and estimation of stature[64,65] in South Africans.

However, very little is known about the forensic application of metatarsal bones in human identification. Byers, Akoshima and Curran[66] derived regression equations for stature reconstruction from measurements of metatarsal bones obtained from the Terry Collection at the Smithsonian Institute, University of New Mexico. Similar equations were also formulated from measurements of metatarsals of South Africans[67], Portuguese[68], Americans[69], and Japanese[70]. In addition, the maturation of the proximal epiphysis of the fifth metatarsal has been reported to be useful in the estimation of age[71]. To date, few studies have investigated the usefulness of the measurements of the metatarsals in the estimation of sex[72–76]. Robling and Ubelaker[72] subjected measurements of the metatarsal of American whites and blacks to discriminant function analysis and obtained an average accuracy in correct classification that ranged from 83 to 100%.

Since discriminant function equations are population-specific, measurements of metatarsals were also used in the derivation of population-specific equations in different population groups. These include Japanese[70], contemporary Americans[73], Egyptians[74], Greek[75] and Italians[76] with average accuracies accuracies of 74.1%, 86% to 100% and 80% to 96% respectively. To date, no study has been conducted on the estimation of sex from measurements of metatarsals in any South African population group. It is the aim of this study to assess the usefulness of the length of metatarsal bones in the estimation of sex of South African Africans (also known as Black South Africans) using a discriminant function and logistic regression equations.

Materials and methods

Ethics approval for the current study was obtained from the Sefako Makgatho University Research Ethics Committee (SMUREC/M/61/2019: IR). The research data were collected from human skeletonized remains housed in the Raymond A. Dart Collection of Human Skeletons, School of Anatomical Sciences, University of the Witwatersrand, Johannesburg, South Africa[77]. This collection is one of the biggest in the world with over 2,500 complete modern human skeletons that were derived from cadavers of unclaimed bodies from hospitals in Gauteng province prior to 1958[77]. Since then, the number of skeletons in the collection has increased due to the contributions from cadavers obtained for teaching and research purposes through the Body Donor programme of the School of Anatomical Sciences, University of the Witwatersrand, Johannesburg[77].

Data were collected from two samples. The calibration sample consisted of 50 males and 50 females, which were selected by a simple random sampling technique. This sample was used in the derivation of logistic and discriminant function equations for the estimation of sex. Metatarsals without any evidence of fracture or pathological conditions, which belonged to South African blacks were used. The test sample consisted of metatarsals from 25 individuals (15 males and 10 females) which were obtained from the Raymond A Dart Collection of Human Skeletons, Johannesburg. Consideration was given to this population group because it is the largest population group in South Africa[78] and are more likely to be victims of crime.

The following six measurements of metatarsal bones were taken using a Vernier caliper:

(i) Lengths of first, second, third and fourth metatarsals (M1– M4): This is the linear distance taken along the longitudinal axis of the bone from the apex of the capitulum to the midpoint of the articular surface of the base of the bone[67].
(ii) Functional length of the fifth metatarsal (M5F): This is the linear distance between the apex of the capitulum of the fifth metatarsal and the dorsoplantar midpoint of the intersection between the fourth metatarsal and cuboid facets[67].
(iii) Morphological length of the fifth metatarsal (M5P): This is the linear distance between the apex of the capitulum and the tip of the tuberosity[67].

The data analysis was carried out in SAS 9.4 Software Version 6 of the SAS System for Windows. All inferences are based on 95% confidence interval (5% significance level). Preliminary exploratory analyses included presenting metatarsal measurements from males and females as means and standard deviations. Student's *t-test* statistics were used to test for sex differences between each measurement from males and females. Assessment of internal consistency of the metatarsal measurements was done using Cronbach's alpha (R) and technical error of measurement (TEM).

Subsequently, univariate, multivariable logistic regression analysis (LRA) and direct discriminant function analysis (DFA) were performed on the metatarsal measurements. The stepwise procedure was used to select the best subset of measurements for sex discrimination using both LRA and DFA. From these analyses, coefficients and constants were obtained and utilized for the derivation of the DFA and LRA equations. For both LRA and DFA, we present the estimated sensitivity (sens), specificity (spec) and overall accuracy (total correct classification) based on the reported thresholds (sectioning points) to assess the sex estimation of the two methods. A 'leave-one-out' classification procedure was used in testing the validity of the derived functions. The original accuracy obtained for each function was thus cross-validated in the process and the cross-validated classification rates (CVCR) were reported.

Results

We assessed the measurement error using TEM and the internal consistency of metatarsal variables using the Cronbach's alpha for reliability (R). Table 1 shows that the relative TEM for measurements ranged from 0.8% for M4 to 1.1% for M1. The obtained values for the relative technical error of measurement (rTEM) was lower than the acceptable limit of 1.5% as suggested by Perini et al.[79]. High values of Cronbach's alpha scores were obtained for all measurements of the metatarsals. These ranged between 0.95 and 0.97 as shown in Table 1. Similarly, pairwise correlations (Figure S1) revealed strong positive linear relationships between the metatarsal measurements. Descriptive statistical summaries including means and standard deviations for each of the measurements of the metatarsal bones from both sexes are shown in Table 2. The mean values for all the male measurements from the metatarsal bones are significantly larger than female mean measurements ($p \leq 0.05$) indicating sexual dimorphism.

The results from logistic regression models and discriminant function analysis are presented for each metatarsal in Table 3. For all measurements, the normality test was

Table 1. Internal consistency of the metatarsals data: Relative technical error of measurement (TEM) and coefficient of reliability (standardized Cronbach's alpha) for metatarsal data.

Variables	rTEM	Cronbach's alpha (R)
M1	1.1	0.97
M2	1.1	0.95
M3	1.0	0.95
M4	0.8	0.96
$M5_F$	1.1	0.95
$M5_P$	0.9	0.96

Table 2. Descriptive statistics of measurements of metatarsals.

	Females			Males			
Variables	No	Mean	SD	No	Mean	SD	p-value
M1	50	63.44	3.57	50	67.12	3.77	<0.0001
M2	50	71.47	4.16	50	75.55	3.44	<0.0001
M3	50	68.39	4.34	50	70.63	3.54	0.0058
M4	50	66.44	4.27	50	71.12	3.62	<0.0001
$M5_F$	50	58.85	4.14	50	61.38	3.29	0.0009
$M5_P$	50	69.02	5.21	50	71.95	4.43	0.0032

done using the Shapiro-Wilk test and Kolmogorov–Smirnov test, but in both tests the p-values were not statistically significant ($p > 0.05$) suggesting that the data followed a normal distribution. The highest average accuracy obtained in correct sex classification was obtained for M4 (71%) in both DFA and LRA. However, the lowest average accuracies for DFA and LRA was obtained for M3 (56%) and M5p (60%) respectively. The classification average accuracy of each of the metatarsal measurement used in the LRA and DFA is as shown in Figure S2.

In the multivariate analysis of variance, the assumption of homogeneity of variance-covariance matrices was violated, hence a pooled covariance matrix was used. The unstandardized coefficients, constants, sectioning points and average accuracies are presented for the multivariate functions for both DFA and LRA in Table 4. Stepwise discriminant function analysis of all measurements yielded an average accuracy of 80% in which M2, M3, and M4 were selected. The same measurements, i.e. M2, M3, and M4 were selected in the stepwise logistic regression analysis with a similar average accuracy (81%). Various combinations of measurements were subjected to direct analysis using DFA and LRA. The highest average accuracy was obtained from a combination of M1, M2, M3 and M4 using DFA (function 2, Table 4). The same combination of measurements yielded a lower average accuracy (81%) using LRA (Function 8, Table 4). Various other combinations of measurements are arranged in descending order of average accuracy in Table 4. The range of average accuracy for multivariate functions using DFA is 80–84% (functions 2 to 6, Table 4) while that for functions derived using LRA is 79–81% (functions 8 to 12, Table 4).

Cross-validation of the functions derived from the multivariate analysis was performed using the leave-one-out classification and a test sample. In the former, the average accuracy remains essentially unchanged with the drop in average accuracy ranging between 1% (Functions 1 and 3, Table 4) and 5% (Function 9, Table 4). The validation functions 1 to 5 (Table 4), derived from DFA, on an independent test sample yielded an average accuracy in correct sex classification of 76% to 80%. Also, validation of LRA functions produced a similar range of average accuracy (76% to 84%).

Discussion

Variation of the skeletal biology among various populations is a well-known phenomenon[1,46,72]. The skeletal variation necessitates further research, particularly in forensic anthropology for the establishment of biological profile during human identification. In forensic anthropology, development of both temporal and population-specific standards to establish the biological profile are extremely important considering the high

Table 3. Variables and coefficients for univariate analysis using DFA and LRA.

	DFA						LRA					
Measurements	1	2	3	4	5	6	7	8	9	10	11	12
M1		0.28						0.27				
M2			0.26						0.29			
M3						0.25				0.14		
M4	0.25						0.30					
M5F				0.27							0.19	
M5P					0.207							0.13
Constant	−17.37	−18.02	−19.26	−16.36	−14.57	−17.54	−20.55	−17.75	−20.48	−9.88	−11.52	−9.2
Sectioning point†	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.52	0.58	0.38	0.44	0.46
Average accuracy (%)	71.00	70.00	63.00	59.00	58.00	56.00	71.00	70.00	69.00	63.00	61.00	60.00
Cross validation (%)	71.00	70.00	63.00	59.00	58.00	56.00	71.00	70.00	69.00	63.00	61.00	66.00

†P(Male): Values greater than or equal to the sectioning point are males and vice versa

Table 4. Variables and coefficients for multivariate analysis using DFA and LRA.

	DFA					LRA				
	Stepwise	Direct				Stepwise	Direct			
Measurements	1	2	3	4	5	6	7	8	9	10
M1		0.10	0. 09	0.10			0.14		0.14	0.14
M2	0.33	0.26	0.26	0.26		0.59	0.51		0.50	0.51
M3	−0.46	−0.45	−0.46	−0.42	−0.30	−0.88	−0.86	−0.49	−0.90	−0.83
M4	0.30	0.30	0.29	0.32	0.45	0.59	0.81	0.76	0.58	0.67
M5F				−0.10						−0.21
M5P		−0.02			0.01		−0.06	−0.30		
Constant	−12.81	−13.55	−13.47	−13.37	−10.83	−23.60	−23.94	−16.46	−23.46	−23.21
Sectioning point†	0.00	0.00	0.00	0.00	0.00	0.34	0.48	0.48	0.50	0.50
Average accuracy (%)	80.00	84.00	83.00	83.00	80.00	81.00	81.00	81.00	80.00	78.00
Cross-validation (%)	79.00	82.00	82.00	80.00	80.00	81.00	81.00	76.00	80.00	78.00
Test sample validation (%)	76.00	80.00	80.00	80.00	80.00	76.00	84.00	76.00	76.00	76.00

†P(Male): Values greater than or equal to the sectioning point are males and vice versa

crime rates in some countries including South Africa[41,45,46,80]. In the current study, we analysed the usefulness of length measurements of these bones in generating equations for correct estimation of sex in the social identifiable black South African population group. Metatarsal bones have a high recovery rate in forensic situations because of their large numbers and as well as their smaller size, that increases the surface area to volume ratio thereby making them less susceptible to taphonomy[75].

The findings from the current study indicate that the mean total length of the metatarsal bones of males were significantly larger than their female counterparts. Subsequent discriminant function analysis (DFA) and logistic regression analysis (LRA) of individual bone measurements showed low to moderate sexual dimorphism with the average accuracy in correct sex estimation that ranged from 56% to 71%. However, the combination of length measurements from various metatarsal bones produced acceptably high sex estimation accuracies using both DFA (80 – 84%) and LRA (79 – 81%). The differences in the magnitude of the average accuracies in sex estimation generated by both univariate and multivariate equations further supports the concept that multiple measurements both from a single bone or different bones produce higher classification rates that are useful in both fragmentary and intact bones. The result of the cross-validation of the equations generated in this study using both DFA and LRA as well as the use of test sample further confirms the forensic utility of these equations as the change in average accuracies are within a reasonable limit. However, the low to moderate average accuracies in sex estimation obtained from the univariate analysis in this study are of little or no forensic utility.

Previous studies in different parts of the world[70,72–76] have shown that various linear and volumetric measurements of metatarsals are useful in the estimation of sex with various degrees of average accuracies. Robling and Ubelaker[72] analysed data obtained from the length, midshaft diameter, superoinferior height of head and base, and mediolateral width of head and base of each of the five metatarsals of Americans obtained from the Terry collection. They obtained an average accuracy of 86% to 95% in correct sex classification, which is higher than the average accuracy (74%) obtained by Case and Ross[73] using metatarsals from the same collection. It is plausible that the skeletons analysed in these two studies differ in terms of year of birth and in terms of the lifestyle of the individuals whose skeletons were analysed. These may explain the apparent lack of sexual dimorphism in the metatarsals of contemporary Americans[73], which is a further proof that equations generated for human identification should be derived at opportune intervals. In Greeks[75], a range of average accuracy of 81–90% was obtained which is similar to that obtained by Robling and Ubelaker[72]. The inclusion of dimensions such as mediolateral width of head, midshaft and base; and dorsoplantar width of head, midshaft and base could possibly explain the similarity in the average accuracies in both studies.

Gibelli et al.[76]. subjected various linear and volumetric measurements of the first metatarsals of Italians to discriminant function analysis and they obtained a range of average accuracy in correct sex estimation ranging from 79% to 85%. Hishmat et al.[70] performed similar analysis on measurements of the first metatarsal bone in combination with the femur, tibia and fibula of Japanese and they obtained a range of average accuracy between 76% and 98%. Similarly, Moneim et al.[74] obtained a high average classification rate of between 86% and 100% from analysis of measurements of metatarsals of Egyptians. While the results of the multivariate analyses from the current study compare well with that obtained for Italians[76], the average accuracies are generally lower than those presented for Americans[72], Egyptians[74] and Greeks[76]. The most plausible explanation for the difference in the average accuracies observed between the current study and other studies with higher average accuracies[72,74,76] is the inclusion of epiphyseal and midshaft width measurements in these other studies. It appears that the inclusion of these measurements (epiphyseal and midshaft width) in these studies improved the prediction classification rates that were observed.

Epiphyseal and diaphyseal width measurements have been shown to be significantly impacted by physical activity[73] and have been shown to exhibit sexual dimorphism[51,52,74,81–83] compared to length measurements. However, Case and Ross[73] argued that since epiphyseal or diaphyseal measurements are probably more influenced by lifetime activity and that length measurements appear to have a more stable relationship, length measurements should be used in a forensic context where the lifetime activities of an unidentified individual are unknown. The equations derived and presented in the current study all use length measurements of metatarsals and based on the aforementioned observation, these measurements are less impacted by physical activities and are useful in forensic context.

Sexual dimorphism of the metatarsal bones in black South Africans is comparable to other foot bones such as the talus and calcaneus that produced sex estimation classification rates of 80–89% in black South Africans and 80–82% in white South Africans[57–60]. When compared to studies on sex estimation using lower limb long bones, the sex estimation accuracy from the current study are low. Steyn and İşcan[45] presented discriminant function equations using measurements of the femur and tibia of white South Africans with average accuracies of 86–91%. Similarly, Spradley and Jantz[81] reported high classification rates from a combination of measurements of the femur, tibia, fibula and the calcaneus ranging from 81% to 94% in Americans. While studies on the sexual dimorphism of the long bones of the upper limbs of South Africans[46] and Americans[81] reported higher classification rates, results from the current study compare well with those presented for the ulna and radius of black South Africans[49]. Despite high sexual dimorphism displayed by non-metric analysis of the crania and pelvic bones, metric measurements of the cranial and pelvic bones produce comparable sex classification rates to metatarsals measurements used in the current study. In black South Africans, Franklin et al.[42]. presented discriminant function equations for a combination of measurements from the face and calvaria with average accuracies that ranged between 77% and 80%. Facial dimensions were found to be more sexually dimorphic[42]. In contrast to the geomorphometric technique used by Franklin et al.[42], Dayal et al.[43] subjected linear measurements of the cranium of black South Africans to DFA and they presented equations with average accuracies of between 80% and 85%. Studies utilizing measurements of the cranium and mandible of white South Africans yielded similar sex estimation accuracies of 80% to 86%[41].

Numerous studies on various populations indicate that the skeletal biology varies in stature and sexual dimorphism and the South African population is no exception[41,45,46,54,75,81]. The South African population is considered unique and consists of socially identified populations that include the black South Africans, white South African, mixed ancestry/coloured South Africans and Indians[46,50]. The black South African population is considered homogenous although it consists of various bantu speaking tribes who were believed to have migrated from the Nigerian/Cameroon highlands into South Africa within the past 3000 to 5000 years and indigenous South Africans (Khoesan), despite evidences of gene flow among groups[50]. The white South African population, on the other hand, consists of descendants of European colonial settlers from the mainly Netherlands, French, Britain and Germany while the mixed ancestry/coloured population is composed of genetic contributions from the Bantu-speakers, European, Khoesan and Asians[46,50]. Skeletal variation within and between the South African population might be as results of admixture and gene flow among the population groups[46]. In addition, South Africans vary in terms of body size from Americans; black South African skeletal elements are smaller in dimensions and less robust compared to black Americans and white South Africans. However, white South Africans are taller than white Americans[46]. This osteometric difference between population groups is relevant and might help to explain the variations in sexual dimorphism that is evident within and across the population. It, therefore, emphasizes the need for population-specific standards that correctly identify victims of a particular population group in forensic anthropology.

In conclusion, the combination of measurements of metatarsal bones from the black South African population produce acceptably high average accuracies that can be used to estimate the sex of an unidentified individual from skeletonized remains in forensic anthropology. The sex estimation classification rates presented in this study, although lower than that for other population groups, are comparable to the metric accuracy scores from the cranium and other postcranial elements from South Africa. Measurements from the metatarsals of black South Africans are therefore useful as alternatives to highly sexual dimorphic bones in the forensic estimation of sex.

Acknowledgments

The authors appreciate the generosity of those who donated their bodies for teaching and research without which this study would not have been possible. We also thank Prof Maryna Steyn for access to the Raymond A. Dart Collection of Human Skeletons and Mr Brendon Billings for assistance in the retrieval of specimens. The publication of this article was funded by the Qatar National Library.

Disclosure statement

No potential conflict of interest was reported by the authors.

ORCID

M. A. Bidmos http://orcid.org/0000-0002-4993-3093
A. A. Adebesin http://orcid.org/0000-0002-0333-7683
P. Mazengenya http://orcid.org/0000-0003-4733-1563
O. I. Olateju http://orcid.org/0000-0002-4415-1877
O. Adegboye http://orcid.org/0000-0002-9793-8024

References

1. Krogman WM, Isçan MY. The human skeleton in forensic medicine. Springfield (IL): Charles C, Thomas; 1986. p. 413–457.
2. Loth S, Iscan M. Sex determination, encyclopedia of forensic sciences. San Diego: Academic Press; 2000.
3. Introna F, Di Vella G, Campobasso CP, Dragone M. Sex determination by discriminant analysis of calcanei measurements. J Forensic Sci. 1997;42:725–728. doi:10.1520/JFS14192J
4. Giles E. Sex determination by discriminant function analysis of the mandible. Am J Phys Anthropol. 1964;22:129–135. doi:10.1002/(ISSN)1096-8644
5. Kajanoja P. Sex determination of Finnish crania by discriminant function analysis. Am J Phys Anthropol. 1966;24:29–33. doi:10.1002/(ISSN)1096-8644
6. Holland TD. Sex determination of fragmentary crania by analysis of the cranial base. Am J Phys Anthropol. 1986;70:203–208. doi:10.1002/(ISSN)1096-8644
7. Kieser J, Groeneveld H. Multivariate sexing of the human viscerocranium. J Forensic Odontostomatol. 4;1986:41.
8. Song H-W, Qing LZ, Tao JJ. Sex diagnosis of Chinese skulls using multiple stepwise discriminant function analysis. Forensic Sci Int. 1992;54:135–140. doi:10.1016/0379-0738(92)90157-R
9. Ogawa Y, Imaizumi K, Miyasaka S, Yoshino M. Discriminant functions for sex estimation of modern Japanese skulls. J Forensic Leg Med. 2013;20:234–238. doi:10.1016/j.jflm.2012.09.023
10. Dabbs GR, Moore-Jansen PH. A method for estimating sex using metric analysis of the scapula. J Forensic Sci. 2010;55:149–152. doi:10.1111/j.1556-4029.2009.01232.x
11. Papaioannou VA, Kranioti EF, Joveneaux P, Nathena D, Michalodimitrakis M. Sexual dimorphism of the scapula and the clavicle in a contemporary Greek population: applications in forensic identification. Forensic Sci Int. 2012;217:e231–231. doi:10.1016/j.forsciint.2011.11.010
12. Albanese J. A method for estimating sex using the clavicle, humerus, radius, and ulna. J Forensic Sci. 2013;58:1413–1419. doi:10.1111/jfo.2013.58.issue-6
13. Moore MK, DiGangi EA, Ruíz FPN, Davila OJH, Medina CS. Metric sex estimation from the postcranial skeleton for the Colombian population. Forensic Sci Int. 2016;262:286. e281–286. e288. doi:10.1016/j.forsciint.2016.02.018
14. Peckmann TR, Scott S, Meek S, Mahakkanukrauh P. Sex estimation from the scapula in a contemporary Thai population: applications for forensic anthropology. Sci Justice. 2017;57:270–275. doi:10.1016/j.scijus.2017.02.005
15. Torimitsu S, Makino Y, Saitoh H, Sakuma A, Ishii N, Yajima D, Inokuchi G, Motomura A, Chiba F, Yamaguchi R. Sex assessment based on clavicular measurements in a modern Japanese population using multidetector computed tomography. Forensic Sci Int. 2018;285:207. e201–207. e205. doi:10.1016/j.forsciint.2017.10.009

16. Bongiovanni R, Spradley MK. Estimating sex of the human skeleton based on metrics of the sternum. Forensic Sci Int. 2012;219:290. e291–290. e297. doi:10.1016/j.forsciint.2011.11.034
17. Franklin D, Flavel A, Kuliukas A, Cardini A, Marks MK, Oxnard C, O'Higgins P. Estimation of sex from sternal measurements in a Western Australian population. Forensic Sci Int. 2012;217:230. e231–230. e235. doi:10.1016/j.forsciint.2011.11.008
18. Macaluso PJ, Lucena J. Estimation of sex from sternal dimensions derived from chest plate radiographs in contemporary Spaniards. Int J Legal Med. 2014;128:389–395. doi:10.1007/s00414-013-0910-z
19. Chandrakanth H, Kanchan T, Krishan K. Osteometric analysis for sexing of modern sternum–an autopsy study from South India. Leg Med. 2014;16:350–356. doi:10.1016/j.legalmed.2014.07.007
20. García-Parra P, Fernández ÁP, Djorojevic M, Botella M, Alemán I. Sexual dimorphism of human sternum in a contemporary Spanish population. Forensic Sci Int. 2014;244:313. e311–313. e319. doi:10.1016/j.forsciint.2014.06.019
21. Ahmed A, Alshammari F, Alrafiaah A, Almohaisani A, Al-Mohrej O, Alkubaidan F. Estimation of sex in a contemporary Saudi population based on sternal measurements using multidetector computed tomography. Homo. 2017;68:411–421. doi:10.1016/j.jchb.2017.11.001
22. Dibennardo R, Taylor JV. Multiple discriminant function analysis of sex and race in the postcranial skeleton. Am J Phys Anthropol. 1983;61:305–314. doi:10.1002/(ISSN)1096-8644
23. Gonzalez PN, Bernal V, Perez SI. Geometric morphometric approach to sex estimation of human pelvis. Forensic Sci Int. 2009;189:68–74. doi:10.1016/j.forsciint.2009.04.012
24. Mahakkanukrauh P, Ruengdit S, Tun SM, Case DT, Sinthubua A. Osteometric sex estimation from the os coxa in a Thai population. Forensic Sci Int. 2017;271:127. e121–127. e127. doi:10.1016/j.forsciint.2016.11.043
25. Steele DG. The estimation of sex on the basis of the talus and calcaneus. Am J Phys Anthropol. 1976;45:581–588. doi:10.1002/(ISSN)1096-8644
26. Abd-elaleem SA, Abd-elhameed M, Ewis AA. Talus measurements as a diagnostic tool for sexual dimorphism in Egyptian population. J Forensic Leg Med. 2012;19:70–76. doi:10.1016/j.jflm.2011.12.003
27. Navega D, Vicente R, Vieira DN, Ross AH, Cunha E. Sex estimation from the tarsal bones in a Portuguese sample: a machine learning approach. Int J Legal Med. 2015;129:651–659. doi:10.1007/s00414-014-1070-5
28. Ekizoglu O, Inci E, Palabiyik FB, Can IO, Er A, Bozdag M, Kacmaz IE, Kranioti EF. Sex estimation in a contemporary Turkish population based on CT scans of the calcaneus. Forensic Sci Int. 2017;279:310. e311–310. e316. doi:10.1016/j.forsciint.2017.07.038
29. Scott S, Ruengdit S, Peckmann TR, Mahakkanukrauh P. Sex estimation from measurements of the calcaneus: applications for personal identification in Thailand. Forensic Sci Int. 2017;278:405. e401–405. e408. doi:10.1016/j.forsciint.2017.06.035
30. Nathena D, Michopoulou E, Kranioti EF. Sexual dimorphism of the calcaneus in contemporary Cretans. Forensic Sci Int. 2017;277:260. e261–260. e268. doi:10.1016/j.forsciint.2017.04.005
31. Holman DJ, Bennett KA. Determination of sex from arm bone measurements. Am J Phys Anthropol. 1991;84:421–426. doi:10.1002/(ISSN)1096-8644
32. İşcan MY, Loth SR, King CA, Shihai D, Yoshino M. Sexual dimorphism in the humerus: a comparative analysis of Chinese, Japanese and Thais. Forensic Sci Int. 1998;98:17–29. doi:10.1016/S0379-0738(98)00119-4
33. King CA, İşcan MY, Loth SR. Metric and comparative analysis of sexual dimorphism in the Thai femur. J Forensic Sci. 1998;43:954–958. doi:10.1520/JFS14340J
34. Mall G, Hubig M, Büttner A, Kuznik J, Penning R, Graw M. Sex determination and estimation of stature from the long bones of the arm. Forensic Sci Int. 2001;117:23–30. doi:10.1016/S0379-0738(00)00445-X
35. Frutos LR. Metric determination of sex from the humerus in a Guatemalan forensic sample. Forensic Sci Int. 2005;147:153–157. doi:10.1016/j.forsciint.2004.09.077
36. Kranioti EF, Michalodimitrakis M. Sexual dimorphism of the humerus in contemporary cretans—a population-specific study and a review of the literature. J Forensic Sci. 2009;54:996–1000. doi:10.1111/jfo.2009.54.issue-5

37. Charisi D, Eliopoulos C, Vanna V, Koilias CG, Manolis SK. Sexual dimorphism of the arm bones in a modern Greek population. J Forensic Sci. 2011;56:10–18. doi:10.1111/jfo.2010.56.issue-1
38. Boldsen JL, Milner GR, Boldsen SK. Sex estimation from modern American humeri and femora, accounting for sample variance structure. Am J Phys Anthropol. 2015;158:745–750. doi:10.1002/ajpa.22812
39. Clavero A, Salicru M, Turbon D. Sex prediction from the femur and hip bone using a sample of CT images from a Spanish population. Int J Legal Med. 2015;129:373–383. doi:10.1007/s00414-014-1069-y
40. Curate F, Umbelino C, Perinha A, Nogueira C, Silva AM, Cunha E. Sex determination from the femur in Portuguese populations with classical and machine-learning classifiers. J Forensic Leg Med. 2017;52:75–81. doi:10.1016/j.jflm.2017.08.011
41. Steyn M, İşcan MY. Sexual dimorphism in the crania and mandibles of South African whites. Forensic Sci Int. 1998;98:9–16. doi:10.1016/S0379-0738(98)00120-0
42. Franklin D, Freedman L, Milne N. Sexual dimorphism and discriminant function sexing in indigenous South African crania. Homo. 2005;55:213–228. doi:10.1016/j.jchb.2004.08.001
43. Dayal MR, Spocter MA, Bidmos MA. An assessment of sex using the skull of black South Africans by discriminant function analysis. Homo. 2008;59:209–221. doi:10.1016/j.jchb.2007.01.001
44. Kieser J, Moggi-Cecchi J, Groeneveld H. Sex allocation of skeletal material by analysis of the proximal tibia. Forensic Sci Int. 1992;56:29–36. doi:10.1016/0379-0738(92)90143-K
45. Steyn M, İşcan MY. Sex determination from the femur and tibia in South African whites. Forensic Sci Int. 1997;90:111–119. doi:10.1016/S0379-0738(97)00156-4
46. Steyn M, İşcan MY. Osteometric variation in the humerus: sexual dimorphism in South Africans. Forensic Sci Int. 1999;106:77–85. doi:10.1016/S0379-0738(99)00141-3
47. Asala S. Sex determination from the head of the femur of South African whites and blacks. Forensic Sci Int. 2001;117:15–22. doi:10.1016/S0379-0738(00)00444-8
48. Asala SA, Bidmos MA, Dayal MR. Discriminant function sexing of fragmentary femur of South African blacks. Forensic Sci Int. 2004;145:25–29. doi:10.1016/j.forsciint.2004.03.010
49. Barrier I, L'Abbé E. Sex determination from the radius and ulna in a modern South African sample. Forensic Sci Int. 2008;179:85. e81–85. e87. doi:10.1016/j.forsciint.2008.04.012
50. Krüger GC, L'Abbé EN, Stull KE. Sex estimation from the long bones of modern South Africans. Int J Legal Med. 2017;131:275–285. doi:10.1007/s00414-016-1488-z
51. Mokoena P, Billings BK, Gibbon V, Bidmos MA, Mazengenya P. Development of discriminant functions to estimate sex in upper limb bones for mixed ancestry South Africans. Sci Justice. 2019;59:660–666. doi:10.1016/j.scijus.2019.06.007
52. Mokoena P, Billings BK, Bidmos MA, Mazengenya P. Sex estimation using dimensions around the nutrient foramen of the long bones of the arm and forearm in South Africans. Forensic Sci Int. 2017;278:404. e401–404. e405. doi:10.1016/j.forsciint.2017.06.037
53. Macaluso PJ Jr. The efficacy of sternal measurements for sex estimation in South African blacks. Forensic Sci Int. 2010;202:111. e111–111. e117. doi:10.1016/j.forsciint.2010.07.019
54. Patriquin ML, Loth S, Steyn M. Sexually dimorphic pelvic morphology in South African whites and blacks. Homo. 2003;53:255–262. doi:10.1078/0018-442X-00049
55. Dayal MR, Bidmos MA. Discriminating sex in South African blacks using patella dimensions. J Forensic Sci. 2005;50:1294–1297. doi:10.1520/JFS2004306
56. Bidmos M, Steinberg N, Kuykendall K. Patella measurements of South African whites as sex assessors. Homo. 2005;56:69–74. doi:10.1016/j.jchb.2004.10.002
57. Bidmos MA, Dayal MR. Sex determination from the talus of South African whites by discriminant function analysis. Am J Forensic Med Pathol. 2003;24:322–328. doi:10.1097/01.paf.0000098507.78553.4a
58. Bidmos MA, Dayal MR. Further evidence to show population specificity of discriminant function equations for sex determination using the talus of South African blacks. J Forensic Sci. 2004;49:1165–1170. doi:10.1520/JFS2003431
59. Bidmos MA, Asala SA. Discriminant function sexing of the calcaneus of the South African whites. J Forensic Sci. 2003;48:1213–1218. doi:10.1520/JFS2003104

60. Bidmos MA, Asala SA. Sexual dimorphism of the calcaneus of South African blacks. J Forensic Sci. 2004;49:446–450. doi:10.1520/JFS2003254
61. Bunning PSC, Barnett CH. A comparison of adult and foetal talocalcaneal articulations. J Anat. 99;1965:71–76.
62. Bidmos M. Metrical and non-metrical assessment of population affinity from the calcaneus. Forensic Sci Int. 2006;159:6–13. doi:10.1016/j.forsciint.2005.06.005
63. Bidmos MA, Dayal MR, Adegboye OA. Measurements of the talus in the assessment of population affinity. Forensic Sci Int. 2018;287:221.e1–221.e7. doi:10.1016/j.forsciint.2018.03.016
64. Bidmos M, Asala S. Calcaneal measurement in estimation of stature of South African blacks. Am J Phys Anthropol. 2005;126:335–342. doi:10.1002/(ISSN)1096-8644
65. Bidmos M. Adult stature reconstruction from the calcaneus of South Africans of European descent. J Clin Forensic Med. 2006;13:247–252. doi:10.1016/j.jcfm.2005.11.010
66. Byers S, Akoshima K, Curran B. Determination of adult stature from metatarsal length. Am J Phys Anthropol. 1989;79:275–279. doi:10.1002/(ISSN)1096-8644
67. Bidmos MA. Metatarsals in the estimation of stature in South Africans. J Forensic Leg Med. 2008;15:505–509. doi:10.1016/j.jflm.2008.05.007
68. Cordeiro C, Muñoz-Barús JI, Wasterlain S, Cunha E, Vieira DN. Predicting adult stature from metatarsal length in a Portuguese population. Forensic Sci Int. 2009;193:131. e131–131. e134. doi:10.1016/j.forsciint.2009.09.017
69. Pablos A, Gómez-Olivencia A, García-Pérez A, Martínez I, Lorenzo C, Arsuaga JL. From toe to head: use of robust regression methods in stature estimation based on foot remains. Forensic Sci Int. 2013;226:299. e291–299. e297. doi:10.1016/j.forsciint.2013.01.009
70. Hishmat AM, Michiue T, Sogawa N, Oritani S, Ishikawa T, Fawzy IA, Hashem MAM, Maeda H. Virtual CT morphometry of lower limb long bones for estimation of the sex and stature using postmortem Japanese adult data in forensic identification. Int J Legal Med. 2015;129:1173–1182. doi:10.1007/s00414-015-1228-9
71. Davies CM, Hackman L, Black S. The utility of the proximal epiphysis of the fifth metatarsal in age estimation. J Forensic Sci. 2013;58:436–442. doi:10.1111/jfo.2013.58.issue-2
72. Robling AG, Ubelaker DH. Sex estimation from the metatarsals. J Forensic Sci. 1997;42:1062–1069. doi:10.1520/JFS14261J
73. Case DT, Ross AH. Sex determination from hand and foot bone lengths. J Forensic Sci. 2007;52:264–270. doi:10.1111/jfo.2007.52.issue-2
74. Moneim WMA, Hady RHA, Maaboud RMA, Fathy HM, Hamed AM. Identification of sex depending on radiological examination of foot and patella. Am J Forensic Med Pathol. 2008;29:136–140. doi:10.1097/PAF.0b013e318173f048
75. Mountrakis C, Eliopoulos C, Koillias CG, Manolis SK. Sex determination using metatarsal osteometrics from the Athens collection. Forensic Sci Int. 178;2010:e1–178. e7.
76. Gibelli D, Poppa P, Cummaudo M, Mattia M, Cappella A, Mazzarelli D, Zago M, Sforza C, Cattaneo C. Sex assessment from the volume of the first metatarsal bone: a comparison of linear and volume measurements. J Forensic Sci. 2017;62:1582–1585. doi:10.1111/jfo.2017.62.issue-6
77. Dayal MR, Kegley AD, Štrkalj G, Bidmos MA, Kuykendall KL. The history and composition of the Raymond A. Dart collection of human skeletons at the University of the Witwatersrand, Johannesburg, South Africa. Am J Phys Anthropol. 2009;140:324–335. doi:10.1002/ajpa.21072
78. Statistics South Africa, census 2011 statistical release (revised)—P0301.4. Statistics South Africa, Pretoria; 2011. [cited 2019 Dec 5]. Available from: https://www.statssa.gov.za/publications/P03014/P030142011.pdf
79. Perini TA, Oliveira GLD, Ornellas JDS, Oliveira FPD. Technical error of measurement in anthropometry. Rev Bras Med Esporte. 2005;11:81–85. doi:10.1590/S1517-86922005000100009
80. Steyn M. Muti murders form South Africa: a case report. Forensic Sci Int. 2005;151:279–287. doi:10.1016/j.forsciint.2004.05.022
81. Spradley MK, Jantz RL. Sex estimation in forensic anthropology: skull versus postcranial elements. J Forensic Sci. 2011;56:289–296. doi:10.1111/j.1556-4029.2010.01635.x

82. Krüger GC, L'Abbe EN, Stull KE. Sex estimation from the long bones of modern South Africans. Int J Legal Med. 2017;131:275–285. doi:10.1007/s00414-016-1488-z
83. Fasemore MD, Bidmos MA, Mokoena P, Imam A, Billings BK, Mazengenya P. Dimensions around the nutrient foramina of the tibia and fibula in the estimation of sex. Forensic Sci Int. 2018;287:222. e221–222. e227. doi:10.1016/j.forsciint.2018.03.015