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

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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.

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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 dimorphism¹. 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

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 Supplemental data for this article can be accessed [here](#).

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female pelvis¹. The main drawbacks of the non-metric method are its subjectivity as it depends on the expertise of the examiner² and it is considered a complex method³. 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 reproducible².

The metrical method is widely used because of its objectivity as the measurement technique can be assessed and validated using a variety of statistical methods². 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}, sternum⁵³, pelvis⁵⁴ 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 blacks⁶⁰ 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 Steele²⁵, 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 studied⁵⁸. In addition to being 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 Curran⁶⁶ 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 Africans⁶⁷, Portuguese⁶⁸, Americans⁶⁹, and Japanese⁷⁰. In addition, the maturation of the proximal epiphysis of the fifth metatarsal has been reported to be useful in the estimation of age⁷¹. To date, few studies have investigated the usefulness of the measurements of the metatarsals in the estimation of sex^{72–76}. Robling and Ubelaker⁷² 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 Japanese⁷⁰, contemporary Americans⁷³, Egyptians⁷⁴, Greek⁷⁵ and Italians⁷⁶ with average 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 Africa⁷⁷. 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 1958⁷⁷. 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, Johannesburg⁷⁷.

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 Africa⁷⁸ 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 bone⁶⁷.
- (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 facets⁶⁷.
- (iii) Morphological length of the fifth metatarsal (M5P): This is the linear distance between the apex of the capitulum and the tip of the tuberosity⁶⁷.

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.

Variables	Females			Males			p-value
	No	Mean	SD	No	Mean	SD	
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 M5_p (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.

Measurements	DFA						LRA					
	1	2	3	4	5	6	7	8	9	10	11	12
M1		0.28						0.27				
M2			0.26						0.29			
M3				0.27						0.14		
M4	0.25					0.25	0.30					
M5F											0.19	
M5P												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
Gross 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.

Measurements	DFA					LRA				
	Stepwise	Direct				Stepwise	Direct			
		1	2	3	4		5	6	7	8
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
MSP		-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 taphonomy⁷⁵.

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 Ubelaker⁷² analysed data obtained from the length, midshaft diameter, superoinferior height of head and base, and medio-lateral 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 Ross⁷³ 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 Americans⁷³, which is a further proof that equations generated for human identification should be derived at opportune intervals. In Greeks⁷⁵, a range of average accuracy of 81–90% was obtained which is similar to that obtained by Robling and Ubelaker⁷². 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 Italians⁷⁶, the average accuracies are generally lower than those presented for Americans⁷², Egyptians⁷⁴ and Greeks⁷⁶. 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 activity⁷³ and have been shown to exhibit sexual dimorphism^{51,52,74,81–83} compared to length measurements. However, Case and Ross⁷³ 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 İşcan⁴⁵ presented discriminant function equations using measurements of the femur and tibia of white South Africans with average accuracies of 86–91%. Similarly, Spradley and Jantz⁸¹ 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 Africans⁴⁶ and Americans⁸¹ reported higher classification rates, results from the current study compare well with those presented for the ulna and radius of black South Africans⁴⁹. 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 dimorphic⁴². 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 groups⁵⁰. 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 groups⁴⁶. 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 Americans⁴⁶. 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.

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Disclosure statement

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