International Journal of Legal Medicine (2021) 135:1095–1102
https://doi.org/10.1007/s00414-020-02458-y

POPULATION DATA

Accuracies of discriminant function equations for sex estimation using long bones of upper extremities

Mubarak A. Bidmos[1] · **Pedzisai Mazengenya**[2,3]

Received: 7 May 2020 / Accepted: 5 November 2020 / Published online: 11 November 2020

Abstract

One of the scopes of practice of forensic anthropologists is the estimation of sex from skeletal remains. As a result, population-specific discriminant function equations have been developed from measurements of various bones of the human skeletons. Steyn, Patriquin (*Forensic Sci Int* 191 (1-3):113, 2009) noted that the lack of skeletal collections and data from most parts of the world has made this process impractical. Previous attempts to develop global discriminant function equations from measurements of the pelvis showed that population-specific equations are not necessary as equations derived from other populations yielded high sex estimation scores when applied to a different population. However, information on the suitability and applicability of generalised equations in sex estimation using long bones is still scarce. It is, therefore, the aim of this study to assess the accuracies of population-specific discriminant function equations derived from measurements of long bones of the upper limb of South African population groups. Data analysed in the current study were obtained from Mokoena, Billings, Bidmos, Mazengenya (*Forensic Sci Int* 278:404, 2017) and Mokoena, Billings, Gibbon, Bidmos, Mazengenya (*Science & Justice* 6(59):660–666, 2019) in which a total sample of 988 bones (humeri, radii, and ulnae) of South Africans of African descent (SAAD), South Africans of European descent (SAED) and Mixed Ancestry South Africans (MASA) were measured. Stepwise and direct discriminant function analyses were performed on the pooled data. Each function was used to estimate the sex of cases in each population group separately and average accuracies calculated. Thereafter, population-specific discriminant function equations were formulated for each population group and then applied to other population groups. The average accuracies of functions for pooled data ranged between 80.7 and 86.5%. The cross-validation average accuracies remained unchanged for most functions, confirming the validity of derived functions. A drop in average accuracies (0.8–5.3%) was observed when the functions were tested on a sample of SAAD while increased average accuracy was observed for the SAED and MASA (0.5–6.9%). When population-specific functions for a particular population group were applied to other groups, a wide range of a drop in average accuracies was observed (1.3 to 22.4%). This thereby confirms that population-specific equations should not be applied to other population groups. However, discriminant function equations from the pooled data of South Africans are accurate in the estimation of sex and efforts should be made towards the development and validation of such equations from as many bones of the human skeleton.

Keywords Forensic anthropology · Sex estimation · Humerus · Radius · Ulna · Nutrient foramen · Discriminant function analyses · Average accuracies

Introduction

One of the scopes of practice of forensic anthropologists is the estimation of sex from skeletal remains [1, 2]. This process constitutes an important step in the development of the biological profile of an individual from human skeletons [1, 3, 4]. While distinct morphological traits on the pelvis and the skull are sexually dimorphic, their accuracies in correct sex estimation using the non-metric methods are better depending on the level of experience of the examiner [5, 6]. Consequently,

✉ Mubarak A. Bidmos
mbidmos@qu.edu.qa

[1] Department of Basic Medical Sciences, College of Medicine, QU Health, Qatar University, Doha, Qatar

[2] College of Medicine, Ajman University, Ajman, United Arab Emirates

[3] School of Anatomical Sciences, Faculty of Health Sciences, University of the Witwatersrand, Johannesburg, South Africa

measurements of various bones of the human skeletons have been subjected to a number of statistical analysis including the use of discriminant function and logistic regression analyses [7–13]. However, these equations have been shown to be population-specific [14–16] which means that equations derived for a population group when applied to other population groups produce a lower classification rates. Consequently, population-specific equations have been derived for measurements of the skull [17, 18], clavicle [19, 20], long bones of upper and lower extremities [7, 12, 13, 21, 22], sternum [23–25], vertebrae [16], pelvis [6, 26], hand and foot bones [11, 27–33] and tooth dimensions [34] in different parts of the world with acceptably high average accuracies.

In South Africa, a country with one of the highest rates of murder cases in the world [35], similar efforts have been made in the formulation of local standards for sex estimation from the skull [10, 18, 36] and postcranial bones [8, 9, 11–13, 21, 37, 38]. The average accuracies in correct classification using these equations ranged between 56 and 98% [7–9, 18, 32, 37, 39]. These equations have been derived using samples of bones of South Africans of African descent (SAAD) and South Africans of European descent (SAED). Recent attempts at formulating similar equations for Mixed-Ancestry South Africans (MASA), a self-identified social group also known as Coloured, has been successful [7]. The need for population-specific equations is based on the existence of osteometric variations between population groups, and the degree of sexual dimorphism exhibited by measurements on bones from different population groups [6, 40, 41]. However, Steyn, Patriquin [40] highlighted some major drawback in the development and application of population specific discriminant function equations. These include the lack of bone collections or data for formulation of population specific equations in most parts of the world and the need for prior knowledge of the population group of the skeleton before the application of appropriate discriminant function equations.

Thus, Steyn, Patriquin [40] developed global discriminant function equations for sex estimation using measurements of the pelvis and concluded that population-specific equations are not required based on the data from pelvic bones. Subsequently, other researchers have shown that global equations from pooled data of measurements produce a more precise estimate of stature [42] and sex [16, 43] with reasonably high average accuracies which are comparable to and sometimes better than population-specific equations. It is therefore the aim of this paper to (1) formulate global equations for sex estimation using measurements around the nutrient foramen of the long bones of arm of South Africans of African descent (SAAD), South Africans of European descent (SAED) and Mixed Ancestry South Africans (MASA) and (2) compare the average accuracies obtained from the global equations with those obtained from population-specific equations. Dimensions around the nutrient foramen of the bone diaphysis offer an alternative to the midshaft measurements in forensic investigations because the nutrient foramen is easy to identify and dimensions around it are independent of the maximum bone length [13, 44–46].

Materials and methods

Materials

Prior to the commencement of this study, ethical clearance waiver (Certificate Number W-CJ-140604-1) was obtained from the School of Anatomical Sciences, University of the Witwatersrand, Johannesburg. The data analysed in the current study were obtained from two previously published studies [7, 21] in which a total sample of 988 bones (humeri: 327, radii: 325 and ulnae: 336) from South Africans of African descent (SAAD), Mixed Ancestry South Africans (MASA) and South Africans of European descent (SAED) of known sex and age-at-death. These samples were obtained from Raymond A. Dart Collection of Human Skeletons [47] housed in the School of Anatomical Sciences of the University of the Witwatersrand, Johannesburg and the UCT Human Skeletal Collection [48] housed in the Department of Human Biology of the University of Cape Town, South Africa. Skeletons from both collections were mainly derived from cadavers that have been used for dissection as part of the training of medical, dental, physiotherapy and occupational therapy students. The demographic information about the cadavers including ancestry are documented in the catalogue of information of these collections. The distribution of the samples is shown in Table 1.

Methods

Measurements

Five measurements namely maximum length (tl), linear distance from the proximal end of the bone to the nutrient foramen (penf), circumference at nutrient foramen (circ), anteroposterior diameter at nutrient foramen (apdiam) and mediolateral diameter at nutrient foramen (mldiam) were taken on each left bone. In the absence of the left bone, the right

Table 1 Skeletal sample distribution

	Humeri		Radii		Ulnae	
	Females	Males	Females	Males	Females	Males
Dart	134	160	129	153	129	154
UCT	17	25	17	26	16	28
Total	151	185	146	179	145	182

bone was used as there were no significant side differences. The measurements are well described in the previous studies [7, 21]. Data were described and analysed statistically using SPSS version 23 software program.

Statistical analyses

Descriptive statistics including means and standard deviations were calculated for males and females separately for combined populations for the humerus, radius and ulna. Thereafter, a one-way ANOVA test was performed to assess differences between the mean measurements of both males and females for each of the bones. In addition, multivariate analysis of variance (MANOVA) test was performed in order to assess the existence of statistically significant difference between multiple dependent variables at the same time. After establishing that significant differences exist between male and female mean measurements, combined data for all groups were subjected to stepwise and direct discriminant function analyses following the description of Bidmos, Asala [32]. The validity of the functions generated was assessed using the “leave-one-out” classification procedure. This procedure involves the classification of each case in the sample by the function that is generated without the case been tested. For each bone, the top three performing functions with an average accuracy of more than 80% were selected. Each of the nine functions selected was used to predict sex for each of the cases in the three different population groups. The average accuracy in correct sex classification for each of the functions was calculated for each population group separately.

In addition, population-specific stepwise and direct discriminant function equations were formulated for each bone. The best performing population-specific functions for each bone with average accuracies higher that 80% were selected. Each of the population-specific functions for a population group (for example SAAD) was applied on the data from the other two population groups (i.e. MASA and SAED). The average accuracies in correct sex classification was calculated separately for each population group been assessed in order to assess the performance of each population-specific function on other population groups.

Results

The descriptive statistics of all measured variables for pooled data are displayed in Table 2. Males consistently showed higher mean measurements for all variables compared to females. Statistically significant differences were observed between male and female mean measurements at $p \leq 0.05$ for all measurements. Supplementary Table 1 also shows the descriptive statistics of each of the variables for each population group and for both sexes. The MANOVA test shows that there is statistically significant interaction between sex and population group for humeri and radii variables (Supplementary Table 2). However, statistically significant interaction was not observed for ulnae variables (Supplementary Table 2).

The five humeri, radii and ulnae measurements were analysed using stepwise and direct discriminant functions (Table 3). The unstandardised coefficients, constants, average accuracies, cross-validation in correct sex classification and the sectioning points are presented in Table 3. Functions 1, 4 and 7 were derived from

Table 2 Descriptive statistics of measurements around the nutrient foramina of the humerus, radius, and ulna from pooled data

		Females			Males				
	Variables	No	Mean	SD	No	Mean	SD	F-statistics	*p* value
Humerus	tl	151	296.2	18.5	185	321.9	19.0	156.31	< 0.0001
	penf	151	167.9	25.2	185	183.6	28.3	28.12	< 0.0001
	ap	151	18.6	1.9	185	20.6	1.9	98.81	< 0.0001
	ml	151	16.9	1.8	185	19.5	2.0	149.35	< 0.0001
	circ	151	56.9	4.8	185	63.8	5.0	168.52	< 0.0001
Radius	tl	146	221.6	14.3	179	247.7	18.3	197.18	< 0.0001
	penf	146	78.2	11.7	179	87.4	11.8	49.83	< 0.0001
	ap	146	10.2	1.3	179	11.7	1.1	112.76	< 0.0001
	ml	146	13.4	1.6	179	15.2	1.8	91.11	< 0.0001
	circ	146	38.7	4.0	179	43.6	3.6	135.54	< 0.0001
Ulna	tl	145	239.9	15.7	182	264.3	16.9	179.35	< 0.0001
	penf	145	92.3	15.2	182	99.2	16.0	15.874	< 0.0001
	ap	145	12.6	1.6	182	14.9	1.8	144.826	< 0.0001
	ml	145	13.5	1.5	182	15.7	1.6	163.151	< 0.0001
	circ	145	42.8	4.0	182	49.2	4.1	202.415	< 0.0001

Table 3 Unstandardised coefficients, constants, and accuracies for multivariate discriminant function analysis for pooled data

	Humerus			Radius			Ulna		
Measurements	1	2	3	4	5	6	7	8	9
tl	0.029	0.031	0.034	0.043	0.039	0.046	0.031	0.031	0.033
penf									
apdiam					0.338	0.390	0.264		
mldiam	0.178		0.318		0.189		0.248	0.135	
circ	0.080	0.130		0.134				0.121	0.156
Constant	−17.196	−17.621	−16.392	−15.781	−15.699	−15.182	−15.179	−15.503	−15.681
Sectioning point*	−0.090	−0.087	−0.086	−0.091	−0.095	−0.090	−0.108	−0.104	−0.103
Average accuracy (%)	82.4	81.8	80.7	86.5	85.2	85.2	83.5	83.5	82.6
Cross validation (%)	82.4	81.3	80.7	86.2	84.6	84.3	83.5	83.2	82.6

* *P* (Female): Values less than the sectioning point are females and vice versa

the stepwise analysis of measurements of the humeri, radii and ulnae with average accuracies of 82.4%, 86.5% and 83.5% respectively (Table 3). The other functions were formulated from a combination of measurements using direct discriminant function analysis of measurements of the humeri (Functions 2 and 3), radii (Functions 5 and 6) and ulnae (Functions 8 and 9). The average accuracies in correct sex classification ranged between 80.7% (Function 3, Table 3) and 85.2% (Functions 5 and 6, Table 3). The results of the cross-validation using the leave-one-out classification showed that the average accuracy in correct sex classification for most of the presented functions remained unchanged (Table 3). Functions 2, 5 and 6 showed a minimal and insignificant drop in classification rate of between 0.5 and 0.9% thereby confirming the validity of the derived functions from the pooled data. The pooled within-group covariance matrices by sex are presented in Supplementary Table 3.

Table 4 shows the average accuracies following cross-validation of Functions 1 to 9 (Table 3) presented above on samples from each of the population groups. In the SAAD group, a decrease in average accuracies following cross validation was observed and this ranged between 0.8% (Function 3) and 5.3% (Function 4). The other two groups showed an increase in the classification rate. Most of the functions in the MASA group showed an increase in the average accuracies which ranged between 0.7% (Function 8) and 2.8% (Function 4). However, a drop in average accuracy of 0.5% was observed for Function 7 in this population group. All the functions in the SAED population group showed an increase in the average classification rate which ranged between 0.5% (Function 4) and 6.9% (Function 7). The average of the observed changes between the original classification rate and the cross-validation rate were 3.5%, 1.3% and 2.7% for the SAAD, MASA and SAED groups respectively.

The average accuracies and cross-validation accuracies are presented for the top two functions for the humeri (Functions 1, 2, 7, 8, 13 and 14), radii (Functions 3, 4, 9, 10, 15 and 16) and ulnae (Functions 5, 6, 11, 12, 17 and 18) for each population group (Table 5). The cross-validation of SAAD population-specific functions on the same sample showed a slight drop of average accuracies, which ranged between 0.8% (Function 6)

Table 4 Average accuracies and cross-validation accuracies using pooled functions on samples of South Africans of African Descent (SAAD), Mixed Ancestry South Africans (MASA) and South Africans of European Descent (SAED)

Functions from poled data	Bone	Original classification (%)	Cross-validation (SAAD)			Cross-validation (MASA)			Cross-validation (SAED)		
			Female	Male	Average	Female	Male	Average	Female	Male	Average
Function 1	Humerus	82.4	83.1	75.4	79.3	97.7	67.2	82.5	77.1	94.6	82.5
Function 2		81.8	83.1	75.4	79.3	100.0	65.8	82.9	75.0	92.9	84.0
Function 3		80.7	79.7	80.0	79.9	95.5	70.3	82.9	68.8	94.6	81.7
Function 4	Radius	86.5	76.9	85.5	81.2	95.7	82.8	89.3	87.2	86.8	87.0
Function 5		85.2	76.9	87.1	82.0	97.9	76.6	87.3	89.4	86.8	88.1
Function 6		85.2	73.1	87.1	80.1	97.9	76.6	87.3	91.5	84.9	88.2
Function 7	Ulna	83.5	63.6	93.5	78.6	91.1	75.0	83.1	93.3	87.5	90.4
Function 8		83.5	72.7	87.1	79.9	93.3	75.0	84.2	88.9	87.5	88.2
Function 9		82.6	72.7	87.1	79.9	93.3	75.0	84.2	88.9	82.1	85.5

Table 5 Average accuracies and cross-validation accuracies using population-specific discriminant functions on samples of SAAD, MASA and SAED

Pop group	Functions	Original classification (%)	Cross-validation (SAAD)			Cross-validation (MASA)			Cross-validation (SAED)		
			Female	Male	Average	Female	Male	Average	Female	Male	Average
SAAD	Function 1	83.9	83.1	81.5	82.3	72.9	87.7	80.3	84.7	67.7	76.2
	Function 2	80.6	81.4	80	80.6	67.8	90.8	79.3	78.0	78.5	78.3
	Function 3	83.3	84.6	82.3	83.3	57.7	95.2	76.5	76.9	69.4	73.2
	Function 4	84.2	84.6	80.6	82.5	59.6	91.9	75.8	75.0	66.1	70.6
	Function 5	85.5	81.8	85.5	83.8	41.8	98.4	70.1	58.0	91.9	75.0
	Function 6	84.6	83.6	83.9	83.8	49.1	93.5	71.3	54.5	87.1	70.8
MASA	Function 7	85.2	86.7	71.9	79.3	86.4	82.8	84.3	93.3	56.3	74.8
	Function 8	83.3	95.6	70.3	82.95	86.4	81.3	83.3	86.4	65.6	76.0
	Function 9	89.2	95.7	60.9	78.3	89.4	87.5	88.3	97.9	64.1	81.0
	Function 10	86.5	95.7	62.5	79.1	89.4	84.4	86.5	89.4	67.2	78.3
	Function 11	83.5	95.6	59.4	77.5	82.2	84.4	83.5	80.0	75.0	77.5
	Function 12	81.7	97.8	56.3	77.05	82.2	81.3	81.7	77.8	82.8	80.3
SAED	Function 13	88.5	66.7	92.9	79.8	50.0	94.6	72.3	87.5	89.3	88.5
	Function 14	86.5	64.6	94.6	79.6	35.4	92.9	64.2	87.5	83.9	85.6
	Function 15	88.0	87.2	71.7	79.45	68.1	90.6	79.4	89.4	83.0	86.0
	Function 16	88.0	83	79.2	81.1	66.0	92.5	79.3	91.5	83.0	87.0
	Function 17	91.1	95.6	73.2	84.4	44.4	94.6	69.5	93.3	83.9	88.1
	Function 18	85.1	84.4	85.7	85.05	75.6	94.6	85.1	84.4	85.7	85.1

and 1.7% (Functions 4 and 5). However, when SAAD population-specific equations were applied on the MASA and SAED population groups, the range of drop in average accuracies are 1.3–15.4% and 2.3–13.8% respectively. The average in the drop of accuracies for SAAD population-specific functions were 1.0%, 8.2% and 9.7% for SAAD, MASA and SAED groups respectively. The average accuracies for most of the MASA population-specific functions remained unchanged after cross-validation (Table 5: Functions 8, 10, 11 and 12). However, the other two functions showed a drop in average accuracies of 0.9% (Table 5). The application of MASA population-specific functions on the SAAD and SAED population groups showed a drop in average accuracies 0.4–10.9% and 1.4–10.4% respectively (Table 5). The average accuracies remained unchanged for two of the SAED population-specific functions, while the others showed a drop in average accuracies that ranged between 0.9 and 3% (Table 5). The validity of these functions on a sample of SAAD population group showed a drop in average accuracies which ranged between 6.7 and 8.7% (Table 5). A larger drop in average accuracies, which ranged between 8.7 and 22.4% was obtained when SAED population-specific functions were tested on a sample of MASA population group.

Discussion

Estimation of sex remains one of the most vital aspects of the work of forensic anthropologists. Consequently, population-specific equations for estimation of sex from measurements of bones have been published for various bones of the human skeleton [10, 17, 18, 25, 37, 49–51]. These population-specific equations display higher average accuracies in correct sex estimation when applied to samples from the population from which they have been derived. It has therefore been suggested and advised that these population-specific equations should not be applied to other population groups as the degree of sexual dimorphism varies greatly between populations [14, 52]. Nevertheless, the drawback of the application of population-specific equations is that it requires a prior knowledge of the population group of any skeletal material [40].

In the current study, measurements of the humeri, radii and ulnae were shown to be sexually dimorphic which is consistent with the results of other studies from different parts of the world [19, 49, 53–56]. The range of average accuracies obtained for pooled discriminant function equations (DFEs) is comparable to those presented for previous studies in South Africa [37] and for other geographical parts of the world [17]. The average accuracies for the humeri (81–82%), radii (84–86%) and ulnae (83–84%) (Table 3) are consistently lower than those obtained for population-specific DFEs for humeri (81–89%), radii (83–89%) and ulnae (82–91%) (Table 5). Our results also showed increased average accuracies for MASA (0.1–2.8%) and SAED (0.1–6.9%) and a decreased average accuracy for SAAD (0.8–5.3%) when pooled DFEs were cross validated on samples from the respective population groups (Table 4). These observed increases and decreases in the cross-validated average accuracies for samples of different population groups are higher compared to that obtained for the pooled group (0–0.9%) (Table 3). In addition, a drop in average accuracies was observed when population-specific DFEs for SAAD (1.3 to 15.4%) were cross validated on samples of MASA and SAED. Similar results were also observed when population-specific DFEs for MASA (0.4–10.9%) and SAED (0.0–22.4%) were applied on the other two groups (Table 5).

The results of the cross-validation of average accuracies of both pooled DFEs and population-specific DFEs indicate that population-specific DFEs provide a higher classification rate compared to the pooled DFEs. This is in support of findings from previous studies confirming population specificity of DFEs [3, 7–11, 14, 17, 18, 32, 57]. However, it should be noted that the average accuracies presented for DFEs from the pooled data (Table 3) are reasonably high and are useful in the estimation of sex. The advantage of application of these functions in forensic cases is that they can be used without any prior knowledge of the population group.

South Africa with a population of about 58 million people consists of four major population groups that are spread over nine provinces. These distinct socially identifiable population groups are South African of African descent (blacks), South African of European descent (whites), Mixed-ancestry South Africans or Coloureds (MASA) and South Africans of Indian extract (Indians) [9, 35, 37, 58] . Identification of human remains poses a huge challenge in such a country with a diverse population with regard to the application of population-specific equations whether discriminant function equations for estimation of sex or regression equations for estimation of stature. While it is generally believed that population-specific DFEs and regression equations are associated with increased accuracy of estimation of sex and stature, Albanese et al. [59] argued that the assignment of an unknown to a population group is not only problematic but also sometimes impossible.

The possible reasons for this drawback include the lack of biological significance of some traits used in the assignment of population affinity and the difficulty in assigning an individual into a particular group if the individual falls within the boundaries of population groups [59]. Subsequently Albanese et al. [59] presented universal regression equations for estimation of stature from the femur and opined that this has both methodological and theoretical benefits compared to the use of population-specific regression equations. In an earlier study, Steyn, Patriquin [40] proposed the same notion of applicability of universal DFEs for estimation of sex from the pelvic bone.

Steyn, Patriquin [40] assessed the reliability of population specificity of DFEs derived for measurements of pelvic bones of South African whites, South African blacks and Greeks. Their study reported that the average accuracies in correct sex classification using all measured variables of the pelvic bone for the combined group, Greeks, SA whites and SA blacks were 94.5%, 94.8%, 94.5% and 94.5% respectively [40]. Similar results were also obtained in the direct analysis using pubic and ischial length (89–90%) and acetabular diameter (81.6–84.1%) and concluded that population-specific DFEs did not provide a higher classification rate compared to that obtained from pooled data [40]. In addition, the study suggested that it was not necessary to use population-specific DFEs for the estimation of sex using pelvic bones [40].

Macaluso Jr. [43] tested the reliability of pooled data DFEs presented by Steyn, Patriquin [40] on a sample of French pelvic bones. Macaluso Jr. [43] observed that the average accuracies of the pooled data remained unchanged when applied to a French sample and concluded that population-specific equations are not important when it comes to the estimation of sex using measurements of the pelvic bone. One of the reasons given for the lack of population specificity of DFEs from pelvic bone measurements is that it is a highly sexually dimorphic bone and it is designed for parturition, which is common in all population groups [40]. However, this may not be true for other bones of the skeleton other than the pelvic bones [40].

Recently, Hora, Sládek [16] evaluated the concept of population specificity of DFEs derived from measurements of the 12th thoracic vertebra (T12) and the first lumbar vertebra (L1). The study showed that while the two measurements of T12 i.e. anteroposterior body diameter and mediolateral body diameter, were found to be universally applicable in sex estimation, most of the measured variables of the thoracic and lumbar vertebrae showed population specificity in the assignment of sex [16]. The results of the current study are in agreement with the findings of Hora, Sládek [16] within the context of the diversity of population groups within South Africa. The universal application of the presented pooled equations in this study need to be tested in different geographical locations of the world. It should be noted that there may be need for the assessment of the applicability of population-specific DFEs derived from measurements of long bones of the upper and lower extremities due to the differences observed in the robustness of these bones in different population groups. However, this does not preclude an attempt to derive such equations which can be very useful especially during this era of increased international migration. It will become increasingly difficult to determine and choose equations to use during estimation of sex for migrants in different parts of the world.

In conclusion, the current findings indicate that discriminant function equations generated from measurements of humerus, radius and ulna of pooled population data of South Africans present with reasonably high average accuracies. Consequently, they are useful in the estimation of sex in cases when the population affinity is either difficult or impossible to ascertain and their applicability to populations of Southern Africa will require validation studies in individual populations from different countries in the region.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s00414-020-02458-y.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

References

1. İşcan MY, Loth SR (1997) The scope of forensic anthropology. In: Eckert WG (ed) Introduction to forensic sciences. CRC Press, Boca Raton, pp 343–369
2. Krishan K, Chatterjee PM, Kanchan T, Kaur S, Baryah N, Singh R (2016) A review of sex estimation techniques during examination of skeletal remains in forensic anthropology casework. Forensic Sci Int 261:165. e161-165. e168
3. Iscan MY, Steyn M (2013) The human skeleton in forensic medicine. Charles C Thomas Publisher, Springfield
4. Krogman WM, Işcan MY (1986) The human skeleton in forensic medicine. Charles C. Thomas, Springfield, pp 413–457
5. Bruzek J (2002) A method for visual determination of sex, using the human hip bone. Am J Phys Anthropol 117(2):157–168
6. González PN, Bernal V, Perez SI, Barrientos G (2007) Analysis of dimorphic structures of the human pelvis: its implications for sex estimation in samples without reference collections. J Archaeol Sci 34(10):1720–1730
7. Mokoena P, Billings BK, Gibbon V, Bidmos MA, Mazengenya P (2019) Development of discriminant functions to estimate sex in upper limb bones for mixed ancestry South Africans. Sci Justice 6(59):660–666
8. Steyn M, İşcan MY (1997) Sex determination from the femur and tibia in south African whites. Forensic Sci Int 90(1–2):111–119
9. Steyn M, İşcan MY (1999) Osteometric variation in the humerus: sexual dimorphism in South Africans. Forensic Sci Int 106(2):77–85
10. Steyn M, İşcan MY (1998) Sexual dimorphism in the crania and mandibles of South African whites. Forensic Sci Int 98(1–2):9–16
11. Asala SA, Bidmos MA, Dayal MR (2004) Discriminant function sexing of fragmentary femur of South African blacks. Forensic Sci Int 145(1):25–29
12. Bidmos M, Adebesin A, Mazengenya P, Olateju O, Adegboye O (2020) Estimation of sex from metatarsals using discriminant function and logistic regression analyses. Aust J Forensic Sci:1–14. https://doi.org/10.1080/00450618.2019.1711180
13. Fasemore MD, Bidmos MA, Mokoena P, Imam A, Billings BK, Mazengenya P (2018) Dimensions around the nutrient foramina of the tibia and fibula in the estimation of sex. Forensic Sci Int 287: 222. e221-222. e227
14. Burrows AM, Zanella VP, Brown TM (2003) Testing the validity of metacarpal use in sex assessment of human skeletal remains. J Forensic Sci 48(1):1–4
15. Kotěrová A, Velemínská J, Dupej J, Brzobohatá H, Pilný A, Brůžek J (2017) Disregarding population specificity: its influence on the sex assessment methods from the tibia. Int J Legal Med 131(1): 251–261
16. Hora M, Sládek V (2018) Population specificity of sex estimation from vertebrae. Forensic Sci Int 291:279. e271-279. e212
17. Spradley MK, Jantz RL (2011) Sex estimation in forensic anthropology: skull versus postcranial elements. J Forensic Sci 56(2): 289–296
18. Dayal MR, Spocter MA, Bidmos MA (2008) An assessment of sex using the skull of black South Africans by discriminant function analysis. Homo 59(3):209–221
19. Albanese J (2013) A method for estimating sex using the clavicle, humerus, radius, and ulna. J Forensic Sci 58(6):1413–1419
20. Papaioannou VA, Kranioti EF, Joveneaux P, Nathena D, Michalodimitrakis M (2012) Sexual dimorphism of the scapula and the clavicle in a contemporary Greek population: applications in forensic identification. Forensic Sci Int 217(1-3):231. e231-231. e237
21. Mokoena P, Billings BK, Bidmos MA, Mazengenya P (2017) Sex estimation using dimensions around the nutrient foramen of the long bones of the arm and forearm in South Africans. Forensic Sci Int 278:404. e401-404. e405
22. Albanese J, Cardoso HF, Saunders SR (2005) Universal methodology for developing univariate sample-specific sex determination methods: an example using the epicondylar breadth of the humerus. J Archaeol Sci 32(1):143–152
23. Bongiovanni R, Spradley MK (2012) Estimating sex of the human skeleton based on metrics of the sternum. Forensic Sci Int 219(1-3): 290. e291-290. e297
24. Chandrakanth H, Kanchan T, Krishan K (2014) Osteometric analysis for sexing of modern sternum–an autopsy study from South India. Legal Med 16(6):350–356
25. García-Parra P, Fernández ÁP, Djorojevic M, Botella M, Alemán I (2014) Sexual dimorphism of human sternum in a contemporary Spanish population. Forensic Sci Int 244:313. e311-313. e319
26. Gonzalez PN, Bernal V, Perez SI (2009) Geometric morphometric approach to sex estimation of human pelvis. Forensic Sci Int 189(1–3):68–74
27. Case DT, Ross AH (2007) Sex determination from hand and foot bone lengths. J Forensic Sci 52(2):264–270
28. Falsetti AB (1995) Sex assessment from metacarpals of the human hand. J Forensic Sci 40(5):774–776
29. Jee S-C, Bahn S, Yun MH (2015) Determination of sex from various hand dimensions of Koreans. Forensic Sci Int 257:521. e521-521. e510
30. Smith SL (1996) Attribution of hand bones to sex and population groups. J Forensic Sci 41(3):469–477
31. Wilbur AK (1998) The utility of hand and foot bones for the determination of sex and the estimation of stature in a prehistoric population from west-central Illinois. Int J Osteoarchaeol 8(3):180–191
32. Bidmos MA, Asala SA (2003) Discriminant function sexing of the calcaneus of the South African whites. J Forensic Sci 48(6):1213–1218
33. Bidmos MA, Asala SA (2004) Sexual dimorphism of the calcaneus of South African blacks. J Forensic Sci 49(3):446–450
34. Cardoso HF (2008) Sample-specific (universal) metric approaches for determining the sex of immature human skeletal remains using permanent tooth dimensions. J Archaeol Sci 35(1):158–168
35. STATS SA (2019) Governance, public safety and justice survey. , vol Accessed 20 February 2020
36. Franklin D, Freedman L, Milne N (2005) Sexual dimorphism and discriminant function sexing in indigenous South African crania. Homo 55(3):213–228
37. Krüger GC, L'Abbé EN, Stull KE (2017) Sex estimation from the long bones of modern South Africans. Int J Legal Med 131(1):275–285
38. Bidmos M, Steinberg N, Kuykendall K (2005) Patella measurements of South African whites as sex assessors. Homo 56(1):69–74
39. Bidmos MA, Dayal MR (2003) Sex determination from the talus of South African whites by discriminant function analysis. Am J Forensic Med Pathol 24(4):322–328
40. Steyn M, Patriquin M (2009) Osteometric sex determination from the pelvis—does population specificity matter? Forensic Sci Int 191(1-3):113. e111-113. e115
41. Macho GA (1990) Is sexual dimorphism in the femur a "population specific phenomenon"? Z Morphol Anthropol 78(2):229–242

42. Albanese J, Osley SE, Tuck A (2012) Do century-specific equations provide better estimates of stature? A test of the 19–20th century boundary for the stature estimation feature in Fordisc 3.0. Forensic science international 219(1-3):286. e281-286. e283
43. Macaluso PJ Jr (2010) Sex determination from the acetabulum: test of a possible non-population-specific discriminant function equation. J Forensic Legal Med 17(6):348–351
44. Mazengenya P, Billings B (2016) Topographic and morphometric features of the nutrient foramina of the fibula in the South African mixed-ancestry population group and their surgical relevance. Eur J Anat 20(4):329–336
45. Mazengenya P, Fasemore MD (2015) Morphometric studies of the nutrient foramen in lower limb long bones of adult black and white South Africans. Eur J Anat 19(2):155–163
46. Pereira G, Lopes P, Santos A, Silveira F (2011) Nutrient foramina in the upper and lower limb long bones: morphometric study in bones of Southern Brazilian adults. Int J Morphol 29(2):514–520
47. Dayal MR, Kegley AD, Štrkalj G, Bidmos MA, Kuykendall KL (2009) 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 140(2):324–335
48. Maass P, Friedling LJ (2019) Documented composition of cadaveric skeletal remains in the University of Cape Town Human Skeletal Collection, South Africa. Forensic Sci Int 294:219. e211-219. e217
49. Charisi D, Eliopoulos C, Vanna V, Koilias CG, Manolis SK (2011) Sexual dimorphism of the arm bones in a modern Greek population. J Forensic Sci 56(1):10–18
50. Scott S, Ruengdit S, Peckmann TR, Mahakkanukrauh P (2017) Sex estimation from measurements of the calcaneus: applications for personal identification in Thailand. Forensic Sci Int 278:405. e401-405. e408
51. Patriquin ML, Loth S, Steyn M (2003) Sexually dimorphic pelvic morphology in South African whites and blacks. Homo 53(3):255–262
52. Bidmos MA, Dayal MR (2004) Further evidence to show population specificity of discriminant function equations for sex determination using the talus of South African blacks. J Forensic Sci 49(6): 1165–1170
53. Holman DJ, Bennett KA (1991) Determination of sex from arm bone measurements. Am J Phys Anthropol 84(4):421–426
54. Mall G, Hubig M, Büttner A, Kuznik J, Penning R, Graw M (2001) Sex determination and estimation of stature from the long bones of the arm. Forensic Sci Int 117(1–2):23–30
55. Frutos LR (2005) Metric determination of sex from the humerus in a Guatemalan forensic sample. Forensic Sci Int 147(2–3):153–157
56. Kranioti EF, Michalodimitrakis M (2009) Sexual dimorphism of the humerus in contemporary Cretans—a population-specific study and a review of the literature. J Forensic Sci 54(5):996–1000
57. Dayal MR, Bidmos A (2005) Discriminating sex in south African blacks using patella dimensions. J Forensic Sci 50(6):1294–1297
58. Stull KE, Kenyhercz MW, L'Abbé EN (2014) Ancestry estimation in South Africa using craniometrics and geometric morphometrics. Forensic Sci Int 245:206. e201–206. e207
59. Albanese J, Tuck A, Gomes J, Cardoso HF (2016) An alternative approach for estimating stature from long bones that is not population-or group-specific. Forensic Sci Int 259:59–68