Adebesin *et al. Egyptian Journal of Forensic Sciences (2025) 15:19*
https://doi.org/10.1186/s41935-025-00427-3

Egyptian Journal of Forensic Sciences

RESEARCH

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Direct and indirect estimation of stature using measurements of metacarpals of South Africans of African descent

Abduljalil Adebesin[1], Youssef Mohamed[2], Noor Al-Obaidan[2], Mohammed Al-Matwi[2], Oladiran Olateju[3] and Mubarak Bidmos[2*]

Abstract

Background Stature reconstruction is an important component of skeletal analysis in personal identification. The mathematical method has been used in various parts of the world to establish standards for estimation of stature from measurements of intact and fragmentary long bones. While few studies have shown the usefulness of measurements of metacarpals for stature reconstruction in other parts of the world, none has been conducted in any population group in South Africa.

Aim of the study The aim of the current study was therefore to derive regression formulae for South Africans of African descent using both the direct and indirect methods of skeletal stature estimation using measurements of metacarpals.

Materials and methods The sample included 53 male and 50 female South African of African descent skeletons from the Raymond A. Dart Collection of Human Skeletons. Data on total skeletal height (TSH) and measurements of metacarpal were collected and found to be within acceptable technical errors of measurement.

Results Data were normally distributed with mean values significantly higher for males than for females. The range of correlation between TSH and measurements of metacarpal (0.40–0.84) was stronger than between maximum length of metacarpal and other measured variables of metacarpals (0.34–0.66) in both univariate and stepwise regression equations. For direct and indirect functions, 10 univariate and multivariate equations are presented with standard estimate errors (2.4–5.2 cm) and accuracy of 62–88% (within 1 SEE) and 92–99% (within 2 SEE).

Conclusion The derivative functions, specific to South Africans of African descent, add to the suite of formulae to be considered in forensic investigations.

Keywords Forensic anthropology, Skeletal stature estimation, Metacarpals, South Africans of African descent

Background

Stature estimation, an integral part of the process of human identification, can be performed using the anatomical and mathematical methods. The anatomical or Fully's method (Fully 1956) recently updated by Raxter et al. (Raxter et al. 2006) involves the summation of individual skeletal elements to estimate stature. The latter method is based on the relationship between measurements of bones and stature. Dwight in 1894 (cited in Lundy (Lundy 1983)) made the first attempt

*Correspondence:
Mubarak Bidmos
mbidmos@qu.edu.qa
[1] Department of Human Anatomy, Sefako Makgatho Health Sciences University, Ga-Rankuwa, South Africa
[2] College of Medicine, QU Health, Qatar University, Doha, Qatar
[3] School of Anatomical Sciences, Faculty of Health Sciences, University of the Witwatersrand, Johannesburg, South Africa

to reconstruct stature using the anatomical method in the presence of a complete skeleton. Dwight suggested rearticulating a complete skeleton of an individual and using clay to account for soft tissue, thereby producing a close representation of a living person's stature (Lundy 1985). Fully's method (Fully 1956) is considered to be an accurate way of estimating stature (Lundy 1988) and is also not population or sex specific (Raxter et al. 2006). Raxter et al. (Raxter et al. 2006) revised the Fully's method and recommended universal soft tissue correction factors. The universal applicability of these factors has been questioned by some researchers (e.g. Bidmos and Manger (Bidmos and Manger 2012)).

The mathematical method has been widely used in South Africa in the formulation of population and sex-specific regression equations. This is because the documented individual lengths and living statures in the catalogue of the Raymond A. Dart Collection of Human Skeletons have been shown to be inaccurate (Lundy 1985; Bidmos 2005). In addition, this demographic information is not available for some of the individuals in the collection (Lundy 1985; Bidmos 2005). Previous studies (Mendonça 2000; Mall et al. 2001; Radoinova et al. 2002; Hauser et al. 2005; Celbis and Agritmis 2006; Petrovečki et al. 2007; Trotter and Gleser 1958) have shown that the maximum length of intact long bones of the upper and lower extremities is reliable in estimating stature in different population groups worldwide. Similar studies conducted in South Africa using intact humerus, radius, ulna, femur, tibia, and fibula (Dayal et al. 2008; Lundy 1987) showed comparable results. In addition, measurements of the skull (Ryan and Bidmos 2007), the sacrum (Pininski and Brits 2014), fragments of the femur and tibia (Chibba and Bidmos 2007; Bidmos 2008a, 2008b; Spies 2018), calcaneus (Bidmos and Asala 2005; Bidmos 2006), and metatarsals (Bidmos 2008c) have also been used for stature reconstruction in South Africa with reasonable standard error of estimate (SEE). Since these bones are not always available for forensic analysis, it has therefore become necessary to use other bones such as metacarpals for stature reconstruction.

Musgrave and Harneja (Musgrave and Harneja 1978) conducted the first investigation on stature reconstruction from measurements of metacarpals using a sample of predominant white adults at the Bristol Royal Infirmary Hospital. The correlation coefficient of metacarpals and stature ranged between 0.49 and 0.84, while the standard error of estimates (SEE) for the equations was 4.71 to 8.15 cm. Similarly, Meadows and Jantz (Meadows and Jantz 1992) presented regression equations to estimate stature from the lengths of metacarpals of Americans using samples from the Terry Collection. Similar studies were also conducted to assess the usefulness of metacarpal bones in the estimation of stature in Turks (Sağir 2006), Guatemalan (Himes and Malina 1977), and Japanese children (Kimura 1992).

Furthermore, metrical and morphological features of the metacarpal have been demonstrated to be reliable in the estimation of population affinity (Lazenby 2002) and sex (Sallie et al. 2022; Manolis et al. 2009). The medullary canal width of the metacarpals has also been found to correlate with age (Kusec et al. 1988). Due to the high level of criminality within South African society which criminals make every effort to hide the identity of their victims by mutilation and dismemberment (Steyn 2005; Steyn et al. 2019; Bhootra and Weiss 2006), it has become necessary that regression equations be formulated from as many bones as possible from human skeletons. Since the metacarpals have been shown to provide a reasonable degree of accuracy in stature estimation in other population groups, it is therefore the aim of this study to assess the usefulness of measurements of metacarpals of South Africans of African descent in the estimation of adult skeletal stature.

Materials and methods

Before the commencement of this study, approval for the examination of human skeletal remains that are housed in the Raymond A. Dart Collection of Human Skeletons (Dayal et al. 2008) in the School of Anatomical Sciences, University of the Witwatersrand, Johannesburg, was granted by the University's Human Research Ethics Committee (Medical) (clearance certificate: W-CBP-220504–01). A total of 103 (53 males and 50 females) individuals were selected by a simple random sampling. The inclusion criteria for the selected skeletons that were used in this study include those with known sex, population affinity, age at death, and *postmortem* lengths of the individuals. This demographic information is available in the catalogue of the Raymond A. Dart Collection of Human Skeletons.

For the current study, the earliest birth in the sample was recorded in 1904, and the latest was in 1980. The age at the time of death of the selected samples ranged between 19 and 77 years. The mean and median ages were 46.2 and 45 years respectively with a standard deviation of 14.2 years. The lower limit of 18 years was selected because skeletal maturity would have been completed and a significant stature increase is not noted as reported by Trotter and Gleser (Trotter and Gleser 1951). The upper limit of 77 years was selected to avoid pathological changes such as excessive osteophytic lipping of the vertebral column and pathological fracture which usually affects bones in the elderly. Skeletons with damaged or broken bones, excessive osteophytic lipping, pins and plates, and other pathological conditions were also excluded from the study.

Previous studies have shown that the documented individual lengths in the catalogue of the Raymond A. Dart Collection of Human Skeletons are unreliable (Lundy 1988; Bidmos 2005). Consequently, the anatomical method as revised by Raxter et al. (Raxter et al. 2006) was used in calculating skeletal height which is also known as total skeletal height (TSH) as a proxy for stature. It is important to note that correction factors, representing the soft tissues values in living height, should be added to the TSH to obtain stature estimate. The procedure to derive skeletal height involves the use of complete skeletons which included the skull, cervical vertebrae from C2 (including the odontoid process) to S1, the femur, the tibia, and articulated talus and calcaneus. In a few cases where extra vertebrae were present, they were included in the estimation of TSH as recommended by Lundy (Lundy 1985, 1988).

The following measurements that constitute TSH were taken on each skeleton using either the osteometric board or a sliding calliper Raxter et al. (Raxter et al. 2006):

1. Basibregmatic height of the skull
2. Maximum height of each vertebra body anterior to pedicles/rib articular facets from C2 to S1
3. Physiological length of the femur
4. Condylomalleolar length of the tibia
5. Articulated height of talus and calcaneus

In addition, four linear measurements and the midshaft diameter of each metacarpal bone were taken using a vernier calliper or a mini-osteometric board. All these measurements were taken on the dorsal surfaces except for the maximum length and midshaft diameter that were taken from the palmar surface following the description of Case et al. (Case et al. 2015):

i) Maximum length (ML): The linear distance from the proximal end to the midpoint of the articular surface of the base parallel to the longitudinal axis of the bone
ii) Base width (BW): The linear distance from the most medial point to the most lateral point of the base and is perpendicular to the long axis of the bone shaft
iii) Base height (BH): The linear distance from the proximal articular end to the junction (ridge) of the bone shaft
iv) Head width (HW): The linear distance from the most medial point to the most lateral point of the head and is perpendicular to the long axis of the bone shaft
v) Midshaft diameter: The linear distance from the most medial point to the most lateral point at the calculated one-half of the maximum axial length

To minimise measurement errors, an intraobserver evaluation of the reliability of the measuring technique was performed on a sample of 20 skeletons using technical error of measurement (TEM). Subsequently, data were collected and analysed using the SPSS (version 24) software. Descriptive statistics including the mean and standard deviation were obtained for TSH and each of the measurements of metacarpals. The data was evaluated for normality of distribution of the measured variables by using the Kolmogorov–Smirnov and Shapiro–Wilk's test methods and histograms. Following confirmation of the normality of the distribution of the dataset, a comparison of means of males and females was done using the one-way ANOVA with the level of significance set at $p \leq 0.05$. Thereafter, univariate and stepwise forward regression analyses were then performed to obtain various combinations of metacarpal variables that can best estimate TSH. From these analyses, the unstandardized coefficient, constant, SEE, and correlation coefficient were obtained.

Results

The intraobserver reliability was assessed through the calculation of absolute and relative technical error of measurement (TEM and rTEM). The results demonstrate an acceptable degree of measurement error as it relates to the size of the measurement and the overall margin of error for each measurement (Perini et al. 2005). Measurement errors for this study were minimal with a range between 0.07 and 0.6 for TEM, while the range for rTEM is between 0.11 and 4.82 (Table 1). These values fall within internationally accepted linear measurement values for rTEM (< 5%) as recommended by Weinberg et al. (Weinberg et al. 2005) and Ward and Jamison (Ward and Jamison 1991).

The means and standard deviations for each of the variables are presented in Table 2. Males display significantly higher mean values for all the measurements than the females ($p < 0.05$) which indicates sexual dimorphism of measurements of metacarpals and skeletal height (TSH).

All measured variables of metacarpals showed a positive correlation with the skeletal height. The functions presented in Table 3 are for the measurements with moderate-to-high correlation with TSH.

The correlation between measurements of metacarpals and TSH ranges from 0.5 to 0.7 in the females and 0.4 to 0.6 in the males (Table 3). The functions are arranged in descending order of correlation of measurement of metacarpal with TSH (Table 3). ML-M2 showed the highest correlation with TSH in both females (0.7)

Table 1 Intraobserver reliability using technical error of measurements (TEM) and relative technical error of measurement (rTEM)

Measurements		TEM	rTEM
M1	ML	0.167	0.36
	BW	0.604	4.246
	BH	0.327	3.588
	HW	0.548	4.013
	MD	0.151	1.332
M2	ML	0.166	0.24
	BW	0.500	3.084
	BH	0.498	4.582
	HW	0.416	3.178
	MD	0.265	3.29
M3	ML	0.073	0.109
	BW	0.436	3.373
	BH	0.52	4.743
	HW	0.466	3.722
	MD	0.128	1.591
M4	ML	0.295	0.521
	BW	0.500	4.575
	BH	0.398	4.821
	HW	0.266	2.418
	MD	0.095	1.515
M5	ML	0.217	0.407
	BW	0.443	3.909
	BH	0.405	4.611
	HW	0.442	4.168
	MD	0.165	2.195

ML maximum length, *BW* base width, *BH* base height, *HW* head width, *MD* midshaft diameter, *NB* all measurements were taken in mm

and males (0.6), while the least correlation was displayed by MD-M5 in females (0.5) and MD-M2 in males (0.4). These functions also presented with the lowest SEE which ranges between 4.6 to 6.0 cm in females and 4.4 to 5.2 cm in males (Table 3). The result of the evaluation of the accuracy of TSH estimation using each of the functions is also presented in Table 3. The estimated TSH falls within 1 SEE in 64–74% of cases in females, while the accuracy is higher at 2 SEE (92–98%). Males also showed a similar range of percentage accuracy with the estimated TSH within 1 SEE in 62–76% of cases and within 2 SEE in 94–98% of cases.

Regression equations with various combinations of measurements of metacarpals that best estimate TSH are shown in Table 4. They are arranged in increasing order of correlation and decreasing order of SEE.

In females, the magnitude of the correlation coefficients obtained for these functions which range from 0.7 to 0.8 is higher than those obtained from the use of individual variables as shown in Table 3. A similar result was also obtained for the males in which the range of correlation is between 0.6 and 0.8 (Table 4). In addition, the SEE for these functions which ranges between 4.4–5.0 cm for the females and 3.3–4.6 cm for the males are lower than those obtained for the Functions utilising individual variables of metacarpals (Table 3). An evaluation of the accuracy of the presented multivariate functions showed that the estimated TSH falls within 1 SEE in 84–88% of cases in the females, while the accuracy is higher at 2 SEE (97–99%). The range of accuracy in the males in which the estimated TSH is within 1 SEE is 64–79% of cases and within 2 SEE in 94 to 98% of cases.

All measured variables of metacarpals in both sexes were significantly correlated with the maximum length of metacarpals (ML) ($p < 0.01$). The univariate regression equations for estimating ML are presented in Table 5. In the female sample, HW-M5 showed the highest correlation with ML-M5 (0.7), while the lowest correlation was displayed by BW-M4 with ML-M4 (0.5) (Table 5). For the males, the range of correlation coefficient is between 0.3 for BW-M4 and 0.5 for MD-M4 (Table 5). The SEEs for the functions in the females (2.4–3.9 cm) are similar to those obtained in the males (2.3–3.6 cm). The range of accuracy of the Functions in which the estimated ML falls within 1 SEE and 2 SEE in the females is 62–86% and 92–98%, respectively. A similar range of accuracy was obtained in males for 1 SEE (62–76%) and 2 SEE (93–100%).

Discussion

Stature estimation remains an important component of the process of human identification from recovered or discovered skeletal remains. In the presence of a full skeleton, forensic anthropologists often use the anatomical method in the reconstruction of stature. However, forensic anthropologists do not usually have access to a complete set of human remains from which the demographic information of the deceased including stature could be estimated. In some forensic cases, the recovered remains are in a state of dismemberment or incomplete, which requires the reconstruction of *premortem* stature from the available components of the skeleton. This constraint has led to the formulation of regression equations from intact and fragments of various bones of the human skeleton (Dayal et al. 2008; Ryan and Bidmos 2007; Bidmos and Asala 2005; Steele 1970; Byers et al. 1989; Simmons et al. 1990; Holland 1995; Chiba and Terazawa 1998) including the metacarpals (Musgrave and Harneja 1978; Meadows and Jantz 1992).

One of the goals of this study was to assess the reliability and accuracy of using metacarpal measurements to estimate total skeletal height (TSH) in a South African of African descent. In determining the reliability of

Table 2 Descriptive statistics of total skeletal height (TSH) (in cm) and measurements of metacarpals (in mm) of South Africans of African descent

Measurements	Males		Females		*t*-statistic	*p*-value
	Mean	Std. dev.	Mean	Std. dev.		
TSH	153.4	5.6	142.5	6.8	8.901	0.0001
ML-M1	47.2	2.5	44.0	4.4	3.200	0.0001
BW-M1	15.3	1.1	13.5	1.2	1.800	0.0001
BH-M1	9.3	0.7	8.7	1.0	0.600	0.0006
HW-M1	14.7	1.1	12.9	1.0	1.800	0.0001
MD-M1	12.5	1.2	10.8	1.0	1.700	0.0001
ML-M2	69.7	3.5	65.3	4.1	4.400	0.0001
BW-M2	16.6	1.3	14.8	1.3	1.800	0.0001
BH-M2	10.6	1.4	9.8	0.9	0.800	0.0009
HW-M2	13.8	1.1	12.2	1.0	1.600	0.0001
MD-M2	8.6	0.8	7.6	0.7	1.000	0.0001
ML-M3	69.3	3.9	65.0	4.3	4.300	0.0001
BW-M3	13.8	1.2	12.5	1.2	1.300	0.0001
BH-M3	11.0	1.8	9.8	1.6	1.200	0.0006
HW-M3	13.5	1.0	12.1	0.8	1.400	0.0001
MD-M3	8.7	0.7	7.7	0.6	1.000	0.0001
ML-M4	58.7	3.0	55.4	3.8	3.300	0.0001
BW-M4	11.7	0.9	10.4	1.0	1.300	0.0001
BH-M4	8.5	0.9	7.8	0.9	0.700	0.0001
HW-M4	11.9	0.8	10.7	0.8	1.200	0.0001
MD-M4	7.2	0.6	6.2	0.5	1.000	0.0001
ML-M5	54.3	2.8	50.6	3.2	3.700	0.0001
BW-M5	12.0	1.0	10.5	1.0	1.500	0.0001
BH-M5	8.8	0.8	8.1	0.8	0.700	0.0001
HW-M5	11.6	0.9	10.1	0.8	1.500	0.0001
MD-M5	8.5	0.9	7.2	0.8	1.300	0.0001

TSH total skeletal height (in cm), *ML* maximum length (in mm), *BW* base width (in mm), *BH* base height (in mm), *HW* head width of metacarpal (in mm), *MD* midshaft diameter (in mm)

measurements obtained for the study, we have shown that the degree of measurement error was within the acceptable standard (Weinberg et al. 2005; Ward and Jamison 1991). Declaration of the uncertainty in the field of forensic science is necessary to determine if a proposed function is appropriate or not (Taylor and Kuyatt 1994). Obviously, this cannot be limited only to the degree of errors associated with forensic standards but also extended to the accuracy of the raw data from which they are developed, knowing the error rates are a necessary measure needed to determine the weight of evidence. The appropriate weight of the evidence cannot be known without some indication of the level at which the technique fails (Ellison 2000).

Similarly, it is important to apply the Functions to the community from where the sample was drawn and also need to be time bound due to temporal changes in human body. Previous authors (Tobias 1985; Price et al. 1987; Henneberg and Berg 1990) have shown that the direction and rate of secular trends are changing and can also be more pronounced in certain populations. However, the individuals in the current sample are not materially different in size from the contemporary South Africans, although there were contradictory reports on the matter. Negative secular trends in the size and proximity of the lower limbs were reported amongst South Africans of African descent of the early twentieth century (Price et al. 1987; Tobias and Netscher 1977), while Louw and Henneberg (Louw and Henneberg 1954) observed small increases in the statures of all the South African population groups. Furthermore, it has been argued that between 56 and 99% of the variance in height is due to genetics, while less than 25% are attributable to environmental influences (Henneberg and Berg 1990; Bielicki et al. 1981; Jedlińska 1985). The environmental stressors for the

Table 3 Univariate equations for stature estimation (in cm), correlation, and standard error of estimate from measurements of metacarpals (in mm)

	Equations	Correlation	SEE	Accuracy	
				1 SEE	2 SEE
	Male				
1	1.02 (ML-M2) + 83.08	0.63	4.4	73.6	96.2
2	0.80 (ML-M3) + 97.90	0.56	4.7	69.8	96.2
3	2.30 (BW-M2) + 115.36	0.54	4.7	67.9	94.3
4	4.42 (MD-M3) + 114.85	0.54	4.8	64.2	98.1
5	0.98 (ML-M4) + 96.16	0.52	4.8	66.0	94.3
6	1.16 (ML-M1) + 98.49	0.52	4.8	75.5	94.3
7	3.22 (BW-M4) + 115.68	0.49	4.9	69.8	98.1
8	0.85 (ML-M5) + 107.12	0.43	5.1	67.9	94.3
9	3.40 (BH-M1) + 121.84	0.42	5.1	62.3	96.2
10	2.93 (MD-M2) + 128.20	0.40	5.2	73.6	98.1
	Female				
1	1.23 (ML-M2) + 62.55	0.74	4.6	74.0	94.0
2	1.46 (ML-M5) + 68.97	0.68	5.0	74.0	94.0
3	1.21 (ML-M4) + 75.78	0.67	5.1	72.0	94.0
4	1.04 (ML-M3) + 75.03	0.66	5.2	64.0	90.0
5	3.86 (HW-M2) + 95.55	0.55	5.7	70.0	96.0
6	4.58 (HW-M5) + 96.46	0.54	5.8	70.0	96.0
7	2.89 (BW-M3) + 106.49	0.51	5.9	72.0	98.0
8	0.76 (ML-M1) + 109.19	0.49	6.0	74.0	94.0
9	4.31 (HW-M4) + 96.23	0.48	6.0	70.0	92.0
10	4.05 (MD-M5) + 113.21	0.48	6.0	70.0	98.0

ML maximum length, *BW* base width, *BH* base height, *HW* head width, *MD* midshaft diameter, *M1* first metacarpal, *M2* second metacarpal, *M3* third metacarpal, *M4* fourth metacarpal, *M5* fifth metacarpal

Table 4 Univariate equations for estimation of maximum length of metacarpals (in mm) from measurements of metacarpals (in mm) correlation and standard error of estimate

	Equations	Correlation	SEE	Accuracy	
				1 SEE	2 SEE
Male					
1	2.414 (MD-M4) + 41.412	0.48	2.6	62.3	100.0
2	1.006 (BH-M3) + 58.3	0.48	3.4	67.9	98.1
3	2.698 (MD-M3) + 45.759	0.47	3.5	62.3	98.1
4	1.352 (HW-M2) + 51.096	0.43	3.2	69.8	96.2
5	1.914 (MD-M2) + 53.273	0.42	3.2	66.0	98.1
6	1.115 (BW-M2) + 51.251	0.42	3.2	67.9	100.0
7	1.341 (HW-M5) + 38.84	0.41	2.6	75.5	92.5
8	1.265 (BW-M3) + 51.833	0.39	3.6	64.2	96.2
9	0.856 (HW-M1) +34.644	0.37	2.3	73.6	94.3
10	1.192 (BW-M4) + 44.704	0.34	2.8	69.8	96.2
Female					
1	2.62 (HW-M5) + 24.183	0.66	2.4	70.0	94.0
2	2.726 (HW-M2) + 32.129	0.64	3.2	68.0	92.0
3	2.896 (MD-M2) + 43.279	0.51	3.5	74.0	98.0
4	1.609 (BW-M2) + 41.442	0.50	3.6	68.0	94.0
5	2.565 (HW-M3) + 33.935	0.50	3.8	74.0	96.0
6	2.346 (HW-M4) + 30.149	0.48	3.3	76.0	96.0
7	1.683 (BW-M3) + 43.944	0.47	3.8	68.0	94.0
8	2.055 (MD-M1) + 21.81	0.46	3.9	86.0	98.0
9	2.067 (BH-M2) + 45.074	0.46	3.7	66.0	96.0
10	1.681 (BW-M4) + 37.896	0.45	3.4	62.0	98.0

ML maximum length, *BW* base width, *BH* base height, *HW* head width, *MD* midshaft diameter, *M1* first metacarpal, *M2* second metacarpal, *M3* third metacarpal, *M4* fourth metacarpal, *M5* fifth metacarpal

individuals in the sample and current inhabitants of South Africa have not changed significantly.

The evaluation of the mean of the measured variables of the metacarpals for the male and the female samples in the current study showed that the male values were statistically significantly higher than those of the females (Table 2). This indicates sexual dimorphism of the measured variables of metacarpals and agrees with the observation from numerous studies that reported a well-recognised phenomenon in which the male bones are generally heavier, thicker, sturdier, and, specifically, longer than those of the females (Kusec et al. 1988; Kanahashi et al. 2024; Brzobohatá et al. 2016; Schneider et al. 2015; Barrio et al. 2006; Martin and Atkinson 1977). In comparison, the mean values between the males and females were highly significant for all the measurements. This finding was comparable to the studies of Manolis et al. (Manolis et al. 2009) and Barrio et al. (Barrio et al. 2006).

The correlation coefficient is a measure of the relationship between independent and dependent variables. In this study, moderate-to-high correlations were observed between the maximum length of metacarpal bones (ML) and skeletal height (TSH). In univariate analysis, the range of correlation coefficient in males (0.4–0.6) is comparable to that obtained in females (0.5–0.7) (Table 3). A higher degree of correlation between the measurements of metacarpals and TSH was obtained in the multivariate analysis with a similar range in males (0.6 and 0.8) compared to females (0.7 and 0.8). The combined range of correlation for both univariate and multivariate analyses in the current study is comparable to that obtained in the study by Meadows and Jantz (Meadows and Jantz 1992) (0.4–0.8) for samples that were obtained from the Terry Collections and modern samples of Americans. Conversely, the degree of correlation coefficient between measurements of metacarpals and stature obtained in the current study is slightly stronger than that reported by Musgrave and Harneja (Musgrave and Harneja 1978). Similarly, in comparison with other South African studies, the correlation values for the current study compared favourably with the metatarsal studies by Bidmos

Table 5 Multivariate equations for stature estimation (in cm), correlation, and standard error of estimate from measurements of metacarpals (in mm)

				Accuracy %	
	Equations	Correlation	SEE	1 SEE	2 SEE
	Male				
1	1.681 (BH-M1) − 0.932 (MD-M1) + 0.744 (ML-M2) + 1.122 (BW-M2) + 0.977 (BH-M2) + 1.090 (BW-M3) − 1.113 (BH-M3) + 1.698 (MD-M3) + 1.695 (BW-M4) − 2.226 (HW-M4) + 57.551	0.84	3.3	77.4	94.3
2	0.7000 (ML-M2) + 1.374 (BW-M2) + 1.048 (MD-M2) + 72.798	0.71	4.0	77.4	96.2
3	0.789 (ML-M2) + 1.417 (BW-M2) + 74.942	0.70	4.1	79.2	96.2
4	0.481 (ML-M3) + 0.796 (BW-M3) + 2.731 (MD-M3) + 85.241	0.66	4.3	73.6	96.2
5	0.750 (ML-M4) + 2.326 (BW-M4) + 82.163	0.65	4.4	75.5	96.2
6	0.864 (ML-M1) + 0.823 (BW-M1) + 2.323 (BH-M1) + 78.442	0.61	4.5	64.2	98.1
7	0.966 (ML-M1) + 2.346 (BHM-1) + 86.000	0.59	4.6	67.9	94.3
	Female				

Table 5 (continued)

				Accuracy %	
9	2.203 (MD-M5) − 1.816 (HW-M5) + 1.301 (HW-M1) + 1.455 (ML-M2) − 0.715 (BW-M2) − 4.696 (MD-M3) + 4.139 (MD-M4) + 54.325	0.80	4.4	88.0	98.0
10	1.919 (MD-M5) − 1.762 (HW-M5) + 0.965 (HW-M1) + 1.380 (ML-M2) − 4.313 (MD-M3) + 3.889 (MD-M4) + 53.092	0.79	4.4	87.0	98.0
11	1.915 (MD-M5) + 1.219 (ML-M2) − 3.545 (MD-M3) + 2.977 (MD-M4) + 58.061	0.78	4.4	84.0	98.0
12	1.131 (ML-M2) + 0.934 (BH-M2) + 59.658	0.75	4.6	87.0	97.0
13	1.215 (ML-M5) + 0.780 (BW-M5) + 1.619 (MD-M5) + 61.193	0.73	4.8	86.0	98.0
14	1.242 (ML-M5) + 2.129 (MD-M5) + 64.350	0.72	4.8	87.0	98.0
15	1.044 (ML-M4) + 1.155 (HW-M4) + 1.853 (MD-M4) + 60.950	0.71	5.0	87.0	98.0
16	1.134 (ML-M4) + 2.602 (MD-M4) + 63.748	0.70	5.0	86.0	97.0
17	0.844 (ML-M3) + 1.465 (BW-M3) + 69.407	0.70	5.0	84.0	99.0

Table 5 (continued)

				Accuracy %	
18	0.819 (ML-M3) + 1.279 (BW-M3) + 0.512 (HW-M3) + 67.138	0.70	5.0	86.0	99.0

ML maximum length, *BW* base width, *BH* base height, *HW* head width, *MD* midshaft diameter, *M1* first metacarpal, *M2* second metacarpal, *M3* third metacarpal, *M4* fourth metacarpal, *M5* fifth metacarpal

(Bidmos 2008c) ranging from 0.54 to 0.72 cm and the intact bones of the upper and lower extremities by Lundy (Lundy 1987) with a value of 0.62–0.90 cm. The moderate-to-strong correlations obtained in this study therefore confirm the effectiveness of measurements of metacarpals in the estimation of TSH.

The SEE is considered a measure of the accuracy of a regression equation and is defined as a measure of the anticipated accuracy of a stature estimate for an individual from the same population from which data were collected for the development of the equation (Trotter and Gleser 1958). An equation with a large value of SEE is considered to have a low accuracy and vice versa. In the current study, the SEE of univariate and multivariate regression equations for the estimation of TSH from measurements of metacarpals of the males (3.3–5.2 cm) are comparable to that obtained for the females (4.4–6.0 cm) (Tables 3 and 5). The lower SEE obtained for the males in the current study is consistent with other studies on the reconstruction of stature in the South African population, for example using fragments of tibia, and Spies et al. (Spies 2018) recorded 3.69–4.07 cm for the males compared to 4.23–5.20 cm that was obtained for the females. Bidmos (Bidmos 2008a) also found lower SEE in males (3.73–3.75 cm) compared to 4.06–4.18 cm for females. When comparing our metacarpal equations with previous studies, it is observed that the SEE was lower than Meadows and Jantz (Meadows and Jantz 1992) who obtained 4.68–5.97 cm and 5.49–6.30 cm obtained by Musgrave and Harneja (Musgrave and Harneja 1978). Although the SEE recorded by Meadows and Jantz (Musgrave and Harneja 1978) were considered higher than those for the long bones (Byers et al. 1989; Grieshaber 2001), it is generally proportional to that of the fragmented femur. Kimura (Kimura 1992) argued that the metacarpal length produced a more accurate estimation than other bone fragments and reported that the 2nd and 3rd metacarpal length estimates were better, whereas, in terms of using fragments, the 4th metacarpal midshaft produced the best model (Kimura 1992). The observations of Kimura (Kimura 1992) are supported by the current study with 2nd metacarpal length having the best model in both the male and female groups. It is thus important to note that the accuracy of all the equations is between 62 and 88% for a SEE.

Estimation of TSH from measurements of long bones including metacarpals can be carried out using direct and indirect methods. The first method involves the direct estimation of TSH from the ML and other measured variables of metacarpals. The univariate and multivariate regression equations that can be used in this approach are presented in Tables 3 and 5, respectively. The second method is a two-stage process which involves an initial estimation of ML using regression equations presented in Table 4 and the subsequent estimation of TSH from the estimated ML. One of the earliest attempts at evaluating the accuracy of the direct and indirect methods was carried out by Steele (Steele 1970) who argued that despite the two-step approach of the indirect method, it provided a more accurate estimation of stature compared to the direct method. However, Bidmos (Bidmos 2009) and Spies et al. (Spies 2018) reported that the adjusted SEEs from the use of the indirect method were higher than those obtained from the direct method. They argued that the direct is more accurate (lower SEEs of regression equations) than the indirect method. In addition, they reported that the direct method is more efficient as it is less complicated and easier to apply. The current study shows that both direct and indirect methods can reconstruct the stature using metacarpal, despite the lower correlations of indirect methods compared to direct methods.

Conclusion

The current study demonstrated the usefulness of measurements of metacarpals in the estimation of TSH in South Africans of African descent. The mean lengths for males are generally higher than for females. Regression formulae to estimate TSH using the measurements of the metacarpal were derived based on the procedure suggested by Raxter et al. (Raxter et al. 2006). Moderate-to-strong correlation coefficients were obtained for the direct method from 0.40 to 0.84 and generally lower coefficients between the maximum lengths of metacarpals and other measured variables of metacarpals. The SEE for the multivariate equations was lower (3.3–5.0) than for univariate Eqs. (4.4–6.0) more so in males. Thus, when an intact metacarpal is available, it is preferable to use a multivariate model.

Abbreviations

SEE	Standard error of estimate
TSH	Skeletal height
ML	Maximum length
BW	Base width
BH	Base height
HW	Head width
MD	Midshaft diameter
ANOVA	Analysis of variance
TEM	Technical error of measurement
rTEM	Relative technical error of measurement

Acknowledgements

The authors wish to thank those who donated their bodies to science so that forensic anthropological research could be performed. Results from research such as this can potentially increase global knowledge which can add to the depth of forensic science. We are also grateful to the School of Anatomical Sciences of the University of the Witwatersrand for giving access to the Raymond A Dart Collection of Human Skeletons.

Authors' contributions
AA: Conception and design of the study, data acquisition, and writing of manuscript. YM, NA and MA: Analysis and interpretation of the data. OO: Data acquisition and writing of manuscript. MB: Conception and design of the study, analysis and interpretation of the data, writing of manuscript . All authors reviewed the manuscript.

Funding
Not applicable.

Data availability
Data will be provided on request.

Ethics approval and consent to participate
Approval was granted by the University's Human Research Ethics Committee (Medical) (Clearance Certificate: W-CBP-220504–01).

Consent for publication
All authors give consent for publication.

Competing interests
The authors declare no competing interests.

Received: 21 August 2024 Accepted: 18 February 2025
Published online: 04 April 2025

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