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Reconstruction of skeletal height using measurements of metacarpals in a South African population group

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Abstract

Stature is a key biological attribute in personal identification and remains a fundamental aspect of forensic investigations. Although long bones are preferred for stature estimation because of their strong correlation with height, they are often unavailable due to fragmentation or incomplete skeletal remains. This study aimed to develop stature estimation equations for South Africans of European descent using metacarpal measurements. The sample comprised 52 male and 50 female complete skeletons from the Raymond A. Dart Collection of Human Skeletons. Stature was calculated using Fully's method, and five metacarpal dimensions were recorded with acceptable technical errors of measurement. All metacarpal measurements displayed significant sexual dimorphism, with males showing larger mean values than females, except for the base heights of the third (BH-M3) and fourth (BH-M4) metacarpals, which did not differ significantly between the sexes. Correlations between stature and metacarpal measurements ranged from weak-to-moderate in males (r = 0.23–0.39) and moderate in females (r = 0.34–0.59). Ten univariate and multivariate regression models were generated, with female models producing lower standard errors of estimate (SEE = 5.0-6.1 cm) than male models (SEE = 6.1–6.6 cm), indicating greater predictive accuracy in females. These findings demonstrate that metacarpal measurements can provide reasonably accurate stature estimates in South Africans of European descent and may serve as useful additions to existing forensic stature estimation methods.

Background

Stature, defined as an individual's height, represents a fundamental biological parameter that can be estimated from various components of the post-mortem skeleton (Işçan & Steyn, 2013). Within forensic anthropology, stature estimation constitutes a critical element of the biological profile, facilitating the identification process by enabling comparisons between reconstructed height and documented living stature (Steyn & Smith, 2007). The accuracy and reliability of such estimations, however, are highly dependent on the availability of appropriate, population-specific reference standards. In the South African context, such data remain limited or entirely lacking for certain population groups (Bidmos & Brits, 2025), thereby constraining the utility of stature estimation in forensic casework.

The need for robust stature estimation methods is particularly acute in South Africa, where the number of unidentified decedents remains high, often in association with elevated levels of violent crime (Statistics South Africa, 2025). Forensic anthropologists play a central role in addressing this challenge by reconstructing biological profiles that typically include age at death, sex, population affinity, and stature derived from skeletal remains (Lundy, 1985, Kusec et al., 1988, Manolis et al., 2019, Mendonça, 2000, Pininski, &. Brits, 2014). Among these components, stature provides a valuable parameter for narrowing the pool of potential matches and supporting the identification process.

Two principal approaches are commonly employed in stature estimation: the anatomical and mathematical methods. The anatomical method, also referred to as Fully's method, reconstructs stature by combining measurements of all skeletal elements contributing to overall height. Initially proposed by

Dwight (1894) and later refined by Fully (1956), this approach incorporates measurements of the skull, vertebral column, femur, tibia, and articulated foot elements, with adjustments for soft tissue components (Fully, 1956; Lundy, 1985). While this method yields estimates that closely approximate living stature when complete remains are available, it is limited by its dependence on skeletal completeness and its labor-intensive nature (Lundy, 1985).

In contrast, the mathematical method offers a more practical and widely applicable alternative in forensic contexts (Isçan & Steyn, 2013). This approach employs regression equations to estimate stature from one or more skeletal measurements, without requiring a complete skeleton. Its applicability is particularly relevant in South Africa, where concerns have been raised regarding the reliability of documented living stature in skeletal collections such as the Raymond A. Dart Collection of Human Skeletons (Dayal et al., 2009). Mathematical models typically rely on correlations between total skeletal height (TSH) and specific skeletal dimensions, with TSH serving as a foundational parameter for estimating living stature.

Long bones, especially the femur and tibia, are most commonly used in stature estimation due to their strong correlation with overall body height (Isçan & Steyn, 2013). However, in their absence, alternative skeletal elements such as the skull, sacrum, and hand bones have been explored, though with reduced predictive accuracy (Meadows & Jantz, 1992; Brits 2014; Bidmos & Adebesin, 2020) Brits. Among these, metacarpals present a promising option due to their frequent preservation in both forensic and archaeological contexts, as well as the relative ease and precision with which they can be measured. These characteristics underscore the importance of developing population-specific regression models based on metacarpal dimensions. Early investigations into stature estimation using metacarpals were conducted by Musgrave & Harneja (1978), who analyzed hand radiographs from adult British individuals and reported modest correlation coefficients and standard errors of estimate. Subsequent work by Meadows & Jantz (1992), utilizing data from the Terry Collection and radiographs of modern American populations, demonstrated comparable correlations and slight improvements in estimation error. Since then, studies in diverse populations including those from Turkey (Sagir 2006), Egypt (Zaher et al., 2011), South Africa (Adebesin et al., 2025) and Thailand (Anjani et al., 2025) have further validated the utility of metacarpals in stature estimation.

Adebesin et al. (2025) developed population- and sex-specific regression equations to estimate adult stature from metacarpal measurements in a sample of 103 Black South African skeletons, demonstrating that metacarpal measurements show moderate to strong correlations with stature ($r \approx 0.40–0.84$). In addition, the study found that direct estimation of stature from metacarpal measurements is more accurate and practical, with standard errors of estimate range between 3.3 and 6.0 cm for multivariate models. Given the high incidence of dismemberment and fragmentation of human remains in South African forensic cases (Steyn & Brits, 2019), the development of reliable population specific stature estimation methods for other population groups is of particular importance. Accordingly, the present study aims to evaluate the utility of metacarpal measurements in estimating adult skeletal

stature among white South Africans, with the objective of generating population-specific reference data to enhance forensic identification efforts.

Materials and methods

The present study utilized skeletal material from the Raymond A. Dart Collection of Human Skeletons (Dayal et al. 2009), housed at the School of Anatomical Sciences, University of the Witwatersrand, Johannesburg. The sample comprised 102 individuals (52 males and 50 females) classified as white South Africans, largely of Dutch, French, German, and British ancestry (Steyn & Işcan, 1998). Previous studies have shown that this group exhibits distinct osteometric characteristics relative to other European populations, justifying its consideration as a separate population in anthropological and forensic research (Morris, 1994; Steyn & Işcan, 1998). Individuals were selected through simple random sampling, and only those with documented age at death, sex, population affinity, and postmortem stature were included.

According to collection records, the individuals represented a lifespan spanning 1893 to 1998. The oldest individual died at 75 years (1968), while the youngest died at 29 years (1975). This age range ensured complete skeletal maturity, with no further expected increase in stature (Trotter & Gleser, 1951). Specimens showing conditions including extensive osteophyte formation, damaged or incomplete elements, presence of surgical implants, or other pathological abnormalities were excluded to preserve data reliability.

Because documented living statures in the Raymond A. Dart Collection of Human Skeletons have been questioned in prior studies (Lundy 1988, Bidmos 2005), total skeletal height (TSH) was calculated as a proxy for stature using the revised anatomical method of Raxter et al. (2006). This involved summing the contributions of key skeletal elements, including the skull, vertebrae, femur, tibia, and the articulated talus and calcaneus. Any additional vertebrae were incorporated into the calculation following Lundy's (1985, 1988) recommendations.

The measurements that were taken for the calculation of TSH included basibregmatic height of the skull, maximum vertebral body heights of C2 to S1, physiological femoral length, condylomalleolar tibial length, and the combined height of the talus and calcaneus. In addition, five standard osteometric variables were recorded for each metacarpal: maximum length, base width, base height, head width, and midshaft diameter. All measurements of metacarpals were taken using a Vernier calliper or mini-osteometric board, with maximum length and midshaft diameter measured on the palmar surface and the remaining variables on the dorsal surface, following the protocol as described by Case et al. (2015). These are defined as follows:

1. Maximum Length (ML): The linear distance from the proximal end to the midpoint of the articular surface of the base, measured parallel to the longitudinal axis of the bone.
2. Base Width (BW): The linear distance between the most medial and most lateral points of the base, taken perpendicular to the long axis of the bone shaft.

3. Base Height (BH): The linear distance from the proximal articular surface to the junction (ridge) where the base meets the shaft of the bone.
4. Head Width (HW): The linear distance between the most medial and most lateral points of the metacarpal head, perpendicular to the longitudinal axis of the shaft.
5. Midshaft Diameter: The linear distance across the shaft measured at the midpoint of the maximum length, from the most medial to the most lateral point.

Measurements were taken by the first author and recorded to the nearest millimetre. To minimise measurement error and ensure reliability, a test-retest procedure was conducted on a subsample of 20 skeletons. Intra-observer variability was evaluated using the technical error of measurement (TEM). Following this, data collection and analysis were performed using SPSS software (version 24). Descriptive statistics were calculated for total skeletal height (TSH) and each metacarpal measurement. The normality of the data distribution was assessed using the Kolmogorov-Smirnov and Shapiro-Wilk tests, complemented by histogram inspections. Upon confirmation of normal distribution, a one-way analysis of variance (ANOVA) was employed to compare mean values between males and females, with the significance level set at $p \leq 0.05$. Subsequently, univariate and stepwise forward regression analyses were conducted to identify the optimal combinations of metacarpal variables for estimating TSH. These regression analyses yielded unstandardized coefficients, constants, standard errors of estimate (SEE), and correlation coefficients.

Results

Intra-observer reliability was evaluated by calculating both the absolute and relative technical error of measurement (TEM and rTEM). The findings from this study indicate an acceptable level of measurement error in relation to the magnitude of the measurements and their corresponding margins of error (Perini et al. 2005). Specifically, TEM values ranged from 0.07 to 0.6, while rTEM values ranged from 0.11% to 4.82% (Table 1). These results are within internationally accepted thresholds for linear measurements, with rTEM values below 5% (Weinberg et al. 2005).

[Table 1 here]

The means and standard deviations for all measured variables are presented in Table 2. Males demonstrated significantly higher mean values across all measurements compared to females ($p < 0.05$), except for BH-M3 and BH-M4, indicating overall sexual dimorphism in metacarpal dimensions and total skeletal height (TSH).

[Table 2 here]

All metacarpal variables demonstrated positive correlations with total skeletal height (TSH). The functions presented in Table 3 for males correspond to measurements that showed weak to moderate correlations with TSH, whereas those for females demonstrated predominantly moderate correlations.

[Table 3 here]

The correlation between metacarpal measurements and TSH ranged from 0.34 to 0.59 in females and from 0.23 to 0.39 in males (Table 3). The functions are arranged in descending order based on the strength of correlation between metacarpal measurements and TSH. In females, ML-M2 showed the highest correlation with TSH (0.60), whereas in males, HW-M3 demonstrated the highest correlation (0.40). The lowest correlations were observed for ML-M4 in females (0.30) and MD-M4 in males (0.20). These functions also yielded the lowest standard error of estimate (SEE), ranging from 5.2 to 6.1 cm in females and 6.2 to 6.6 cm in males (Table 3).

Table 4 presents regression equations derived from various combinations of metacarpal measurements for estimating TSH. The equations are ordered by increasing correlation coefficients and decreasing standard error of estimate (SEE).

[Table 4 here]

In females, the correlation coefficients for these functions (ranging from 0.6 to 0.7) are higher than those derived from individual variables, as shown in Table 3. A similar pattern was observed in males, where the correlation coefficients range from 0.4 to 0.5 (Table 4). Furthermore, the standard error of estimate (SEE) for these functions, ranging from 5.0 to 5.3 cm in females and 6.1 to 6.5 cm in males, is lower than that associated with functions based on individual metacarpal variables (Table 3).

Discussion

Stature estimation constitutes a fundamental aspect of forensic anthropological investigations, particularly in cases involving unidentified human remains. As one of the core biological profile parameters, alongside age, sex, and ancestry, stature contributes significantly to the reconstruction of a decedent's premortem identity. Accurate estimation of stature assists forensic specialists in the individualization process by narrowing the pool of potential matches through comparison of the estimated height with documented records of missing persons or known individuals (Steyn & Smith, 2007). Consequently, reliable methods for stature reconstruction are indispensable in both medico-legal and humanitarian contexts.

The accuracy of stature estimation is largely dependent on the availability and application of population-specific standards. Human populations differ considerably in body proportions due to genetic, environmental, nutritional, and socioeconomic factors (Ruff, 2002; Roseman & Auerbach, 2015; Bogin, 2020). As a result, regression equations developed for one population may not yield comparable levels of accuracy when applied to another. South Africa presents a particularly compelling context for the development of population-specific stature estimation models because of its heterogeneous population structure. The country comprises four major population groups, with Black South Africans constituting the majority (81.8%), while individuals of European (7.1%), Indian/Asian (2.6%), and Mixed ancestry (8.5%) represent substantial minority groups (SSA). Given these biological differences, it is essential to

develop comprehensive and population-specific regression functions that can accurately estimate stature within each group. Such standards enhance forensic accuracy and reduce errors associated with the indiscriminate application of equations derived from other populations.

The present study evaluated the utility of metacarpal measurements for stature estimation in a sample of White South Africans. Assessment of intra- and inter-observer reliability revealed acceptable levels of measurement precision, consistent with the recommendations of Perini et al. (2005) and Weinberg et al. (2005). This confirms that the metacarpal dimensions employed in the study can be measured reproducibly and are suitable for forensic application. In addition, further findings demonstrated that various metacarpal dimensions exhibit statistically significant positive correlations with total skeletal height (TSH), indicating their usefulness as predictors of stature (Tables 3 and 4). The observed correlations support previous research suggesting that hand bones, particularly the metacarpals, retain a proportional relationship with overall body size and can therefore serve as valuable elements in forensic stature reconstruction. The observed correlations are consistent with previous studies demonstrating that metacarpal dimensions are significantly associated with stature and retain a proportional relationship with overall body size, thereby supporting the use of hand bones as valuable indicators in forensic stature reconstruction (Musgrave & Harneja, 1978; Meadows, 1990; Adebesin et al., 2025).

Sexual dimorphism was evident across all metacarpal measurements, with males generally exhibiting larger mean dimensions than females. This observation is consistent with well-established patterns of skeletal dimorphism reported in numerous anthropological studies (Rogers & Saunders,1994; Asala, 2001; Bulygina et al., 2006; Gonzalez,2012; Işcan & Steyn, 2013; Brzobohatá et al., 2015). Despite the larger dimensions observed in males, the regression models developed for females produced stronger correlations and lower standard errors of estimate (SEE), suggesting greater predictive accuracy in the female sample. These findings may reflect lower variability in body proportions among females within the study population, resulting in more stable stature prediction models.

Analysis of the univariate regression equations revealed interesting sex-specific patterns. Among females, regression equations based on the maximum lengths of the metacarpals consistently generated more accurate stature estimates than equations derived from metacarpal fragments. These results underscore the value of preserving complete metacarpal bones whenever possible in forensic investigations involving female remains. In contrast, among males, measurements related to metacarpal head width and midshaft diameter emerged as superior predictors of stature. This finding suggests that in male individuals, robusticity-related dimensions may reflect overall body size more effectively than bone length. Such sex-specific differences highlight the importance of developing separate regression equations for males and females rather than relying on pooled-sex models.

Multivariate regression analyses further improved the accuracy of stature estimation. The combined use of multiple metacarpal dimensions resulted in stronger correlation coefficients and lower SEE values compared with most univariate models (Konigsberg & Jantz, 2018). These findings are consistent with the principle that incorporating multiple skeletal variables captures a greater proportion of the variation

in stature and therefore enhances predictive performance. Notably, the multivariate equations developed for females outperformed those developed for males, further emphasizing the stronger stature-metacarpal relationship observed in the female sample.

The SEE is widely regarded as one of the most important indicators of the predictive accuracy of a regression equation. It quantifies the average deviation between observed and predicted values, with lower SEE values indicating greater precision and reliability. Consequently, forensic practitioners generally prefer regression equations characterized by low SEE values because they provide narrower confidence intervals around stature estimates. In the present study, multivariate regression equations consistently produced lower SEE values than univariate models, demonstrating the superior accuracy of combined-variable approaches.

The findings in this study agree with previous studies conducted in diverse populations.
Lundy & Feldesman (1987), Dayal et al. (2008a), Cui & Zhang (2013), and Torimitsu et al. (2016) all reported that multivariate regression models yielded more accurate stature estimates and lower SEE values than equations based on single skeletal measurements. The results presented in Tables 3 and 4 corroborate these earlier observations and provide further evidence for the effectiveness of multivariate approaches in forensic stature estimation. The consistency of these findings across different populations reinforces the value of integrating multiple skeletal dimensions into predictive models.

Although intact long bones are generally preferred for forensic stature estimation because they typically produce the lowest standard errors of estimate (SEE) and the highest prediction accuracy, complete long bones are seldom recovered in many forensic and archaeological contexts. Taphonomic processes, trauma, mass disasters, and postmortem fragmentation frequently result in incomplete skeletal remains, necessitating the use of long-bone fragments and alternative skeletal elements for stature reconstruction (Bidmos, 2008a; Işcan & Steyn, 2013; Carvalho et al., 2023; Landsman, 2024; Concato et al., 2026). Consequently, considerable research has focused on developing population-specific regression equations based on fragmentary bones and other skeletal components, enabling stature estimation with varying but generally acceptable levels of accuracy in White South African populations ((Dayal et al., 2008; Chiba & Bidmos 2007; Bidmos & Adebesin 2020). The findings of the present study compare favorably with those reported for other skeletal elements previously investigated in White South Africans, as summarized in Table 5. This concordance highlights the utility of metacarpal measurements as an additional resource for forensic identification when more commonly used skeletal elements are unavailable.

The lower SEE values observed among White South African females compared with their male counterparts are consistent with findings reported in many osteometric studies (Dayal et al., 2008; Brits, 2014; Bidmos, 2008a). Females often exhibit lower levels of skeletal variability within population samples, resulting in stronger predictive relationships between skeletal dimensions and stature and, consequently, more accurate regression models (Steyn & Işcan, 1998; Fortes de Oliveira et al., 2012; Bidmos et al., 2023). To our knowledge, the only notable exception within the White South African

literature is the set of univariate regression equations derived from calcaneal dimensions (Bidmos 2006), for which males demonstrated prediction accuracies that were comparable to, or better than, those of females (Table 5). Overall, the present results reinforce the importance of sex-specific stature estimation standards and further demonstrate that metacarpal measurements provide a reliable alternative for stature reconstruction in situations where intact long bones are unavailable.

[Table 5 here]

The standard errors of estimate (SEE) obtained in the present study (5.2–6.6 cm) were within the range anticipated for stature estimation based on small skeletal elements. However, the low to moderate correlations observed between total skeletal height (TSH) and metacarpal dimensions (r = 0.23–0.59), particularly among males, were unexpected. These correlation coefficients are considerably lower than those reported for other populations, including Black South Africans (r = 0.40–0.74) (Adebesin et al., 2025), White and Black Americans (r = 0.57–0.83) (Meadows & Jantz, 1992), and a White British sample (r = 0.53–0.67) (Musgrave & Harneja, 1978). The relatively weaker associations observed in the current sample may reflect population-specific variation in skeletal proportions, differences in sample composition, or the influence of environmental and genetic factors affecting body size and limb proportions.

Conclusion

Despite the comparatively low correlation coefficients, the regression equations derived in this study demonstrated acceptable predictive performance and provide a useful means of estimating stature in White South Africans when more informative skeletal elements are unavailable. In forensic contexts, where fragmentary remains are frequently encountered, even skeletal elements with moderate associations to stature can contribute valuable information to the biological profile. Therefore, the metacarpal-based equations presented here represent a worthwhile addition to the existing suite of stature estimation standards available for South African populations. Their application may enhance the identification process, particularly in cases involving incomplete remains, while also expanding the range of population-specific forensic standards available for stature reconstruction in the South African context.

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

Declarations

Author Contribution

1. Conception and design of the study: AJA, MAB2. Data acquisition: AJA, BB3. Analysis and interpretation of the data: AJA, YAM, MAB4. Contribution of materials and analysis tools: AJA, BB, MAB5. Writing of paper: AJA, YAM, BB, MAB

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Tables

Tables 1 to 5 are available in the supplementary files section

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