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Assessing the accuracy of the program *Stature* for stature estimation in White South Africans

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ABSTRACT

In 2016, Polcerová and Králik created an open-access software program, *Stature*, designed to automate the estimation of living stature in forensic and archaeological cases. This program includes 22 equations from 13 publications, based on both anatomical and mathematical methods to automate stature estimations. This program does not currently include any population data relating to South Africa, and therefore, this study aimed to assess the accuracy of the program *Stature* to estimate living stature from the skeletal remains of White South African adults. The living stature of 40 male and 20 female White South African adults from the Raymond A. Dart Collection of Modern Human Skeletons was automatically estimated by the program (ELS_P). These estimates were then compared to stature estimates generated by the multivariate equation using the physiological length of the femur and tibial length formulated specifically for the estimation of stature of White South Africans (ELS_D). The vast majority of the ELS_P significantly under- or overestimated the living stature of this sample, however various ELS_P did estimate stature with a sufficient degree of accuracy. It was found that the estimates which were significantly different were associated with the largest inaccuracies, biases, and SEE values and are not applicable to this population group. The equations, using standardised measurements, which were not significantly different could accurately estimate the living stature of White South Africans, however, it is recommended that the data of White South African populations be incorporated into the program *Stature* for increased accuracy and diversity.

Introduction

Forensic anthropologists are often consulted in medico-legal investigations of death when unidentified human remains are found in advanced stages of decomposition or are skeletonised [25]. The primary aim of the forensic anthropologist is to aid in the identification of the individual from their skeletal remains by using a biological profile and any unique indicators that may persist on their skeleton [18]. The biological profile includes the estimation of population affinity, age-at-death, sex, and living stature (LS). The LS of an individual is additionally considered a factor of individualisation, which could aid in the inclusion or exclusion of an individual depending on their recorded height [42], as this provides specific details regarding an individual and does not just serve to categorise them. As the recorded height of an individual is regularly self-reported, it is often not an accurate representation of their true LS [40,51]. As such, cadaveric stature (CS), which is the measured height of a decedent taken prior to embalming, is sometimes preferred when describing the deceased. There is, however, no agreement amongst forensic anthropologists on how to measure CS, whether the decedent should be measured in the supine position or with the use of a pivot table that allows for the individual to be measured in the upright position [11,45,44]. Additionally, CS tends to be larger than LS due to the postmortem decompression of the joints and reduced muscular tension [11,45,6]. As there is no consensus in the literature regarding the conversion of CS to LS [33,45,6,11], it is recommended that LS be directly estimated from the skeleton.

Stature can be estimated using one of two methods, the anatomical or the mathematical method [39]. The anatomical method, first

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described by Dwight in 1894 (as cited by [30]), modified by Fully [21] and later revised by Raxter et al.[35], calculates the total skeletal height (TSH) of an individual to which an appropriate soft tissue correction factor is added to estimate LS. This TSH is calculated using the sum of the height of the cranium, the anterior vertebral body heights (C2-S1), the physiological length of the femur, the condylar-malleolar length of the tibia, and the articulated height of the talus and calcaneus [35]. Several soft tissue correction factors have been derived to convert TSH to LS using the anatomical method. The addition of a soft tissue correction factor aims to compensate for the lack of soft tissue associated with skeletal remains, including the skin of the scalp and heel, as well as the cartilages of the hip, knee, ankle, and intervertebral discs [35,7]. Fully [21] recommended that the generalised soft tissue correction factors of either 10 cm, 10.5 cm, and 11 cm be added to the TSH of individuals considered to be short (TSH $\leq$ 153.5 cm), average (TSH: 153.6 cm – 165.4 cm), and tall (TSH $\geq$ 165.5), respectively. These factors, however, were shown to underestimate the LS of individuals from modern populations [6,10,14,29,26]. As such, Raxter et al. [35] developed a soft tissue regression equation (one with an age correction and one without) to more accurately convert TSH into LS. These soft tissue regression equations were thought to be applicable to all individuals, however, subsequent research within a South African context has shown that there is evidence that these equations are specific to the population and sex from which they are derived [14,29,7,10].

When a complete and intact skeleton is recovered, the anatomical method is preferred as it can be applied to all individuals regardless of sex or population and is known to give the most accurate description of LS [32,35]. The anatomical method is, however, time-consuming and complete skeletal remains are rarely encountered in forensic cases [5]. As such, the mathematical method is more frequently used during these investigations. The mathematical method makes use of the statistical relationship between various bone lengths and stature, in the form of stature-bone ratios and regression equations, to estimate LS from skeletal remains [39].

Stature-bone ratios are formulated based on the correlation between long bone lengths and stature. The resulting correlation produces a constant multiplication factor that can be applied to a bone length to estimate LS. These ratios are, however, rarely implemented in modern forensic investigations as they have been concluded to overestimate the stature of taller individuals while underestimating the stature of shorter individuals [30,39]. Additionally, these ratios do not comply with the Daubert requirement for the presentation of scientific evidence in the courtroom, as the method lacks associated probability assessments [18].

Regression equations are formulated using the linear relationships between bone measurements and stature. While this method is less time-consuming than the anatomical method and can be applied to intact and fragmentary remains [41], it is both population- and sex-specific [16,25,30,39,45]. It has been suggested that these equations only be applied to individuals from the sex and population from which they were derived. It is, however, important to note that the use of a general equation, not contingent on the sex or population affinity of the unknown individual, will produce more accurate estimations of LS than incorrectly classifying the individual and applying an inappropriate equation to estimate LS [1]. Additionally, Albanese and colleagues [1] are critical of the classifications of population groups as they are often classified based on nationality (i.e., Portuguese) and not necessarily based on biology. They therefore proposed that generic stature estimation equations be used to estimate the LS of unknown skeletal remains.

While plotting the regression equations of various population groups, Sjøvold [38] noted that the regression lines produced similar slopes and that only the intercepts of these equations varied. Sjøvold [38] therefore suggested that the line of organic correlation be implemented instead of linear regression analysis. Organic correlations are formulated using major axis regression analysis of the line of organic correlation and are considered both population and sex non-specific [38]. Although these equations were initially derived using the data from various White population groups (White American: [45]; French: Olivier 1963 as cited in [38]; German: [4] etc.), other populations were later included (e.g., Japanese: Fujii 1960 as cited in [38]). Organic correlation equations are known to be less precise than regression equations [39], however they are considered sufficiently accurate when making estimates of LS from skeletal remains of unknown sex and population groups [38]. Therefore, these organic correlations could theoretically be applied to all population groups, including South Africans.

In 2016, Polcerová and Králik created an open-access software program, *Stature*, to automate the estimation of LS, which is now also available at http://stature.sci.muni.cz/. The authors included numerous stature estimation techniques from a total of 13 peer-reviewed publications based on a variety of European and American populations. The program estimates LS using the anatomical method, as well as stature-bone ratios, regression equations, and organic correlations. This program was tested on two data sets, one of archaeological (Sedláčková 2013 as cited in [34]) and the other of modern Australian [37] descent. The program accurately estimated the stature of these two data sets in 4 and 7 min, respectively [34], and was considerably faster than when these statures were manually estimated. As the anatomical method and organic correlations are considered to be independent of sex and population affinity, it is possible that the program *Stature* could be used to estimate the LS of individuals from South African populations. Furthermore, although modern White South Africans are descendants of European populations, they are known to be osteologically distinct from these individuals [42], and the regression equations included in the program *Stature* are not expected to accurately estimate the LS of White South Africans. Since the regression equations used to estimate the LS of South Africans [8,16,31] are not currently included in the program, the applicability of this program in a South African context is unknown. The aim of this study was therefore to assess the accuracy of the program *Stature* for the automated estimation of LS from the skeletal remains of White South African adults.

Materials and methods

Sample

The osteometric data used in this study were derived from White South African skeletons from the Raymond A. Dart Collection of Modern Human Skeletons (commonly known as the Dart Collection), housed in the School of Anatomical Sciences at the University of the Witwatersrand, Johannesburg, South Africa. The stature estimation data included in the program *Stature* [34] are derived from studies based on European [33,9,43,4,12,19], and White and Black American [45] populations. As the estimation of LS of White South Africans has largely been conducted using the techniques derived from European and White American data [16], the skeletons of White South Africans were used to assess the applicability of the program within a South African context. Ethical approval was granted under a waiver procured by the School of Anatomical Sciences from the Human Research Ethics Committee - Medical, University of the Witwatersrand (Ethics no.: W-CJ-140604–1) for research related to these skeletons.

A total of 60 White South African adult skeletons (20 female and 40 male) were viable for measurement. Skeletons were excluded for analysis on the basis of being incomplete or presenting with pathologies, damage or trauma which may have influenced the skeletal measurements used. This sample was limited as there are fewer White than Black, and fewer female than male South African skeletons currently held within the Dart Collection [17].

Only skeletons between the ages of 21 and 60 years (birthyears between 1876 and 1955) were included to ensure that growth had completely ceased [15] and that the degenerative effects of aging did not significantly affect stature [13]. The epiphyses of each long bone were assessed to ensure that the fusion line between the epiphysis and

Table 6
The means, standard deviations (SD), paired t-test results, inaccuracies, and biases (in cm) of the ELS$_P$ using regression equations compared to ELS$_D$ for the male sample.

Regression Equations	n	Mean	SD	p-value	Inaccuracy	Bias
[33] (H1)	40	168.30	5.18	0.00	2.89	-1.89
[33] (R1)	39	167.67	4.52	0.00	3.25	-2.41
[33] (F1)	40	169.55	4.48	**0.06***	1.59	-0.65
[33] (T1b)	40	169.78	4.83	**0.22***	1.51	-0.42
[33] (F1, H1)	40	169.28	5.05	0.02	1.89	-0.91
[33] (H1 +R1)	39	168.44	5.22	0.00	2.54	-1.64
[33] (H1, R1)	39	168.06	5.23	0.00	2.89	-2.02
[33] (F1 +T1b)	40	170.13	5.01	**0.84***	0.95	-0.06
[33] (F1, T1b)	40	170.14	4.96	**0.87***	0.95	-0.05
[33] (H1, R1, F1, T1b)	39	169.49	5.16	**0.10***	1.51	-0.59
[9] (H2) (± 4,90)	40	173.12	4.70	0.00	3.52	2.93
[9] (R1b) (± 5,40)	39	170.51	4.04	**0.37***	2.32	0.43
[9] (F1) (± 4,80)	40	171.52	3.92	0.00	1.99	1.33
[9] (T1b) (± 4,70)	40	171.83	4.03	0.00	1.94	1.64
[43] (H1) (± 5,00)	40	171.77	5.01	0.00	2.76	1.57
[43] (R2) (± 5,00)	39	175.48	5.00	0.00	5.40	5.40
[43] (U2) (± 5,20)	39	173.60	5.48	0.00	3.87	3.52
[43] (F1) (± 4,90)	40	172.42	5.01	0.00	2.30	2.22
[43] (T1) (± 4,60)	40	174.93	4.23	0.00	4.74	4.74
[43] (Fi1) (± 4,40)	39	174.38	4.87	0.00	4.37	4.37
[45] (H1) (± 4,05)	40	173.49	5.51	0.00	3.88	3.29
[45] (R1)	39	172.57	5.22	0.00	3.08	2.49
[45] (U1) (± 4,32)	39	171.96	5.56	0.00	2.99	1.89
[45] (F1) (± 3,27)	40	172.22	5.67	0.00	2.12	2.03
[45] (T1) (± 3,37)	40	175.58	5.08	0.00	5.39	5.39
[45] (R1)	39	172.95	5.20	0.00	2.96	2.94
[45] (F1 +T1) (± 2,99)	40	173.89	5.58	0.00	4.02	4.02
[45] (F1, T1) (± 2,99)	40	173.78	5.74	0.00	3.59	3.59
[45] (H1, T1) (± 3,26)	40	175.10	5.35	0.00	4.90	4.90
[45] (H1, F1, T1) (± 2,99)	40	173.79	5.77	0.00	3.59	3.59
[12] (H1)	40	176.12	5.81	0.00	6.05	5.92
[12] (F1)	40	175.85	5.54	0.00	5.65	5.65
[12] (H1, F1)	40	176.02	5.85	0.00	5.82	5.82
[19] (H1)	40	175.54	5.27	0.00	5.39	5.35
[19] (F1)	40	174.46	5.15	0.00	4.27	4.27
ELS$_D$ (F1b+T1)	40	170.19	5.00	-	-	-

* Not significantly different

M17, Th10, and S1 measures for inter-observer were deemed less repeatable. The unstandardised measurements presented with the largest errors. Therefore, it is imperative that the definitions of these measurements be revisited in future studies and that only the equations of the standardised measurements be used to estimate the LS of White South Africans when alternative estimation techniques are not available.

As expected, the male measurements and estimates were all consistently larger than those of the female sample. These results support the consensus that there are sex differences between the statures of males and females as presented in other South African [16,31,42,8] and international [23,45,49] studies.

This study assessed the accuracy of using the program *Stature* for the estimation of LS in White South Africans. The estimated LS of the current sample using the Dayal et al. [16] (F1 +T1) equation was 160.76 cm (± 5.55 cm) for females and 170.24 cm (± 5.00 cm) for males. These average heights are noticeably shorter than the heights documented by Steyn and Smith [42] for White South African males (178.45 ± 6.85 cm) and females (166.08 ± 6.08 cm) of the South African military. It is, however, important to note that these discrepancies could be attributed to the differences in the sample types of these two studies. While the documented heights by Steyn and Smith [42] are often considered the reference sample of modern living South African populations, these heights are taken from the reported heights of men and women of the South African military. Self-reported heights are often incorrectly reported on whereby individual's may overestimate [51] or underestimate [39] their actual LS. Similarly, the current sample is derived from the skeletons in the Dart Collection. It is well documented that the effects of secular change [17,2,22,27] often affect the relationship of bones to stature within these skeletal collections and could, therefore, explain these discrepancies. This is also demonstrated in White North American populations where the skeletons of the Robert J. Terry Anatomical Skeletal Collection presented with shorter statures for males (170.39 ± 7.34 cm) and females (160.68 ± 7.51 cm) [45] than modern White North American males (178.00 ± 0.39 cm) and females (162.4 ± 0.21 cm) [20]. The heights of the skeletons in the Terry Collection [45] are also similar in stature to the skeletons of the Dart Collection.

In the present study, none of the ELS$_P$ obtained using the anatomical method were significantly different from ELS$_D$ (Table 2). Therefore, the estimations of LS that are produced using the anatomical methods incorporated into the program *Stature* [21,3,35] can estimate the LS of White South Africans with a sufficient degree of accuracy. This is unsurprising as the anatomical method is widely considered to be independent of sex and population affinity [30,32,35,39]. It is, however, important to note that these estimations are associated with large inaccuracies and biases. Fully's [21] method presented with the largest inaccuracy and bias which supports the consensus that this method significantly underestimates the stature of modern South African populations [14,29,35,6,7,10]. The Raxter et al. [35] and Auerbach's [3] anatomical methods can be used to estimate the LS of White South Africans with a sufficient degree of accuracy. It should, however, be noted that the stature estimates of Raxter and et al. [35] are known to significantly underestimate the LS of South Africans [14,29,7,10] and should be used cautiously.

The ELS$_P$ generated using the organic correlation equations were based on the equations by Sjøvold [38] and Zeman and Králík [52]. These two studies utilize the measurements of H1, R1, R2, U1, F1, F2, T1, T1b, and Fi1 (Table 1 and Figs. 3, 5, and 6) to generate population and sex non-specific stature estimates. While organic correlations are considered to be independent of sex, Zeman and Králík [52] argued that only the maximum length of the humerus (H1) was both sex and population non-specific and therefore caution should be taken when applying the other equations within a South African context. The current results appear to contradict the conclusions of Zeman and Králík [52] as several of Sjøvold's [38] organic correlations estimated LS with sufficient accuracy. While the majority of the organic correlations currently included in the program *Stature* were significantly different from the ELS$_D$, the ELS$_P$ equations utilizing measurements of the forearm and tibia did not differ significantly from ELS$_D$ and presented with the smallest inaccuracies and biases (Tables 3 and 4). As a result, when alternative methodologies are unavailable, the estimation of LS in White South Africans can accurately be estimated with the program *Stature* using the organic correlations of the forearm and the tibia in both males (R1, R2, U1, T1b) and females (R1, U1, T1b).

The ELS$_P$ generated from the regression equations were based on the equations by Pearson [33], Breitinger [9], Telkkä [43], Trotter and Gleser [45], Bach [4], Černý and Komenda [12], and Dobisíková et al. [19]. These population and sex-specific regression equations utilized the measurements of H1, H2, R1, R1b, R2 U1, U2, F1, T1, T1b, and Fi1 (Table 1 and Figs. 1, 2, 3, and 5). Unlike the anatomical method and the organic correlations, which are universally applicable, regression equations are significantly dependent on the population group and sex from which they are derived [45,46]. It is therefore unsurprising that the vast majority of the regression equations which are currently incorporated into the program *Stature* significantly under- or overestimated the LS of White South Africans (Tables 5 and 6). These significantly different results produced the largest inaccuracies as well as the largest under- and overestimations of LS, with the greatest inaccuracies and biases being produced by the unstandardised measurements. However, some equations did produce ELS$_P$ estimates that did not differ significantly from ELS$_D$. Many of these equations in the male sample are those of Pearson [33], which are derived from a relatively small sample of French men and, therefore, would not be recommended to estimate the

LS of White South African males. Additionally, many of these equations do not comply with the Daubert criteria for the presentation of forensic evidence in a legal setting as they are not associated with a measure of accuracy (i.e., SEE values), and should not be used in modern forensic cases.

From these results, it is clear that the measurements of the lower limb yielded smaller inaccuracies than the measurements of the upper limb, while standardised measurements produced more accurate results than the unstandardized measurements. Although various equations included in the program *Stature* could, theoretically, estimate the LS of White South Africans with sufficient accuracies, it is the recommendation of this study that standardised measurements be favoured over unstandardized measurements as these produced the highest degree of reproducibility, and smaller inaccuracies and biases. It is also important to note that the stature estimates generated by the program *Stature* and Dayal et al. [16] are represented as point estimates with an associated SEE value. The SEE associated with the regression and organic correlation equations gives an indication of the accuracy of the equation, and therefore the estimates of stature generated from them [30,46]. The greater the SEE value, the less accurate that estimate is likely to be. While the stature estimates are represented as such, they were compared and analysed using the point estimates only.

In conclusion, while these various methods have shown to estimate the LS of White South Africans with sufficient accuracies, caution should be taken when using the program *Stature* within a South African context as South African derived stature estimation techniques have not been included in this program. Though the anatomical method is widely believed to be universally applicable, the soft tissue correction factors associated with this method could be both population- and sex-specific [14,29,35,6,7,10]. Additionally, Zeman and Králik [52] criticised the organic correlations derived by Sjøvold [38] and claimed that only the maximum length of the humerus be universally applied. Similarly, only a few regression equations were found to accurately estimate the LS of White South Africans despite the widely accepted suggestion that these equations should not be applied to individuals from which they were not derived. Therefore, to circumvent these uncertainties, it is recommended that the regression equations specifically derived for the estimation of LS of White South Africans by Dayal et al. [16] be included within the program *Stature* prior to the program being used within a South African context.

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CRediT authorship contribution statement

Spies Amy Joy: Conceptualization, Data curation, Formal analysis, Supervision, Writing – review & editing. **Loubser Natasha Rosanne:** Conceptualization, Data curation, Formal analysis, Writing – original draft, Writing – review & editing. **Brits Desiré:** Conceptualization, Data curation, Formal analysis, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

The technical error of measurement (TEM), relative technical error of measurement (rTEM), and coefficient of reliability (R) of the intra- and inter-observer reproducibility of the measurements. Values that are considered to be less repeatable are in bold.

	Intra-observer			Inter-observer		
Measurement	TEM (cm)	rTEM (%)	R	TEM (cm)	rTEM (%)	R
Maximum humeral length (H1)	0.04	0.12	1.00	0.14	0.44	1.00
Biomechanical humeral length (H2)	0.05	0.14	1.00	**0.63**	2.07	0.99
Maximum radial length (R1)	0.02	0.10	1.00	0.17	0.72	0.99
Radial parallel length (R1b)	0.06	0.26	1.00	0.28	1.24	0.98
Biomechanical radial length (R2)	0.08	0.35	1.00	**0.47**	2.07	0.93
Maximum ulnar length (U1)	0.02	0.08	1.00	0.11	0.42	1.00
Biomechanical ulnar length (U2)	0.06	0.27	1.00	**1.38**	**5.85**	**0.45**
Maximum femoral length (F1)	0.02	0.05	1.00	**0.41**	0.91	0.98
Physiological femoral length (F1b)	0.03	0.06	1.00	0.08	0.19	1.00
Biomechanical femoral length (F2)	**1.69**	4.19	**0.74**	**2.90**	**7.43**	**0.23**
Maximum tibial length (T1)	0.09	0.24	1.00	0.24	0.64	0.99
Tibial medial length (T1b)	0.08	0.21	1.00	**0.50**	1.37	0.96
Maximum fibular length (Fi1)	0.03	0.10	1.00	0.19	0.53	0.99
Talo-calcaneal height (TC)	0.07	1.12	0.98	0.28	4.56	**0.70**
Basio-bregmatic height (M17)	0.06	0.48	0.99	**0.42**	3.30	**0.49**
Vertebral height of C2	0.02	0.51	1.00	0.02	0.60	1.00
Vertebral height of C7	0.05	3.51	0.92	0.05	3.26	0.94
Vertebral height of Th10	0.03	1.49	0.98	0.11	**5.00**	**0.72**
Vertebral height of L5	0.05	1.70	0.95	0.06	2.11	0.92
Vertebral height of S1	**0.75**	2.29	0.90	0.14	4.47	**0.65**

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