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Revision of the Fully Technique for Estimating Statures

Michelle H. Raxter,[1]* Benjamin M. Auerbach,[2] and Christopher B. Ruff[2]

[1]*Department of Anthropology, George Washington University, Washington, DC 20052*
[2]*Center for Functional Anatomy and Evolution, Johns Hopkins University School of Medicine, Baltimore, Maryland 21205*

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ABSTRACT The "anatomical" method of Fully ([1956] Ann. Legale Med. 35:266–273) for reconstructing stature, involving the addition of skeletal elements from the calcaneus to the skull, has been increasingly used in anthropological and forensic contexts, but has undergone little systematic testing on samples other than the original sample used to develop the technique. The original description by Fully of the method also does not provide completely explicit directions for taking all of the necessary measurements. This study tested the accuracy and applicability of his method, and clarified measurement procedures. The study sample consisted of 119 adult black and white males and females of known cadaveric statures from the Terry Collection. Cadaveric statures were adjusted to living statures, following the recommendations of Trotter and Gleser ([1952] Am. J. Phys. Anthropol. 10:469–514). We obtained the best results using maximum vertebral body heights (anterior to the pedicles) and measurement of the articulated talus and calcaneus height in anatomical position. Statures derived using the original Fully technique are strongly correlated with living statures in our sample (r = 0.96), but underestimate living stature by an average of about 2.4 cm. Anatomical considerations also suggest that the correction factors applied by Fully to convert summed skeletal height to living stature are too small. New formulae are derived to calculate living stature from skeletal height. There is no effect of sex or ancestry on stature prediction. Resulting stature estimates are accurate to within 4.5 cm in 95% of the individuals in our sample, with no directional bias. Am J Phys Anthropol 130:374–384, 2006.

Statures estimated from human skeletal remains play an important role in assessing health (Steegmann and Haseley, 1988; Pietrusewsky et al., 1997), sexual dimorphism (Frayer, 1980), and general body size trends (Feldesman et al., 1990; Ruff, 2000; Holliday, 2002) among past populations. There are two main types of method available for adult stature estimation: "mathematical" and "anatomical" (Dwight, 1894; Lundy, 1985). The mathematical method uses regression formulae (or ratios) based on the correlation of individual skeletal elements to living stature. Long bone regressions produce the most accurate estimations, as long bones are the elements most highly correlated to total stature. Some of the most commonly used regression equations are those devised by Trotter and Gleser (1952, 1958) based on American whites and blacks in the Smithsonian's Terry Collection. Many authors, including Trotter and Gleser (1952, 1958), cautioned against using stature regression formulae derived from one population for other populations (Pearson, 1899; Stevenson, 1929; Dupertuis and Hadden, 1951). Human proportions vary systematically between populations (Eveleth and Tanner, 1976; Ruff, 1994; Holliday, 1997; Holliday and Ruff, 1997), and so the most accurate mathematical estimates of stature will be obtained when the population being investigated is as similar as possible in proportions to the population used to create the formulae (Holliday and Ruff, 1997). Long bone regression equations based on populations with a variety of body proportions have been developed (Telkka, 1950; Allbrook, 1961; Genoves, 1967; Olivier, 1976; Lundy, 1983; Sjovold, 1990; Radoinova et al., 2002).

The anatomical method involves the direct reconstruction of stature by measuring and adding together the lengths or heights of a series of contiguous skeletal elements from the skull through the foot. Thus, differences in body proportions, e.g., trunk length to lower limb length, are intrinsically incorporated into the method. The development of the anatomical method is generally attributed to Fully (1956), although earlier attempts were made (discussed in Stewart, 1979a; Lundy 1985). Many authors consider the anatomical method, when applicable, to provide the best approximation of living stature (Olivier, 1969; El Najjar and McWilliams, 1978; Stewart, 1979a; Lundy, 1985; Ousley, 1995). Statures derived using the anatomical method can also be used to formulate more accurate regression equations for specific populations with unknown living statures (Lundy, 1983, 1987; Feldesman and Lundy, 1988; Jungers, 1988; Sciulli et al., 1990; Sciulli and Giesen, 1993; Formicola and Franceschi, 1996). The anatomical method is practical in both forensic and archaeological cases, provided that sufficient material is preserved. The common reasons it is not used are related to the speed of an investigation or incomplete remains. However, in cases when nearly complete skeletons are recovered, a predilection for speed comes at the cost of providing a more reliable estimate of living stature. The advantages and disadvantages of both the mathemati-

*Correspondence to: Michelle H. Raxter, Department of Anthropology, George Washington University, Hortense Amsterdam House, 2110 G St. NW, Washington, DC 20052.
E-mail: mhraxter@gwu.edu

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cal and anatomical methods were further elaborated on by Lundy (1985). The issue of when the anatomical method or a long bone regression method is most applicable in situations where some skeletal elements are missing is addressed elsewhere (Auerbach et al., 2005).

THE FULLY TECHNIQUE

In 1955, the Ministère des Anciens Combattants et Victimes de la Guerre called on Georges Fully to examine and identify bodies of Frenchmen killed during World War II at Mauthausen, a German concentration camp in Austria (for more on Fully's life and works, see Stewart, 1979b). Fully (1956) related that the bodies were not incinerated in the crematory, but were buried without coffins in a former soccer field. He found the skeletons in a good state of preservation. Most of the individuals were buried without identification, but a number of them were discovered wearing an identification plaque secured to their wrists by a leather or metal bracelet. Fully was able to identify the individual by matching the number on the plaque to corresponding records. Identification was further confirmed by descriptions from families. Living statures of the individuals were also attained from the Mauthausen records. Individuals included both Frenchmen and males of other European nationalities.

The anatomical reconstruction method of Fully (1956) is based on 102 adult males from this sample. He directed that the following measurements be taken:

- Basion-bregma height of the cranium.
- Maximum height of the corpus of the C2–L5 vertebra measured separately. The atlas is not measured because its height is included between the superior and inferior margins of the axis, including the odontoid process.
- Anterior height of the first sacral segment.
- Oblique (physiological) length of the femur.
- Maximum length of the tibia without the spine, and including the malleolus.
- Articulated height of the talus and calcaneus, from the most superior point on the talus to the most inferior point on the calcaneus.

For the femur, tibia, and talus and calcaneus, the average value of the right and left measurements should be used in calculating skeletal height. These individual skeletal measures are then added together to obtain skeletal stature.

Fully (1956) presented correction factors that are to be added to calculated skeletal height to attain a final estimation of living stature, as follows:

Skeletal height equal to or below 153.5 cm, add 10 cm.
Skeletal height between 153.6–165.4 cm, add 10.5 cm.
Skeletal height equal to or above 165.5 cm, add 11.5 cm.

Although these are usually interpreted as "soft-tissue" correction factors, in fact they incorporate other corrections as well, as discussed below.

Fully (1956) compared estimates using his method to estimates using long bone regression formulae by Rollet (1889) as well as Manouvrier (1892) (both based on a French sample). Fully (1956) found that with the methods of Rollet (1889) and Manouvrier (1892), the difference between estimated and true living stature reached 90 mm, while differences using his method did not exceed 35 mm. Fully (1956) also reported that 41.66% of his estimates were within 10 mm of true values, compared to only 25% with those of Rollet (1889) and Manouvrier (1892).

Though the "anatomical" method of Fully (1956) for reconstructing stature has been increasingly employed for estimating stature (Snow and Williams, 1971; Marquer, 1972; Feldesman and Lundy, 1988; Jungers, 1988; Sciulli et al., 1990; Formicola, 1993; Formicola and Franceschi, 1996), until recently only a few limited tests of this technique on other samples were carried out. In a forensic case, Snow and Williams (1971) employed Fully's method and compared its estimate to estimates using the long bone regression equations of Trotter and Gleser (1958) on a 45-year-old white male. They reported that the overall mean of the antemortem measurements of an individual's height was particularly close to that using Fully's method, and they recommended Fully's technique to substantiate estimates obtained using Trotter and Gleser (1958). Lundy (1988) used Fully's method on skeletal remains of three white male US servicemen of known living stature, and compared the estimates to those obtained using the regression formulae of Trotter and Gleser (1958). He found Fully's method (1956) to be as accurate as the regression formulae, and in one case to be more accurate.

Very recently, two larger studies of Fully's method were reported. King (2004, and personal communication) examined 36 US whites and blacks derived from the William M. Bass Donated Collection, and found that the stature estimates using Fully's technique were generally lower than cadaveric statures, with larger underestimates among blacks. Bidmos (2005) measured 156 skeletons of South African blacks and whites obtained from the Dart Collection, and again found that overall, the Fully technique (1956) produced underestimates when compared to cadaveric stature, although not among white males. Such comparisons are important, since the original method of Fully (1956) was developed exclusively on European males, and earlier tests of the method (Snow and Williams, 1971; Lundy, 1988) were also all on European-derived males. Both King (2004) and Bidmos (2005) suggested the possibility of errors in Fully's original correction factors. However, Bidmos (2005) also noted potential errors in cadaveric stature measurements for the Dart Collection, and both studies utilized supine cadaveric lengths for statures, which may lead to additional errors (Terry, 1940).

Because of imprecision in the way in which some of the original skeletal dimensions of Fully (1956) were described, there is also some uncertainty regarding the exact measurement technique that should be used when employing the method, which may also have added to errors in previous studies when comparing predicted to true statures. This includes, in particular, measurement of vertebral body heights, tibial length, and talus/calcaneus height. Fully directed that maximum height of each vertebra be measured, but was not specific as to exactly where on the vertebral body this should be taken. Fully stated that he measured the length of the tibia excluding the spine and including the malleolus on a Broca osteometric board, which includes an opening on the vertical endplate to accommodate the proximal spines. Modern osteometric boards do not normally include such an opening and commonly use a track for the movable piece, making this measurement difficult to duplicate. Fully also did not detail the exact positioning of the articulated talus and calcaneus during his measurement of their height.

This study tests the accuracy and applicability of the method of Fully (1956) to a large, ancestrally diverse sample of males and females of known (cadaveric) stature, and clarifies measurement procedures. Based on our results, we propose modifications to Fully's technique that incorporate new "soft-tissue" correction factors. We also address the issue of age correction of statures.

MATERIALS AND METHODS

The skeletal sample consisted of 29 black females, 25 white females, 33 black males, and 32 white males, all adults of known age, ancestry, sex, and cadaveric statures from the Terry Collection at the National Museum of Natural History, Smithsonian Institution. All individuals lived in the St. Louis area, and died between the early and mid-20th century. Ages ranged from 21–85 years, with a mean age of 54 years.

Individuals who exhibited trauma, such as improperly healed fractures or significant osteophytic lipping on the necessary elements that would have impeded proper measurement, were eliminated from the sample. Individuals with collapsed vertebrae were also eliminated. Cases with fused vertebrae (n = 4) were included, since their measurement would still produce an accurate estimate of living stature, though the number of fused vertebrae for each individual did not exceed three. Fully (1956) prescribed taking the average value of the measurements of the femur, tibia, and talus and calcaneus when both sides of the bone are present, and that procedure was followed here whenever possible. Several individuals with a usable long bone, talus, or calcaneus from only one side were included in the sample (femur, n = 2; tibia, n = 8; talus and calcaneus, n = 4).

The method of Fully (1956) estimates living stature; thus, for comparison, cadaveric statures, available from collection records, were adjusted to living stature by subtracting 2.5 cm, as recommended by Trotter and Gleser (1952) for the Terry sample. As described by Terry (1940), cadavers were measured while in the upright "standing" position, on a specially constructed board.

Statures derived using the technique of Fully (1956) have sometimes been adjusted for age effects (Sciulli et al., 1990; Bidmos et al., 2005), i.e., the known reduction of stature with aging (Trotter and Gleser, 1951; Friedlaender et al., 1977; Galloway, 1988; Cline et al., 1989; Chandler and Bock, 1991; Giles, 1991). Trotter and Gleser (1952) recommended adjusting statures derived from their long bone regression formulae downward by $0.06 \times (\text{age} - 30)$ (age in years, stature in cm), based on a previous study (Trotter and Gleser, 1951). However, for the purposes of applying the technique of Fully (1956), it is apparent that some of the factors that lead to height loss in older adults, including in particular vertebral collapse or partial collapse, are already incorporated into the technique, i.e., by measuring actual vertebral heights (not, in effect, estimating them, as is done with long bone regressions). This suggests that a somewhat smaller age-correction factor may be appropriate when using Fully's technique. Also, other investigators suggested alternative age corrections (see Discussion). Therefore, in addition to applying the recommended age adjustment of Trotter and Gleser (1952), we empirically investigated the effect of age on stature estimation.

The skeletal measurements used in the technique of Fully (1956) were described earlier. Specific procedures and illustrations are given in detail in the Appendix. Most measurements are straightforward, but as noted earlier, some are open to interpretation. Two vertebral body heights were tested here: anterior midline height, and maximum height of the vertebrae anterior to the pedicles and facets (when present). We favor the maximum vertebral body height measurement, for reasons shown later, and this is the dimension used in all analyses unless explicitly noted otherwise. However, we also tested measurement at the anterior midline point, as it is the simplest point to approximate on the vertebra, and was utilized (Tibbetts, 1981; Formicola, 1993) or implied (Fig. 2 in Lundy, 1988) in some previous applications of Fully's method.

Measurement of maximum length of the tibia without the proximal spines was tested on the black female sample (n = 29), using three different types of osteometric boards: a Broca osteometric board (includes an opening on the vertical endplate to accommodate proximal spines), a modern osteometric board (no opening on the vertical endplate, and uses a track for the movable piece), and a trackless osteometric board (no opening on vertical endplate, and no track for a movable piece). Mean differences between measurements, using each of the different methods, were assessed using paired *t*-tests.

Following our interpretation of the original description by Fully (1956) (see Discussion), we measured the combined height of the articulated talus and calcaneus in "physiological position," i.e., with the anterior end of the calcaneus raised up from the measuring surface (see Appendix for description and illustration).

Differences between estimated and true statures were assessed using paired *t*-tests. Several types of comparisons between sex and ancestry groups were carried out. Multiple analysis of variance (ANOVA) was used to assess the effects of sex and ancestry (and age) on stature estimation. Average prediction errors between estimated and true statures were determined for the pooled sample and each sex/ancestry group. These were calculated as both directional (i.e., maintaining positive and negative signs) and absolute values, which can be taken to signify systematic directional and random differences, respectively. Means and 95% confidence intervals (CIs) were calculated for directional prediction errors. For absolute prediction errors, medians and lower 95% ranges are reported because of their highly skewed distributions.

A bivariate scatter of estimated statures against true statures was generated and used to evaluate possible size effects on errors. To maintain proportionality over the size range represented in the sample, data were plotted on a logarithmic scale, and compared to a line of equivalence.

Cumulative interobserver error in obtaining skeletal statures was assessed by independently measuring 20 individuals in the sample by two of us (M.H.R. and B.M.A.), with measurement error calculated following the procedure of White (2000).

All statistics were carried out using Microsoft Excel XP and SYSTAT 11. Graphs were produced using Microsoft Excel XP and Adobe Photoshop 6.0.

RESULTS

Paired *t*-tests performed on mean maximum length of the tibia (average of right- and left-side values) without the proximal spines on a Broca osteometric board, modern osteometric board, and trackless osteometric board show significant differences between all pairwise combinations ($P < 0.05$), with measurements using the modern osteometric board (with a track) possessing the highest average value (361.4 mm), followed by the trackless osteometric board (360.0 mm), and finally the Broca board (359.0 mm). It is recommended that, with respect to applying the

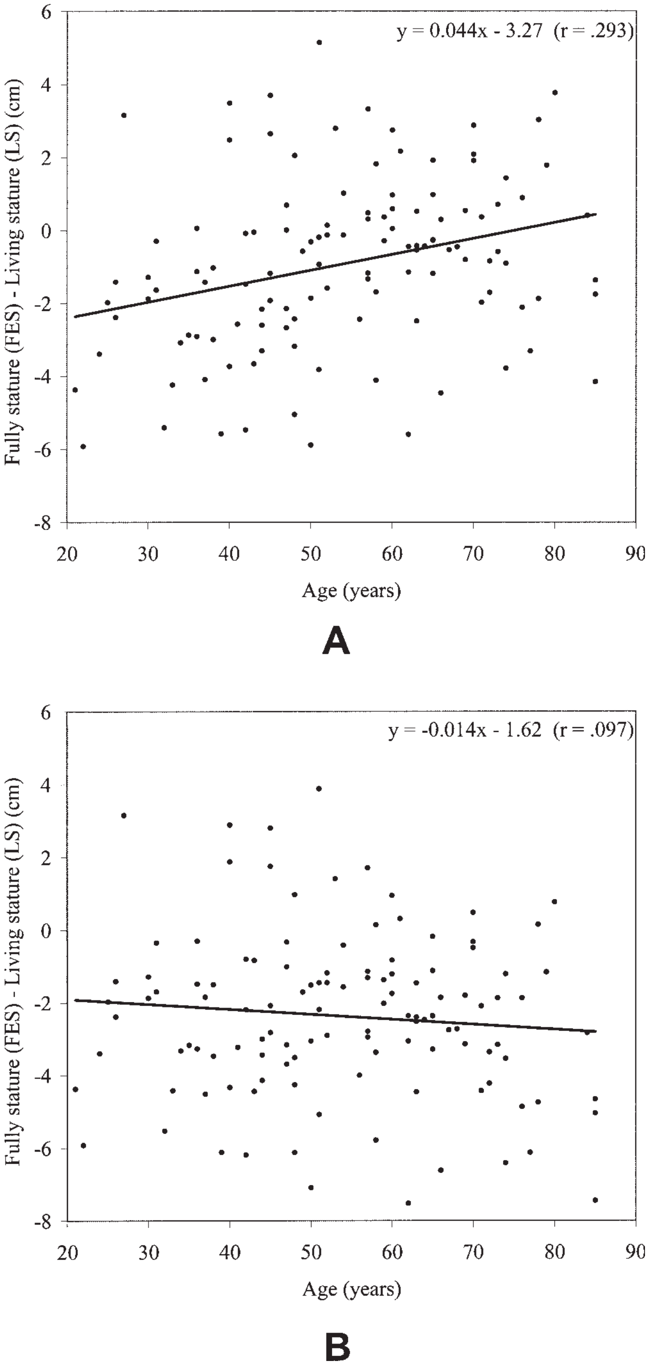

Fig. 1. Difference between estimated statures of Fully (1956) and living statures against age. **A:** Not adjusted for age. **B:** Adjusted for age, following recommendation of Trotter and Gleser (1951, 1952), by subtracting 0.06 cm for each year beyond 30 years. Least squares regressions plotted through data.

method of Fully (1956), a trackless osteometric board be used to measure maximum length of the tibia without the proximal spines, since this most closely approximates the measurement with a Broca board (within 1 mm), and a Broca board will generally not be available to most researchers. The trackless osteometric board tibial length measurement was used in all subsequent analyses.

The difference between stature estimated using the Fully (1956) technique (FES) and living stature (LS) is plotted against age in Figure 1. Figure 1A shows results without any age adjustment to FES. As expected, there is a significant positive correlation with age ($r = 0.293$, $P = 0.001$), i.e., FES progressively increases relative to LS with aging. When age-related declines in stature are factored in, using the recommendation of Trotter and Gleser (1951, 1952) (Fig. 1B), there is no significant correlation of prediction errors with age ($r = 0.097$, $P > 0.20$), although there is some suggestion of a slight negative trend, i.e., the recommended adjustment by Trotter and Gleser (1951, 1952) appears to slightly "overcompensate" for age declines in FES (also see below).

TABLE 1. Comparison of Fully estimated (FES) and living (LS) statures

	FES − LS (cm)		
	Mean	SE	P^1
FES, not age-adjusted	−0.92	0.21	<0.001
FES, age-adjusted[2]	−2.37	0.21	<0.001
Only individuals under age 40 years (not age-adjusted)	−2.44	0.43	<0.001

[1] Paired *t*-tests.
[2] Based on Trotter and Gleser (1951, 1952): subtract 0.06 × (age −30).

Correlations between FES and LS, adjusted and nonadjusted for age, are strong ($r = 0.95$–0.96), but it is apparent from Figure 1 that FES underestimates LS on average. Comparisons of mean differences between FES and LS are shown in Table 1, adjusted and nonadjusted for age (using the adjustment of Trotter and Gleser, 1952). In addition, to avoid aging effects, results are shown only for individuals in our sample under 40 years of age ($n = 23$) (not corrected for age effects, which in any event would be very small in this age range). FES significantly underestimates LS in every comparison. Without age correction, the average underestimation is 0.9 cm, and with age correction, it is 2.4 cm. Comparisons within younger individuals yield very similar results to those for the age-corrected total sample, i.e., about a 2.4-cm average underestimation.

Similar comparisons using anterior midline vertebral heights (not shown) yield greater discrepancies between FES and LS, as would be expected, since anterior midline heights produce smaller vertebral column lengths than maximum vertebral body heights. The mean difference between FES and LS using anterior midline heights is −2.55 cm (±0.21 SE) for non-age-adjusted values, and −4.01 cm (±0.21 SE) for age-adjusted values. For individuals under age 40 years, the mean difference is −3.85 cm (±0.45 SE).

The systematic underestimation of LS by FES suggests that the "soft-tissue" correction factors incorporated into the method of Fully (1956) may be in error, a hypothesis supported by previous studies (King, 2004; Bidmos, 2005) and other anatomical considerations presented in the Discussion. Rather than attempting to calculate an additional correction factor to be added to the original factors of Fully (1956), it is more efficient to simply recalculate overall corrections based on the skeletal heights (SKH) of Fully (1956), i.e., the sum of the lengths or heights of the skeletal elements included in the method (see above and Appendix).

We first tested for effects of age, sex, and ancestry on the prediction of LS from SKH using ANOVA. Results are shown in Table 2. As expected, given the results presented above, age has a significant effect on the prediction of LS. However, neither ancestry ($P > 0.40$) nor sex ($P > 0.15$) has a significant effect on prediction. This indicates that a

TABLE 2. ANOVA: prediction of living stature from skeletal height, with age, sex, and ancestry as covariates[1]

Source	Mean square	F-ratio	*P*
Skeletal height	3,448.8	699.0	0.000
Age	55.0	11.1	0.001
Sex	9.5	1.9	0.17
Ancestry	3.3	0.7	0.41
Error	4.9		

[1] Multiple r: 0.957.

single prediction equation should be universally applicable, regardless of sex or ancestry. A similar ANOVA, but using anterior midline vertebral heights to calculate SKH (results not shown), produces a similar age effect, but also a significant effect of sex ($P < 0.05$) and close-to-significant effect of ancestry ($P = 0.11$) on the prediction of LS. For this reason, and because anterior midline vertebral heights underestimate stature to a greater degree than maximum vertebral body heights (see above), we recommend using the maximum vertebral height measurement.

The equation for estimating LS from SKH (both in cm), when age (years) is known or can be estimated, is:

$$\text{Living stature} = 1.009 \times \text{Skeletal height} - 0.0426 \times \text{age} + 12.1 (r = 0.956, \text{SEE} = 2.22). \quad (1)$$

The correction coefficient for age is similar to that demonstrated earlier (Fig. 1A), and again indicates a slightly smaller adjustment than the 0.06 cm/year recommended by Trotter and Gleser (1951, 1952).

A log-log regression of estimated LS using this equation against true LS is shown in Figure 2. The slope is virtually equivalent to 1.0, and there is no apparent heteroscedasticity, indicating no size effects on estimation errors.

Table 3 shows directional and absolute prediction errors between LS estimated using our equation and true LS, for the total pooled sample and each subgroup. Mean directional errors are very small for each subgroup (in each case, nonsignificantly different from 0, $P > 0.60$, *t*-tests). ANOVA indicates no significant effects of sex or ancestry on prediction errors ($P > 0.30$), and 95% CIs for subgroups range from just under ±6 cm for white males to about ±3.5 cm for white females. Median absolute errors range between about 1–1.5 cm, except for white males (just over 2 cm). Ninety-five percent of all individuals are estimated to within 4.4 cm, with white males showing the most variability (4.7 cm) and black males the least (3.3 cm).

Because exact ages may be difficult to estimate in many archaeological and forensic situations, we also calculated an equation for estimating LS from SKH without the age correction term:

$$\text{Living stature} = 0.996 \times \text{Skeletal height} + 11.7 (r = 0.952, \text{SEE} = 2.31). \quad (2)$$

This equation produces stature estimates that are only slightly less accurate (lower r, higher SEE) than those from Equation (1). Directional prediction error is slightly greater than that for Equation (1), with a mean of −0.08 cm and a 95% CI of ±4.56 cm (compared to ±4.37 cm) in the total pooled sample. Random error is also slightly larger, with a median of 1.46 cm (compared to 1.12 cm for Equation (1)), and a lower 95% range to 4.50 cm (compared to 4.36 cm). Again, there are no significant effects of ancestry or sex on

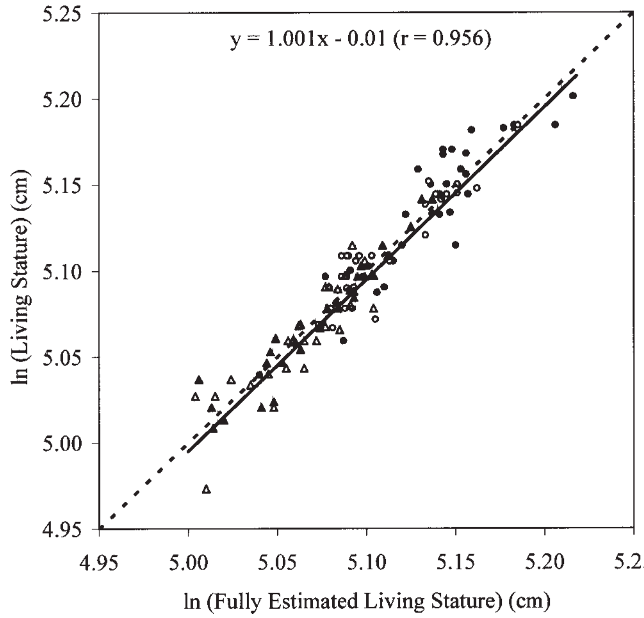

Fig. 2. Living statures against new living stature estimates derived from Equation (1) (logarithmic scale). Open triangles, black females; open circles, black males; solid triangles, white females; solid circles, white males. Dotted line indicates equivalence; solid line is least squares regression through pooled data points.

TABLE 3. Directional and absolute prediction errors, new estimated – living statures (cm)

		Estimated[1] – Living		| Estimated – Living |	
Sample	n	Mean	95% CI[2]	Median	95% limit[3]
Total pooled	119	0.01	±4.37	1.12	4.36
Black females	29	0.32	±4.66	1.56	4.21
White females	25	0.14	±3.46	0.98	3.77
Black males	33	−0.05	±3.75	1.06	3.32
White males	32	−0.31	±5.75	2.14	4.72

[1] Stature = 1.009 × Skeletal height − 0.0426 × age + 12.1.
[2] 95% CI for individual values about mean.
[3] Lower 95% limit of individual values.

prediction errors using Equation (2) ($P > 0.30$, ANOVA), and prediction errors within subgroups are comparable to those shown in Table 3.

The interobserver measurement error for total summed skeletal height in 20 individuals measured by two observers is minimal, with an average difference between observers of 0.16 cm.

DISCUSSION

The results of this study indicate that statures calculated using the anatomical method of Fully (1956) are strongly correlated with living statures, but that there is a systematic bias, resulting in an average underestimation of stature of about 2.4 cm using this technique. This finding is similar to those reported recently by King (2004, personal communication) and Bidmos (2005). The average underestimation of King (2004) matched ours (2.4 cm), while the average underestimation by Bidmos (2005) was greater (4.3 cm) (our calculations from his Table 2). However, Bidmos (2005) noted several irregularities in cadaveric measurements of his sample that would tend to lead to overestimation of cadaveric stature, and thus greater underestimates using Fully's technique. Both of these studies also relied on supine measurements of cadaveric length, which may lead to additional errors (Terry, 1940). Problems in cadaveric measurement procedures may explain why Bidmos (2005) only obtained correlations between Fully-estimated and living statures of 0.45–0.79 in his sex/ancestry subsamples. Our overall correlation (age-corrected values, as in Bidmos, 2005) between FES and LS was 0.96, with correlations within sex/ancestry subgroups of 0.89–0.97.

The systematic underestimation of living stature here using the original technique of Fully (1956) seems unlikely to be a product of inadequate reduction of cadaveric statures to living statures, necessary because of postmortem decomposition and loosening of soft-tissue joint components. The 2.5-cm downward adjustment of cadaveric stature recommended by Trotter and Gleser (1951, 1952) is actually more than that recommended by some previous investigators, e.g., 2 cm recommended by Manouvrier (1892), and 1.2 cm and 2 cm for males and females, respectively, recommended by Pearson (1899). Although there is doubt that the same constant is applicable to all cadavers, not considering age, body size, and methods of preservation or stature measurement, cadaver statures recorded for the Terry Collection are considered reliable (Ousley, 1995), and since the correction by Trotter and Gleser (1951, 1952) was based on the collection itself, it should be a relatively accurate modification for the purposes of the present study.

Similarly, it is unlikely that misinterpretations of the original skeletal measurement directions of Fully (1956) account for the underestimation of stature found here. In every case where there was some room for interpretation (measurement of vertebral heights, tibial length, and talus/calcaneus height), we chose the maximum possible height or length dimension (for discussion, see below). Thus, our skeletal height measurements should have been maximal.

The other potential source of error in living stature estimation are the "soft-tissue" correction factors applied to the skeletal heights of Fully (1956). As noted earlier, these factors are actually not only a product of missing soft tissue, but rather are empirically derived correction factors that incorporate all additions to (or subtractions from) skeletal height to arrive at living stature. For example, Bidmos (2005) pointed out that the tibial malleolus does not contribute directly to stature, and yet is included in Fully's tibial length measurement. Anatomical components that contribute to Fully's recommended correction factors are listed in Table 4. The major soft-tissue component is the summed height of the intervertebral disks. These are stated to constitute a fifth of the postaxial vertebral column length below C2 (Bannister et al., 1995, p. 513). The average summed height of C3–L5 in our sample is 44.4 cm, which gives an estimated summed intervertebral disk height of 11.1 cm. Very similar results are obtained if the average intervertebral disk heights of Kapandji (1974, p. 38) are used (his estimate is slightly higher, but he also appeared to have measured disk heights at the center of the vertebral endplates, which would slightly increase disk thickness). It is likely that these estimates are based on healthy younger adults. For example, the estimate by Kapandji (1974) of average lumbar intervertebral disk thickness is 9 mm, which compares with an average lumbar disk thickness of 8.2 cm reported for normal 25–36-year-old males (mean of anterior and posterior disk heights, Table 1 in Tibrewal and Pearcy, 1985).

TABLE 4. Anatomical components of Fully technique "soft-tissue" correction factor in our sample

Component	Height contribution (cm)
Intervertebral disks[1]	10.1
Articular cartilage in hip, knee, and talocrural joints[2]	1.2
Scalp	0.3
Heel	1.0
Odontoid process to basion	0.7
Base of S1 to acetabular roof[3]	3.6
Distal projection of tibial malleolus	−1.5
Correction for vertebral column curvature[4]	−3.0
Total	12.4

[1] Based on average skeletal length of vertebral column in our sample (see text).
[2] 0.2 cm per surface × 6 surfaces.
[3] (Anterior sacral promontory to acetabular roof) − S1 height.
[4] Estimated vertebral column length (59.3 cm) × 0.05.

Thus, since our sample averaged 54 years of age, and the majority of aging changes in stature occur in the vertebral column (Friedlaender et al., 1977), our estimated summed disk thickness needs to be adjusted downward accordingly. Age declines in stature attributable to soft-tissue changes appear to be slightly over 0.4 cm/decade (see above). Applied to our sample, this produces a mean age correction of about 1 cm, resulting in an estimated summed intervertebral disk height of 10.1 cm. Articular cartilage in the hip, knee, and ankle joints is estimated to be about 2 mm thick (Stockwell, 1971; his data indicate thicknesses of 2.16–2.26 mm, but they were for young adults, so are adjusted downward slightly for the present sample). Scalp thickness is estimated at 3 mm. Heel pad thickness (under load) is estimated to be 1.0 cm (Prichasuk, 1994; Hsu et al., 1998).

In addition to these soft-tissue components, there are several "gaps" or "overlaps" in the skeletal measurements taken as part of the technique of Fully (1956). The odontoid process does not reach basion; the average distance between these two points is about 7 mm (Harris et al., 1994; data from their Fig. 3, adjusted for radiographic magnification). There is also a vertical gap between the inferior edge of S1 and the acetabular roofs. Since the S1 vertebral height is measured parallel to the anterior surface of the sacrum (see Appendix), which is angled posteriorly, this actually adds a bit more to the "S1 height," i.e., decreases the gap between it and the acetabulae. Thus, we estimated the effective gap by measuring a series of articulated pelves in our sample, held in anatomical position, from the anterior edge of the sacral promontory to a line connecting the two most superior portions of the acetabulae, and subtracted our S1 height from this. The average effective gap was 3.6 cm. As noted earlier, the tibial malleolus projects distally beyond the tibiotalar articulation; the average vertical distance from the center of the distal tibial articular surface to the tip of the malleolus in our sample was 1.5 cm. Because this is an overlap, it is subtracted from the correction factor (Table 4). Finally, the vertebral column is not straight in the sagittal plane. The actual vertical height of the column averages 95% of its total (curved) length (Kapandji, 1974, p. 20). Our estimated average total vertebral column length (C1–L5), including intervertebral disks, is 59.3 cm, giving an average subtraction of 3.0 cm.

The total predicted correction factor for an average individual in our sample, anatomically determined, is thus an addition of 12.4 cm (Table 4). The average "soft-tissue" correction factor of Fully (1956) applied to our sample was 10.2 cm. Based on the anatomical reconstruction in Table 4, this is 2.2 cm too small, which is very close to the average 2.4-cm underestimation of stature that we found using his technique. Thus, both our empirical results and predicted anatomical reconstruction of stature suggest that Fully may have underestimated the true correction factors to be added to skeletal height. This still does not explain why he apparently obtained good results for his sample (Fully, 1956). One possibility is that the living stature data available for his sample were slightly depressed over true living statures, due to the nature of the situation in which they were measured (see above). If so, this would have led to an underestimation of correction factors. As discussed earlier, other researchers also reported good results using the technique of Fully (1956) (Snow and Williams, 1971; Lundy, 1988), but these were for very small samples. The only other large comparative studies of which we are aware (King, 2004; Bidmos, 2005) also concluded that Fully had underestimated skeletal height to living height correction factors.

Unlike both King (2004) and Bidmos (2005), however, we found no evidence for any sex- or ancestry-related effects on the accuracy of stature prediction using Fully's technique. This is reassuring, since it implies that the technique should be equally applicable to a variety of skeletal individuals or samples.

Decrease in stature with increase in age in adults is brought about mainly by changes in the vertebral column, i.e., compression of intervertebral disks and vertebral bodies (Friedlaender et al., 1977). As noted earlier, some of these changes (those occurring in the vertebrae themselves) are inherently incorporated into the technique of Fully (1956). Thus, the age adjustment of a little more than 0.04 cm/year, less than the 0.06 cm/year recommended by Trotter and Gleser (1951, 1952), seems reasonable. Several investigators questioned the validity of the age adjustment of Trotter and Gleser (1951, 1952) on other grounds (Galloway, 1988; Cline et al., 1989; Chandler and Bock, 1991; Giles, 1991). Some of these studies (and others cited therein) suggested that reduction in height begins later than 30 years, that the age reduction has a quadratic term, i.e., is nonlinear, and/or that males and females have different age trends in stature loss. In fact, some nonlinearity in stature loss may explain the lack of stature change prior to the fifth decade reported in some studies: a gradually increasing loss beginning in the fourth decade is difficult to pick up without long-term longitudinal data (Chandler and Bock, 1991). The greater rate of loss in females may very well be due to their greater propensity for frank vertebral fracture, at least prior to the eighth decade (Melton and Cooper, 2001). We eliminated any individuals with obvious vertebral compression or wedge fractures. However, compression of vertebral bodies occurs on a continuous scale, which is one reason why it is difficult to precisely define "vertebral fracture" (Black et al., 1991; Eastell et al., 1991). Thus, given the age range of our sample, some individuals likely had partial vertebral fractures, and this may have been more common in females. However, again this would have been reflected in the actual Fully dimensions measured, so that a sex bias in stature estimation should not have been present. We cannot address the issue of the exact age at which stature reduction begins, but the soft-tissue component of stature appeared to decline over the entire age range examined (21–85 years), although we had relatively few individuals under age 30 years (n = 7). In terms of living stature prediction, the constant age adjustment recommended here worked as well as, or better than, one derived specifically for individuals over 30 years of age.

Our study also clarifies several issues regarding osteological measurement techniques. The exact dimension specified by Fully (1956) for vertebral heights of C2–L5 has been open to interpretation by various authors. This is an important issue, since the vertebral column constitutes a large portion (almost one-third on average) of total skeletal stature (Auerbach et al., 2005). The original description by Fully (1956, p. 268) was to take the "hauteur totale," or total height of each vertebral body. This is the translation used by El Najjar and McWilliams (1978). Later, Fully and Pineau (1960, p. 145) indicated taking the "hauteurs maximales," or maximum height of each vertebral body. No mention was made of where around the vertebral body this height was to be taken. This is the interpretation favored by Olivier (1969), Stewart (1979a), and Ubelaker (1999). Formicola (1993, p. 354) measured "maximum midline height," citing Tibbets (1981, Fig. 1) and Lundy (1988, Fig. 2). Lundy phrased the instruction two different ways: "maximum heights of C2 through S1" (Lundy, 1987, p. 54), and "maximum anterior height of each vertebrae" (Lundy, 1983, p. 337, 1985, p. 74, 1988, Fig. 2). The latter description was also followed by Sciulli et al. (1990). Though the illustration by Lundy (1988, Fig. 2) implies measurement at midline, none of his publications specifically state midline as the measuring point. Feldesman and Lundy (1988, p. 586) specified "anterior heights of each vertebra," an interpretation that does not include the explicit direction by Fully (1956) of "maximum" or mention measurement at midline.

We found that measuring the maximum height of the vertebral bodies, wherever it occurred anterior to the pedicles and rib facets (when present), produced the closest correspondence between FES and LS, and also eliminated any sex or ancestry effects on stature prediction from SKH. The position of maximum vertebral body height varied between vertebrae, but often was not found in the most anterior portion of the vertebrae, i.e., at or near midline. The pedicles and facets are excluded from measurement, as they do not factor into skeletal height. The corpus should be measured on the rim, and not beyond it into the portion of the centrum where the vertebral disks are situated (see Appendix). For the purposes of converting anterior midline vertebral heights to maximum heights of C3–L5, so that Equations (1) or (2) can be applied, the average summed difference between them in our sample was 1.6 cm, or 3.6%, i.e., the summed anterior heights of C3–L5 should be multiplied by 1.036.

Fully (1956) stated that he used a Broca osteometric board to measure maximum length of the tibia, excluding the spine and including the malleolus. A Broca osteometric board is not readily available to many investigators. An osteometric board with a track (that runs through the center of the longitudinal axis of the immovable portion of the board) forces the tibia to be measured at an angle, yielding a less accurate measurement of tibial maximum length. We recommend using a trackless osteometric board, which allows the investigator to measure the tibia with the tibial diaphysis in line with the longitudinal axis of the board, and which comes closer to approximating the Broca-board measurement.

Fully (1956) directed taking the measurement of the articulated height of the talus and calcaneus from the most superior point of the talus to the most inferior point of the calcaneus, but did not specify exactly how to articulate and position the elements. The wording of Fully (1956, p. 269) suggests that he had in mind measuring to the inferior "bearing" surface ("surfaces portantes inférieures") of the calcaneus, and this is how Stewart (1979a, p. 219) translated the description, which would imply positioning the calcaneus and talus in anatomical position (since the anterior end of the calcaneus does not contact the ground during weight-bearing). Unfortunately, this interpretation is potentially clouded by the use by Fully (1956) of plural "surfaces" here, although again, the anterior calcaneus is not a "bearing" surface. The method by which we measured the talus and calcaneus was roughly the same manner in which Lundy (1988, Fig. 6) interpreted and illustrated the instruction of Fully (1956). Formicola (1993) disagreed with the interpretation of Lundy (1988), and believed that measurement of the talus and calcaneus in the anatomical position did not correspond to the requirements of Fully (1956), though Fully did not indicate otherwise (see above). Other descriptions of the talus/calcaneus measurement are nonspecific, merely directing measurement of the articulated height of the talus and calcaneus, or presenting a direct translation of the instruction by Fully (1956) quoted above (Olivier, 1969; El Najjar and McWilliams, 1978; Stewart, 1979a; Lundy, 1983, 1985, 1987, 1988; Feldesman and Lundy, 1988; Sciulli et al., 1990; Ubelaker, 1999).

We found that measuring the talus and calcaneus in the anatomical position, with the anterior end of the calcaneus raised from one measuring surface and the other measuring surface placed at a tangent to the middle of the talar articular surface, yields the closest estimates of living stature (see Appendix for illustrations and specific directions). Thus, we recommend this technique in future applications of the method.

As noted earlier, an important advantage of "anatomical" stature reconstruction techniques is that they make no assumptions about body proportions, and thus are applicable in cases where an appropriate reference sample is not available. Do they provide any advantage over "mathematical" regression techniques based on long bone lengths, when such a reference sample is available? To answer this question, we carried out a comparison of our anatomically determined living statures, estimated using Equation (1), and living statures estimated using the regression equations of Trotter and Gleser (1952) for US white and black males and females, based on physiological length of the femur (physiological rather than maximum length of the femur was used to correspond to the femoral dimension included in the technique of Fully, 1956). In some ways, this is a "best-case scenario" for the mathematical technique, since the reference sample used to develop the long bone regressions and this study's sample are both derived from very similar sources: part of the male sample and all of the female sample used by Trotter and Gleser (1952) were from the Terry Collection, and other individuals (US World War II military personnel) were of the same general ancestry and temporal period. As expected given this similarity, mean directional differences between estimated and living statures using femoral length regressions are quite small, with a mean directional error of 0.4 cm over the total sample, and less than a 0.3-cm error in most sex/ancestry samples, except for black males (mean 2-cm error). Thus, the directional bias using the "mathematical" technique in this closely matched sample is comparable to that produced by the "anatomical" technique (except for black males). However, as shown in

TABLE 5. Variability in living stature estimates, using new anatomical and mathematical stature estimation techniques (in cm)

Sample	Anatomical[1]		Mathematical[2]	
	SD	Range[3]	SD	Range
Total pooled	2.2	11.2	3.1	15.9
Black females	2.3	9.1	2.8	11.4
White females	1.7	8.4	3.2	13.6
Black males	1.8	9.0	2.8	12.2
White males	2.8	11.2	3.2	12.2

[1] Calculated from skeletal height, using text Equation (1).
[2] Calculated using stature regression equations of Trotter and Gleser (1952), based on physiological length of femur, corrected for age as they recommended.
[3] Maximum-minimum directional error.

Table 5 for all subsamples and the total pooled sample, the dispersion of absolute differences is always larger using the long bone regression technique. That is, there are more outliers using the long bone regression formulae than using the anatomical technique. This is due to the fact that despite the sex/ancestry specificity of the regression formulae, there are always likely to be some individuals with unusual body proportions. This is not accounted for by long bone regression techniques, but is addressed by anatomical techniques, which are "personalized" for each specimen. Thus, anatomical techniques have advantages, even in this situation that is "ideal" for the mathematical technique. In situations where body proportions cannot be matched with a particular reference sample, estimation errors using long bone regression techniques will be even greater (Lundy, 1983; Holliday and Ruff, 1997; Auerbach et al., 2005).

CONCLUSIONS

Reliable stature estimates reconstructed from skeletal remains will continue to play an important role in assessing a variety of bioanthropological issues, both forensic and archaeological. Most investigators rely on long bone regression techniques to estimate stature because of their simplicity, but if skeletal remains are relatively complete, a better stature estimate can be obtained using an anatomical method. This is particularly true when there are questions regarding the appropriateness of the reference sample used to develop the regression formulae, but even when a good match between reference sample and estimated specimen can be made, there will still be more random error involved in the regression method because of individual differences in body proportions.

However, it is important in applying anatomical methods to measure each skeletal element in a consistent way. When applying the technique of Fully (1956), we recommend that maximum vertebral body heights (anterior to the pedicles) and height of the talus and calcaneus in anatomical position (with the anterior end of the calcaneus raised above the measuring surface) be taken. Measurement of tibial length using a trackless osteometric board produces results closest to those using the Broca board that Fully (1956) employed. When a rigorous measurement technique is followed, interobserver error in total summed skeletal height is very small (0.16 cm, or 0.1%).

The original factors recommended by Fully (1956) to convert summed skeletal height to living stature appear to underestimate the necessary correction by somewhat over 2 cm on average. New regression formulae are presented here that incorporate soft-tissue and other corrections, with and without an age term. Both formulae yield unbiased living stature estimates in all sex and ancestry groups examined here, with 95% of all individuals estimated correctly to within 4.5 cm.

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APPENDIX

Technique of Fully (1956): Revised measurements

Figures 3–5 present the revised measures for all elements used in our analysis of the method of Fully (1956) for stature estimation. When possible, the corresponding measure in Martin (1957) is given at the end of the description (i.e., M-#); the measurement tool for each measure is indicated in parentheses. For all dimensions, do not include any arthritic or osteophytic growths in the measurement. In vertebrae, avoid any midline notches that are present, measure to the rims on the vertebral bodies (i.e., not the centers of the centra), and ensure that the calipers are held as close to perpendicular to the plane of the vertebral body's superior and inferior surfaces as possible. Note that specific measurement locations shown for C2–L5 vertebrae (first column in Fig. 4) are only examples of where height should be taken: the maximum height of each body, within the regions shown in the middle and right columns, should be taken. For paired elements (femur, tibia, and articulated talus and calcaneus), if both sides of the element are complete and present, use the average value of the two measurements when calculating skeletal height.

- Cranial height (Fig. 3): The maximum length between bregma (at the confluence of the coronal and sagittal sutures) and basion (at the anteroinferior margin of the foramen magnum, between the occipital condyles). This measure can be taken with the calipers placed either laterally or posteriorly, relative to the cranium (M-17) (spreading calipers).
- Second cervical vertebra (Fig. 4a): The most superior point of the odontoid process (dens) to the most inferior point of the anterioinferior rim of the vertebral body (sliding calipers).
- 3rd–7th cervical vertebrae (Fig. 4b): The maximum height of the vertebral body, measured in its anterior third, medial to the superiorly curving edges of the centrum (sliding calipers).
- Thoracic vertebrae (Fig. 4c): The maximum height of the vertebral body, anterior to the rib articular facets and pedicles (sliding calipers).
- Lumbar vertebrae (Fig. 4d): The maximum height of the vertebral body, anterior to the pedicles, not including any swelling of the centrum due to the pedicles (sliding calipers).

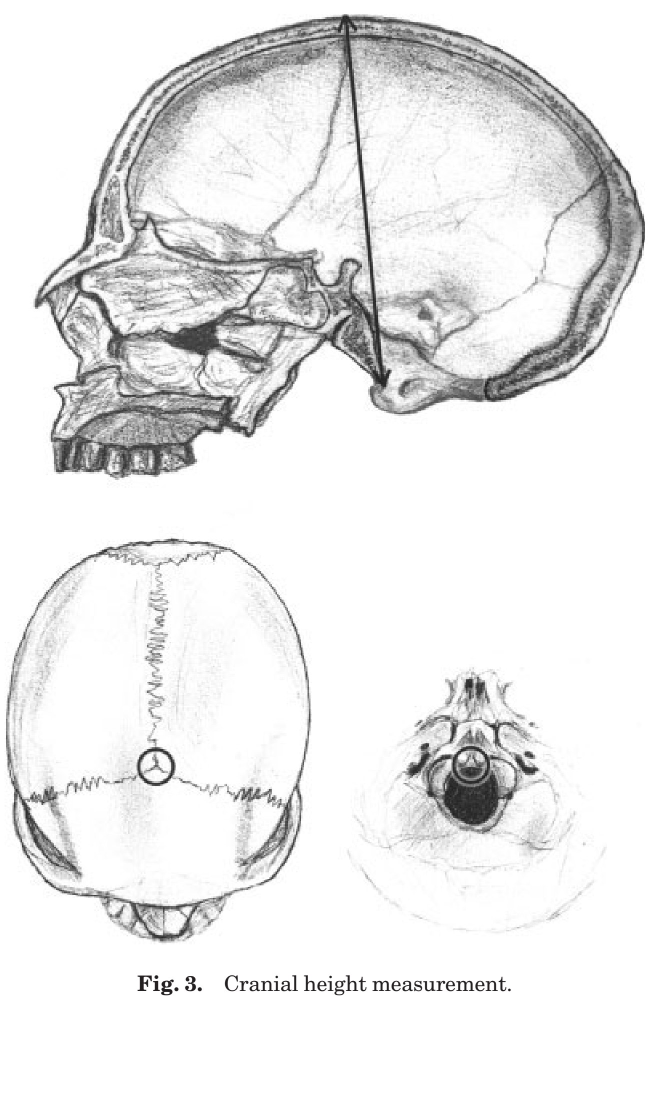

Fig. 3. Cranial height measurement.

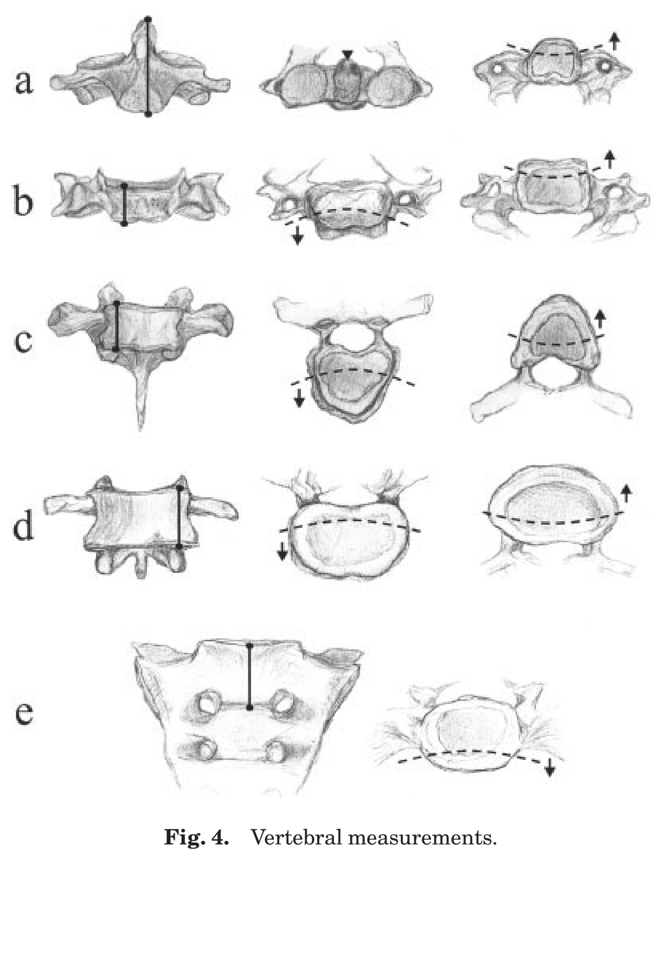

Fig. 4. Vertebral measurements.

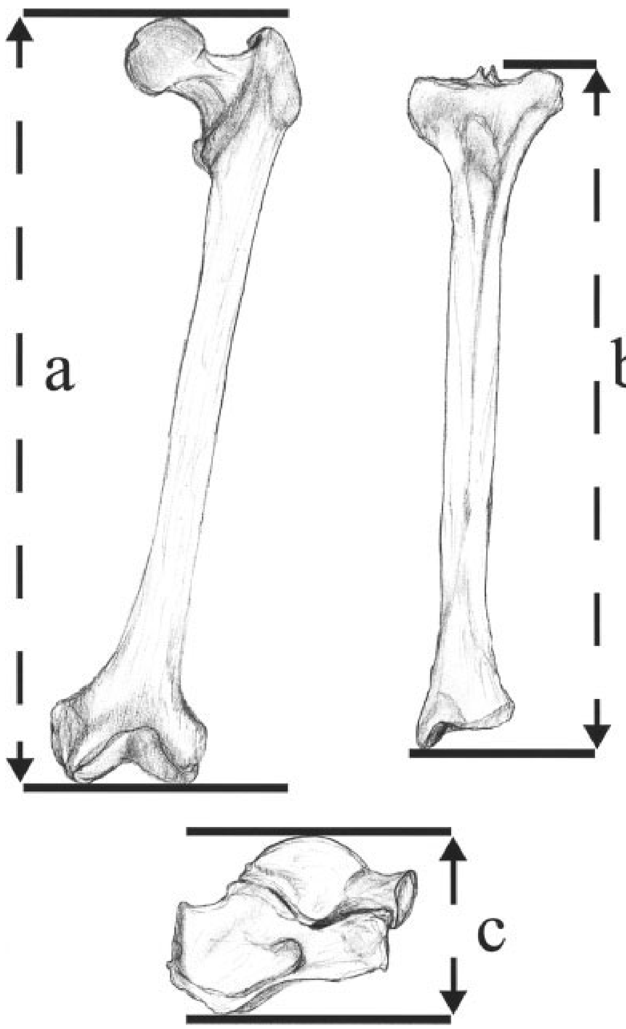

Fig. 5. Lower limb measurements.

- First sacral vertebra (Fig. 4e): The maximum height between the anterior-superior rim of the body (i.e., the sacral promontory) and its point of fusion/articulation with the second sacral vertebra. This most commonly occurs in the midline. Measure with the calipers parallel to the anterior surface of S1 (sliding calipers).
- Femoral physiological length (Fig. 5a): Place the condyles on the stationary end of the osteometric board, flat against the horizontal plane. Set the mobile end against the most superior aspect of the femoral head, parallel to the stationary end. Measure at maximum length (M-2) (osteometric board).
- Tibial length (Fig. 5b): Place the medial malleolus on the stationary end of the osteometric board, with the shaft of the tibia parallel to the long axis of the board. Set the mobile end against the most superior aspect of the *lateral* condyle of the tibia, parallel to the stationary end. We recommend that a trackless osteometric board be used to take this measure, to allow the freedom of the mobile end's placement (M-1) (osteometric board).
- Talus-calcaneus height (Fig. 5c): Articulate the talus and the calcaneus, using the right hand for the left tarsals and vice versa. Use one hand to stabilize the articulation, point the distal articulations away from your palm, with a thumb holding the bones together superior to the peroneal tubercle (where the talus and calcaneus meet), an index finger on the opposite side lateral to the trochlea of the talus, and a middle finger in the sustentacular sulcus. Place the trochlea against the stable end of the osteometric board, with both lateral and medial edges of the trochlea contacting the board. Position the trochlea of the talus so that the stable end of the board forms a tangent to the midpoint of the trochlear surface (Fig 5c). Place the mobile end of the osteometric board against the most inferior point of the calcaneal tuber, parallel to the stable end (osteometric board).

After summing these dimensions to obtain skeletal height, apply either Equation (1) or (2) below to estimate living stature (dimensions in cm, age in years):

$$\text{Living stature} = 1.009 \times \text{Skeletal height} - 0.0426 \times \text{age} + 12.1. \quad \text{(A1)}$$

$$\text{Living stature} = 0.996 \times \text{Skeletal height} + 11.7. \quad \text{(A2)}$$

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