Title: Stature estimation equations for South Asian skeletons based on DXA scans of contemporary adults

Authors: Emma Pomeroy[1]
Veena Mushrif-Tripathy[2]
Jonathan C. K. Wells[3]
Bharati Kulkarni[4]
Sanjay Kinra[5]
Jay T. Stock[6]

Affiliations: [1] School of Natural Sciences and Psychology, Liverpool John Moores University, UK
[2] Deccan College Postgraduate and Research Institute, Pune, India
[3] UCL Great Ormond Street Institute of Child Health, UCL, UK
[4] National Institute of Nutrition, Hyderabad, India
[5] Department of Non-communicable Disease Epidemiology, London School of Hygiene and Tropical Medicine, London, UK
[6] ADaPt Project, PAVE Research Group, Department of Archaeology and Anthropology, University of Cambridge, UK

Pages: 17 + 1 title page + 6 bibliography

Figures: 3

Tables: 7

Abbreviated title: Stature estimation for South Asians

Keywords: Height, Long bones, India, Archaeology, Forensics

Corresponding author:
Dr Emma Pomeroy
School of Natural Sciences and Psychology
Liverpool John Moores University
Byrom Street
Liverpool L3 3AF
UK

Email: e.e.pomeroy@ljmu.ac.uk
Tel: +44 (0) 151 231 2815

Grant sponsorship: British Academy International Partnership and Mobility Scheme Grant (EP and VM), Leverhulme Trust/Isaac Newton Trust Early Career Fellowship (EP). The third survey wave of APCAPS data collection was supported by a Wellcome Trust Strategic Award (Grant No. 084774) and subsidized access to DXA scan facilities given by the National Institute of Nutrition (Directors), Indian Council for Medical Research.

ABSTRACT

Objectives: Stature estimation from the skeleton is a classic anthropological problem, and recent years have seen the proliferation of population-specific regression equations. Many rely on the anatomical reconstruction of stature from archaeological skeletons to derive regression equations based on long bone lengths, but this requires a collection with very good preservation. In some regions, e.g., South Asia, typical environmental conditions preclude the sufficient preservation of skeletal remains. Large-scale epidemiological studies that include medical imaging of the skeleton by techniques such as Dual Energy X-Ray Absorptiometry (DXA) offer new potential datasets for developing such equations.

Materials and Methods: We derived estimation equations based on known height and bone lengths measured from DXA scans from the Andhra Pradesh Children and Parents Study (Hyderabad, India). Given debates on the most appropriate regression model to use, multiple methods were compared, and the performance of the equations was tested on a published skeletal dataset of individuals with known stature.

Results: The equations have standard errors of estimates and prediction errors similar to those derived using anatomical reconstruction or from cadaveric datasets. As measured by the number of significant differences between true and estimated stature, and the prediction errors, the new equations perform as well as, and generally better than, published equations commonly used on South Asian skeletons or based on Indian cadaveric datasets.

Conclusions: This study demonstrates the utility of DXA scans as a data source for developing stature estimation equations and offer a new set of equations for use with South Asian datasets.

The estimation of stature from the skeleton is a classic problem across various subfields of anthropology (Dwight, 1894; Fully, 1956; Fully and Pineau, 1960; Genovés, 1967; Lundy, 1985; Manouvrier, 1893; Nat, 1931; Pearson, 1899; Raxter et al., 2006; Trotter, 1970; Trotter and Gleser, 1952). Traditionally, measurements of the major limb long bones are used to derive multiplication factors (e.g., Kate and Mujumdar, 1976; Pan, 1924; Siddiqui and Shah, 1944) or estimation equations based on linear regression (e.g., Auerbach and Ruff, 2010; Feldesman and Fountain, 1996; Genovés, 1967; Nath and Badkur, 2002; Pomeroy and Stock, 2012; Raxter et al., 2008; Trotter, 1970; Trotter and Gleser, 1952) that can be used to estimate stature from skeletal remains. Reference collections are typically forensic or anthropological skeletal collections comprised of recent individuals whose stature was recorded or measured. While some equations are widely used across samples from diverse geographical regions and varying ancestry (Feldesman and Fountain, 1996; Trotter, 1970; Trotter and Gleser, 1952; Trotter and Gleser, 1958; 1977), the need for population-specific stature estimation methods has long been acknowledged (Nat, 1931; Pan, 1924; Stevenson, 1929) due to inter-population variation in intra-limb, inter-limb and limb-trunk proportions (Bogin and Rios, 2003; Holliday and Ruff, 1997; Katzmarzyk and Leonard, 1998; Meadows and Jantz, 1995; Roberts, 1978; Ruff, 2002; Trinkaus, 1981).

The revision of the Fully technique (Fully, 1956; Fully and Pineau, 1960) by Raxter et al. (2006; 2007) opened up a new source of reference data: relatively complete skeletons, whose true stature is unknown, could serve as reference samples. The revised Fully technique is an 'anatomical' method of stature estimation that involves summing the dimensions of all bones contributing to body height and adding a correction factor for soft tissue (Fully, 1956; Fully and Pineau, 1960; Raxter et al., 2006; Raxter et al., 2007). These more accurate anatomical stature estimates can in turn be used to derive regression equations to estimate stature from individual long bone lengths for use with less complete skeletons. This revised method has contributed to a florescence of population-specific estimation equations over the last decade (e.g., Auerbach and Ruff, 2010; Béguelin, 2011; Durband et al., 2016; Gocha et al., 2013; Maijanen and Niskanen, 2010; Pomeroy and Stock, 2012; Raxter et al., 2008; Ruff et al., 2012).

While the revised Fully method has led to new population-specific stature estimation equations for various worldwide populations, its use is limited where skeletal preservation is anything other than excellent. In regions such as South Asia, where a warm, humid climate and past cultural practices (cremation) have limited the preservation of complete skeletons, other methods must be sought. Some equations have been derived from cadavers of known stature (Athawale, 1963; Kate and Mujumdar, 1976; Kolte and Bansal, 1974; Meshram et al., 2014; Nat, 1931; Nath and Badkur, 2002; Pan, 1924; Patil et al., 1983; Siddiqui and Shah, 1944), but these suffer limitations such as being derived for single skeletal elements (e.g., only the humerus) or just one sex, and a lack of cross-testing across populations within the Indian subcontinent. Typically, archaeological studies in the region still employ regression equations derived from geographically and ancestrally distinct reference samples (particularly Trotter, 1970; Trotter and Gleser, 1952; Trotter and Gleser, 1958; 1977).

With the establishment of large epidemiological cohort studies in many parts of the world, a new potential source of skeletal measurements (Chinappen-Horsley et al., 2007; Clark et al., 2007) for individuals of known stature has become available. Many of these studies take medical scans of the body, such as whole-body magnetic resonance images (MRI) or dual energy X-ray absorptiometry (DXA) in order to assess characteristics such as body composition, and have large samples of hundreds or thousands of individuals.

The purpose of this study is to derive stature estimation equations for South Asians of both sexes using whole body DXA images and measured stature from recent living participants in a major epidemiological study. In doing so, we aim to assess the utility of whole body DXA scans for deriving skeletal measurements. If this approach proves effective, we aim to demonstrate the potential of such large epidemiological datasets for research in osteology and forensic anthropology.

MATERIALS AND METHODS

We used DXA scans from APCAPS (Andhra Pradesh Children and Parents Study), a major epidemiological study of healthy offspring and their parents involving inhabitants of villages surrounding the city of Hyderabad, Andhra Pradesh, India (see Kinra et al., 2013 for an overview). Participants provided assent/informed consent as appropriate for age of participants at that phase of study, and participation was voluntary. The study was approved by the ethics committees of the National Institute of Nutrition, Hyderabad and the London School of Hygiene and Tropical Medicine. Participants had DXA scans at various time points during the study, and scans from the 3rd follow-up were selected for the present study on the basis that some individuals in this population continue to grow into their early 20s, and this follow-up had the highest proportion of individuals who had reached at least this age. A stratified random subsample of 160 individuals (80 female) was selected for analysis from the available dataset to ensure good coverage across the full range of height and body mass (since the data were also used to investigate body mass) and equal numbers of males and females. All DXA scans were performed on a Hologic Discovery A (Bedford, MA, USA) at the National Institute of Nutrition, Hyderabad, that was calibrated daily during the study. During the scan, the participants were asked to lie supine in the centre of the scanning bed with their arms at their sides. Body position was standardized as far as possible for the scans by arranging the subject in a standard position as per the instructions provided in the manufacturer's manual, although the feet were not immobilized. Repeat measurements for 30 participants were conducted that showed that the coefficient of variation for whole-body bone mineral density (BMD) was 0.9%, indicating good standardisation of body positioning (to which whole body BMD is sensitive). Individuals whose scans could not be measured due to movement artifacts or poor positioning were excluded (n = 1).

Standing height was measured to the nearest cm using a portable stadiometer (Leicester Height Measure; Chasmors, Camden, London, UK).

Whole body scan ‘P’ files (Fig. 1) were copied from the Hologic APEX software and opened in ImageJ (Rasband, 1997-2016) using the Hologic P Reader plugin written by Minxuan Dong (Dr Neil Dong, pers. comm. 2015). To enhance the clarity of the skeleton, images were adjusted using automatic brightness and contrast adjustments in ImageJ. The images were scaled based on the known length of the scan image and by testing measured supine body length from the scans with known standing height in 20 randomly selected scans from the sample, reducing supine length by 2.5 cm to account for the supine position (Trotter and Gleser, 1952). Data on the relationship between stature and supine length in the living are rather sparse, and Trotter and Gleser’s (1952) estimate is potentially problematic. However, this figure is mid-way between other estimates and therefore deemed most appropriate, and variation between studies is small. Gray et al. (1985) reported supine length was 3.7 cm greater than standing height for ambulatory hospital patients, while Palmer (1932) reported a difference of approximately 1-2 cm for statures between 1.45 m and 1.80 m in individuals aged up to 20 years. Further clarification in healthy young adults would therefore be beneficial.

Maximum lengths of the humerus (XLH), ulna (XLU), femur (XLF) and fibula (XLFi) and the length of the tibia from the medial plateau to the most distal part of the medial malleolus (approximating complete tibia length, CLT) were measured using the line measurement tool in ImageJ 1.46 (NIH: Rasband, 1997-2016) in a manner that would match standard osteological measurements on dry bone (Bräuer, 1988; Martin and Saller, 1957) as closely as possible. While the tibia measurement CLT is typically taken from the lateral tibial plateau on dry bone, the use of the medial tibial plateau facilitated taking the measurement parallel to the long axis of the bone. However the possibility that this may have reduced the tibia length by a few mm should be noted.

[FIGURE 1 HERE]

One limitation of the whole body DXA scans is their resolution, which for this dataset is approximately 0.35 pixels per mm. This can be partially ameliorated by allowing measurements at the sub-pixel level in ImageJ, although clearly this does not solve the underlying limits of the image resolution. Furthermore, it can be difficult to distinguish the ends of the bones with confidence where bones overlap or due to body positioning. Radius length was therefore not measured as we found that the proximal end was often too indistinct in the scans to identify with confidence. Because of these potential issues with measurement accuracy and reliability, both right and left sides were measured and the mean taken, and all measurements were taken by two observers (VM and EP) independently. The mean of these measurements was then used in subsequent analyses.

To assess the reliability of measurements made on the DXA images, intra-observer error statistics were calculated from repeated measurements of 10 individuals by EP, taken at least 1 day apart. Inter-observer error statistics were calculated for the measurements by EP and VM on the whole dataset. Technical error of measurement (TEM) and the coefficient of reliability (R) were calculated following Ulijazsek and Lourie (1994), and %TEM was calculated as TEM as a percentage of the mean for that measurement. Intra-observer error was low (Table 1), with %TEM of less than 1%. Inter-observer error was considerably higher. Although there are no universally accepted limits for reliability, %TEM ranged from 1.8 to 2.4 %. The coefficient of reliability (r) was lowest for ulna and fibula lengths (0.88-0.91), and highest for femoral length at 0.95-0.96.

[TABLE 1 HERE]

There has been considerable debate over the most appropriate way to derive stature estimation equations from long bone lengths (Hens et al., 2000; Konigsberg et al., 1998; Pablos et al., 2013; Ruff et al., 2012; Sierp and Henneberg, 2016; Sjøvold, 1990; Smith, 2009), and there appears as yet to be no consensus. A known limitation of the widely-used ordinary least squares (OLS) regression is its tendency to overestimate statures of smaller individuals and underestimate those of taller individuals because of the nature of the line fitting process (Sjøvold, 1990). Reduced major axis (RMA) regression reduces this effect and so has been advocated by some, and is considered to be more reliable when extrapolation beyond the range of the original dataset may be necessary and when both the predictor and outcome are measured with error (Auerbach and Ruff, 2004; Ruff et al., 2012; Ruff et al., 1991; Sierp and Henneberg, 2016; Sjøvold, 1990; Smith, 2009). RMA regression minimizes the deviation from the fitted line in both the x and y variables, rather than just the y variable as in OLS regression, and thus results in a symmetrical line (i.e., it makes no difference which variable is placed on which axis) (Sjøvold, 1990; Smith, 2009). Robust regression techniques have also been advocated (Pablos et al., 2013) but rarely applied. These are a group of various methods that are particularly useful where the regression models may be influenced by outliers, since robust regression reduces their influence (Venables and Ripley, 2002).

Given this lack of consensus, stature estimation equations were produced using OLS, RMA and robust regression models so that the results could be compared. Equations were produced for each individual bone and by entering femur and tibia lengths into the same model for OLS and robust equations, since previous studies have shown that including multiple bones in the equation reduces the associated errors. Male and female data were treated separately in light of known sex differences in limb proportions. The performance of the equations was assessed using adjusted R^2 values, standard errors of estimates (SEE: raw and as a percentage of mean stature), prediction errors (measured – predicted stature), and percent prediction errors (%PE = (100*(measured-predicted)/predicted)) (Smith, 1984; 2002). Means and ranges of the raw PE and %PEs are presented. To indicate the magnitude of differences (%PEs can be positive or negative so typically their mean is close to 0), we also present medians of the absolute %PE (|%PE|, which tends to be strongly skewed making means less informative: Ruff et al., 2005).

To assess the performance of the estimation equations on an independent dataset and on dry bone measurement, we tested them on published raw data (i.e., known stature and the measured long bone lengths) of adult male cadavers from Uttar Pradesh, India (Nat, 1931). It is presumed that these were cadavers studied at the Anatomy School at Lucknow, where Nat was a Professor (the only information given is that they were from the 'United Provinces', now incorporated into the modern states of Uttar Pradesh and Uttarakhand). "Stature" of the bodies was measured, and the skeleton was then macerated and measurements taken on bones without their joint cartilage (Nat, 1931). Humerus, ulna, tibia and fibula lengths were measured in a comparable manner to the DXA measurements, but Nat (1931) reports bicondylar femur length, while we measured maximum femur length on the DXAs. Therefore bicondylar femur length was converted to maximum femur length using the regression formula given by Auerbach (2011), based on a mixed sex sample (given no sexual dimorphism in the relationship) of 2,440 individuals. Mean stature, bone lengths and intra-limb indices (ulna: humerus and tibia: femur length ratios) were compared between the APCAPS males and Nat's (1931) dataset using t-tests. Estimates derived from bone measurements using our equations were compared with known stature using PE, %PE and |%PE| as above, and paired t-tests were used to compare documented and estimated statures. As one of the problems with OLS is underestimation of tall statures and overestimation of short statures, to assess whether this was a significant problem, Bland-Altman plots (PE plotted against mean of estimated and measured stature: Altman and Bland (1983)) were produced and correlations between the mean of estimated and measured stature vs. predicted PE calculated.

To put these results in context and evaluate whether equations used in or proposed by other studies give comparably reliable results, stature was also estimated using published equations derived from:

(a) worldwide populations that are often applied to South Asian archaeological skeletons (Feldesman and Fountain, 1996; Trotter, 1970); (b) 'Asian' samples more broadly (Feldesman and Fountain, 1996); and (c) Indian samples (Athawale, 1963; Kate and Mujumdar, 1976; Kolte and Bansal, 1974; Kumar and Reddy, 2016; Meshram et al., 2014; Nath and Badkur, 2002; Patil et al., 1983). Recently, Lukacs et al. (2014) applied equations developed by Raxter et al. (2008) for ancient Egyptians to Mesolithic South Asians, on the basis that these two groups shared similar limb proportions. The performance of these equations was therefore also assessed.

Statistical analyses were performed using SPSS for Windows v. 24.0 (IBM Corp., Chicago) for all analyses except the robust regressions, where the *rlm* function from the MASS package (Venables and Ripley, 2002) was used in R (R Core Team, 2016). This robust regression method reduces (but does not remove) the influence of genuine data points that exercise a high degree of leverage or that are strong outliers, through an iterated re-weighted least squares procedure. Essentially, points lying more distant from the regression line are given a lower weight in the model than those closer to the line (Venables and Ripley 2003). An alpha level of 0.05 to indicate statistical significance was used throughout.

RESULTS

The characteristics of the study sample are presented in Table 2. Mean age at the time of scan is 22.8 years, mean female height is 153.9 cm and mean male height is 166.9 cm. Summary information on the comparative male data from Nat (1931) is presented in Table 2. Males from the APCAPS sample are significantly taller by approximately 3 cm for Nat's upper limb sample and by 6 cm for his lower limb sample, and all bone lengths are significantly longer in the APCAPS males except for XLH. The APCAPS males also have a longer ulna or tibia relative to the humerus or femur respectively ($p \leq 0.015$ for all comparisons).

[TABLE 2 HERE]

For the OLS regressions (Table 3), the highest adjusted R^2 values were for equations employing both the tibia and femur for males (adjusted R^2 = 0.85) or tibia length for females (adjusted R^2 = 0.87). The individual lower limb bones give the next highest adjusted R^2 values, and the individual upper limb bones give the lowest.

The estimation equations derived by OLS, RMA and robust regression (Tables 4 and 5 respectively) give essentially similar errors. SEEs for the OLS equations range from 4.1 cm (female ulna equation) to 2.6 cm (male femur and tibia equation). SEEs are slightly higher for the RMA equations (2.8 – 4.3 cm), but similar for the robust regression equations (2.5 – 4.1 cm: Fig. 2). Similar to the pattern for the adjusted R^2 values, the %PE and %SEE are lowest for the RMA and robust equations combining the tibia and femur, followed by the individual lower limb bones, and greatest for the upper limb bones, and particularly the ulna.

[TABLES 3-5 HERE]

[FIGURE 2 HERE]

Overall our equations perform well on the data from Nat (1931), with median |%PE| between 1.3 and 2.3 % (Supplementary Table 1). The best-performing regression model depends on the measure used, so none is clearly superior to the others. Based on PEs, the OLS and robust regression equations have smaller mean errors than the RMA equations. Mean PEs for the OLS equations range from -0.4 to 1.4 cm and are very similar for the robust equations (-0.6 to 1.5 cm), while those for RMA equations are higher (0.0 to 2.0 cm). Generally the mean PEs are positive, indicating that the equations tend to slightly underestimate measured stature, apart from the humerus equations for OLS and robust models, which overestimate stature.

On the basis of |%PE| the RMA equations for the humerus and femur perform best (median |%PE| = 1.3 and 1.4 respectively), although the |%PE| of the other regression models are only slightly higher. The OLS equations produce the fewest significant differences from the measured statures. In addition to a slight bias (most equations underestimating stature), the PEs correlate with stature (Fig. 3, Supplementary Table 1) for all equations except the RMA regression equations based on the humerus and ulna. Most equations show significant positive correlations with stature, indicating that they overestimate the stature of shorter individuals and underestimate that of taller individuals. However, as predicted, the correlations are consistently lower for the RMA equations, indicating that they result in less bias in estimated stature at the extremes of the height range compared with the OLS and robust regression equations.

[FIGURE 3 HERE]

Comparing the estimates from our equations with those from published equations for Nat's (1931) dataset (Table 6), the new equations perform well overall. With some exceptions described below, differences between measured and estimated statures are more highly significant and mean PEs greater using the published equations. The Trotter and Gleser American White equations (Trotter, 1970) overestimate stature. The smallest mean difference was 1.2 cm for the humerus equation, and the highest mean difference was 8.6 cm for the tibia equation. The Trotter and Gleser American Black equations overestimate stature by a mean of 2.1 - 4.1 cm depending on the equation. The American Black upper limb equations perform better, giving no significant differences between true and estimated stature and mean PEs of 0.6 cm or less. The Feldesman and Fountain equations (Feldesman and Fountain, 1996) for the femur, whether generic or 'race'-specific, give highly significant differences between true and estimated statures but comparable or lower PEs compared with other equations. Those developed for ancient Egyptians by Raxter et al. (2008) generally perform better for the upper limb bones than for the lower limbs. For the upper limb, the differences between true and estimated stature were not significant for the humerus and radius, although there was a significant overestimate of stature using the ulna. All lower limb bones significantly overestimated stature by 1.5-2.0 cm on average, so they performed relatively well compared with equations derived from other non-Indian populations and better for the lower limb.

The India-specific estimation equations perform slightly better overall, but still give more significant differences from true stature than our new equations. The Nath and Badkur (2002) equations developed from modern cadavers from Bhopal, Madhya Pradesh, overestimate stature on average, with the femur and fibula giving particularly high mean prediction errors (5.3 cm and 4.7 cm respectively). The equations based on humerus length underestimate stature significantly. The Kate and Mujumdar (1976) equation based on cadavers from Amritsar and Nagpur and the Kolte and Bansal equations (Kolte and Bansal, 1974) based on cadavers from Aurangabad give the lowest PEs (1.2 cm), and the Meshram et al. (2014) equation based on a sample from Vidarbha, Maharashtra, performs particularly poorly with mean PE of 7.4 cm. In contrast, those based on the femur overestimate stature. Only Kumar and Reddy's (2016) equation based on cadavers from Andhra Pradesh produced predictions that did not significantly differ from the true heights, with a mean PE of 0.9 cm. The Kate and Mujumdar (1976) equations for the femur performed more poorly.

[TABLE 6 HERE]

DISCUSSION

In this study, we have derived stature estimation equations based on humerus, ulna, femur, tibia and fibula lengths measured from DXA scans of contemporary young adults from an urbanizing Indian population. The resulting equations offer a level of error comparable with other widely used equations. Our OLS equations gave SEEs between 2.6 and 4.1 cm, compared with for example, Trotter and Gleser's equations for American Whites and Blacks (Trotter, 1970; Trotter and Gleser, 1952; Trotter and Gleser, 1958; Trotter and Gleser, 1977) with SEEs between 3.0 to 5.1 cm, and Ruff et al.'s (2012) equations for Europeans with SEEs of 2.6 to 4.5 cm. While equations have been derived previously for samples from the Indian subcontinent (Kate and Mujumdar, 1976; Kolte and Bansal, 1974; Kumar and Reddy, 2016; Meshram et al., 2014; Nat, 1931; Nath and Badkur, 2002; Pan, 1924; Patil et al., 1983; Siddiqui and Shah, 1944), the advantages of these new equations are that they are derived for both sexes, multiple long bones, and have been tested on another sample.

Since our new equations were derived from measurements taken on DXA scans, it was important to examine whether they produce accurate predictions from actual bone measurements in individuals of known stature and on skeletonized remains. Available test data were limited, but applying the equations to published data on males from Uttar Pradesh (Nat, 1931) demonstrated relatively good reliability. The OLS equations in particular resulted in few significant differences between measured and estimated statures, and PEs were relatively low, with median |%PEs| of 2.1 or less and mean PEs between -0.4 and 1.4 cm. Particularly compared with prediction errors from other widely-used or South Asia-specific equations, the errors were low and bias minimal. While further testing of our equations on a wider geographical range and on females is highly desirable, the results are very promising.

While Trotter and Gleser's equations have been often used for South Asian material, our results suggest that they substantially overestimate stature in such populations, particularly if using the American White equations. The tibia equation performs particularly poorly, consistent with previous reports (Jantz et al., 1994, 1995) that the tibia measurements used to derive these equations excluded the medial malleolus, even though the original paper describes the measurement as including the medial malleolus. Hence the Trotter and Gleser tibia equations are known to substantially overestimate stature (Jantz et al., 1994, 1995), consistent with our findings. Thus our results indicate that the Trotter and Gleser equations, especially those based on the tibia, are unsuitable for estimating stature from South Asian skeletons. Our results also suggest equations derived for ancient Egyptians by Raxter et al. (2008) perform better than those of Trotter and Gleser, and only slightly worse than our new equations. This is consistent with Lukacs et al.'s (2014) argument that the Egyptian equations were more suitable for south Asians, based on similarities in limb proportions, and supports the utility of comparing intra-limb proportions between reference and study data sets to select the most appropriate equations (e.g., Auerbach and Ruff, 2004).

In general, our equations performed more poorly for Nat's (1931) dataset when based on the tibia, and to a lesser extent, the ulna. This may reflect differences in body size and proportions between the datasets. The APCAPS males are both taller and have relatively longer distal limb segments relative to proximal segments. As Nat's data are historical (Individuals who died in the early 20th century), this may reflect the effects of secular change in body size that occurs disproportionately through increases in total limb length and particularly distal limb segment length (Bogin and Rios, 2003; Jantz et al., 2016; Meadows and Jantz, 1995). In contemporary India, stature is greater in the western and southern regions (including Hyderabad) than in the centre (including Uttar Pradesh), although the difference is less than 1 cm (Shome et al., 2014). Nonetheless, geographic differences may also contribute to some of the discrepancies.

Given known variation in stature and body proportions among populations inhabiting the vast Indian subcontinent, which may include climatic, genetic, developmental and temporal components (Deaton, 2008; Lukacs et al., 2014; Meshram et al., 2014; Perkins et al., 2011; Shome et al., 2014; Siddiqui and Shah, 1944), it is highly probable that no single set of equations will be appropriate for the whole region (Nat, 1931; Nath and Badkur, 2002; Pan, 1924). Rather, as others have advocated (Auerbach and Ruff, 2010) it may be that a set of equations for different populations from South Asia need to be derived, and the most appropriate for a given sample can then be selected based on similarity in limb proportions. A number of large epidemiological studies exist in India (and indeed worldwide) and are collecting DXA or other clinical images that could be used for this purpose. While there are some limitations to using DXA measurements in this way (discussed further below), these may be outweighed by the potential to analyse new datasets from South Asia and other worldwide populations, resulting from the increasing application of DXA in large samples.

Comparing the equations produced using OLS, RMA and robust regression models, there was no clear indication that one performed better than the others in terms of the errors associated with the regression models, or the results from applying them to Nat's (1931) dataset. The advantages and disadvantages of the various regression models have been discussed previously (Hens et al., 2000; Konigsberg et al., 1998; Pablos et al., 2013; Ruff et al., 2012; Sierp and Henneberg, 2016; Sjøvold, 1990; Smith, 2009), and while OLS is criticized for underestimating tall statures and overestimating short statures, the RMA and robust equations did not perform noticeably better in this respect. In fact the RMA equations gave more significant differences between measured and estimated statures in Nat's (1931) dataset, although the correlations between stature and prediction errors were not significant for the RMA humerus and ulna equations, indicating that unlike most of our other equations, the pattern of overestimated statures for shorter individuals and underestimated statures for taller individuals was not a problem.

Based on the model SEEs and PEs for both the original and test datasets, we would recommend using the OLS equations (Table 7) for skeletons from South Asia, except where individuals are taller or shorter than the sample we used to derive the equations, in which case the RMA equations are more appropriate (Aiello, 1992; Konigsberg et al., 1998). If multiple bones are measureable for a single individual, equations with the smallest SEEs (i.e. the femur and tibia equation, followed by other lower limb equations) should be used preferentially to minimize associated errors (Brothwell and Zakrzewski, 2004). If the statures of specific individuals are required, the RMA equations for the ulna or humerus do not systematically over- or underestimate stature for shorter and taller individuals respectively and so may be preferred. Where sample means are of interest, these tendencies should cancel out where mean stature is similar to that of the reference sample.

[TABLE 7 HERE]

It should be noted that while intra-observer error rates for bone measurements from DXA were low, inter-observer error rates were rather high (5- 8 mm for some bones), which may add error to the equations derived from them. Further work to define measurement locations more clearly, the averaging of measurements from multiple observers, and/or the use of higher-resolution scans when they become available, would help to reduce this error. A further caveat for using DXA scans to derive long bone measurements is the possibility of “out of plane” effects on the bone length measurements (Ruff, Raxter and Auerbach, 2012). If the bone is not completely parallel to the X-Ray detector, which it may not be in a living person due to soft tissue or joint flexion during the scan, this might lead to overestimated measurements. We are unaware of any data concerning the magnitude of such effects, but this potential issue deserves investigation and quantification. Another limitation of the DXA-based approach to developing stature estimation equations is that, at least in this sample, we were unable to derive equations based on the radius, since the ends of the bone were not clear enough in the DXA images. Furthermore the measurement technique for the tibia differed slightly from standard osteological definitions. However we anticipate this should make only a small difference to the measurements and estimated stature considering other limitations (e.g., image resolution, “out of plane” effects).

Another factor worth consideration is that bones typically shrink slightly as they dry out. While this is only likely to have a minor effect on the results, given the resolution of the images and the fact that even the femur, the longest bone measured here, shows a difference of about 3 mm between maceration (cartilage already removed) and the dry state (Ingalls, 1927), this may also affect the accuracy of stature estimates from dry bone based on our equations.

In conclusion, the results of this study provide new equations for estimating stature from skeletons of South Asian ancestry that have associated errors that are comparable with those produced for other populations and using other sources of reference data. These results also demonstrate the potential of DXA scans as a source of skeletal measurements for use in paleoanthropological and forensic research. Given the large size of many epidemiological databases and their existence across all major regions of the world, such datasets offer an important new source of data on the relationships between skeletal morphology and soft-tissue phenotype, as well as their relationship to environmental and other variables collected in such databases.

ACKNOWLEDGEMENTS

We gratefully acknowledge funding from a British Academy International Partnership and Mobility Scheme Grant to EP and VM, and a Leverhulme Trust/Isaac Newton Trust Early Career Fellowship to EP. The third survey wave of APCAPS data collection was supported by a Wellcome Trust Strategic Award (Grant No. 084774) and subsidized access to DXA scan facilities given by the National Institute of Nutrition (Directors), Indian Council for Medical Research. Thanks to Minxuan Dong for writing the Hologic P Reader plugin for ImageJ, and to Dr Neil Dong, University of Texas at Tyler, USA, for very kindly making this available to us. Thanks also to Ms K Usha Rani the APCAPS fieldwork team led by Ms Santhi Bhogadi and the National Institute of Nutrition, Hyderabad, for assisting with data access and to Niraj Rai the Centre for Cellular and Molecular Biology, Hyderabad, for logistical support. We would like to thank the Associate Editor and two anonymous reviewers for their thoughtful feedback that helped to significantly improve the manuscript.

LITERATURE CITED

Aiello, L. C. 1992. Allometry and the analysis of size and shape in human evolution. *J. Hum. Evol.* 22, 127-147.

Altman, D. G., & Bland, J. M. 1983. Measurement in medicine: The analysis of method comparison studies. *The Statistician* 32, 307-317.

Athawale, M. C. 1963. Estimation of height from lengths of forearm bones. A study of one hundred Maharashtrian male adults of ages between twenty-five and thirty years. *Am. J. Phys. Anthropol.* 21, 105-112.

Auerbach, B. M. 2011. Methods for estimating missing human skeletal element osteometric dimensions employed in the revised fully technique for estimating stature. *Am. J. Phys. Anthropol.* 145, 67-80

Auerbach, B. M., & Ruff, C. B. 2004. Human body mass estimation: A comparison of "morphometric" and "mechanical" methods. *Am. J. Phys. Anthropol.* 125, 331-342.

Auerbach, B. M., & Ruff, C. B. 2010. Stature estimation formulae for indigenous North American populations. *Am. J. Phys. Anthropol.* 141, 190-207.

Béguelin, M. 2011. Stature estimation in a central Patagonian prehispanic population: Development of new models considering specific body proportions. *Int. J. Osteoarchaeol.* 21, 150-158.

Bogin, B., & Rios, L. 2003. Rapid morphological change in living humans: Implications for modern human origins. *Comp. Biochem. Physiol. A Mol. Integr. Physiol*. 136, 71-84.

Bräuer, G. 1988. Osteometrie. In: Knussman, R., editor. *Anthropologie: Handbuch der vergleichenden biologie des menchen* (pp. 160-232). Stuttgart: Gustav Fisher.

Brothwell, D., & Zakrzewski, S. 2004. Metric and non-metric studies of archaeological human bone. In: Brickley, M., and McKinley, J. I., editors. *Guidelines to the standards for recording human remains* (pp. 27-33): BABAO/IFA.

Chinappen-Horsley, U., Blake, G. M., Fogelman, I., & Spector, T. D. 2007. A method for determining skeletal lengths from DXA images. *BMC Musculoskelet. Disord.* 8, 113.

Clark, E., Ness, A., & Tobias, J. 2007. Gender differences in the ratio between humerus width and length are established prior to puberty. *Osteoporos. Int.* 18, 463-470.

Deaton, A. 2008. Height, health, and inequality: The distribution of adult heights in India. *Am. Econ. Rev.* 98, 468-474.

Durband, A. C., Hill, E. C., & Walshe, K. 2016. Revised stature estimations for individuals from Roonka, South Australia. *Australian Archaeol.* 82, 139-147.

Dwight, T. 1894. Methods of estimating the height from parts of the skeleton. *Medical Record* 46, 293-296.

Feldesman, M. R., & Fountain, R. L. 1996. ''Race'' specificity and the femur/stature ratio. *Am. J. Phys. Anthropol.* 100, 207-224.

Fully, G. 1956. Une nouvelle méthode de détermination de la taille. *Ann. Med. Leg.* 35, 266-273.

Fully, G., & Pineau, H. 1960. Détermination de la stature au moyen du squelette. *Ann. Med. Leg.* 40, 145-154.

Genovés, S. 1967. Proportionality of the long bones and their relation to stature among Mesoamericans. *Am. J. Phys. Anthropol.* 26, 67-77.

Gray, D. S., Crider, J. B., Kelley, C., & Dickinson, L.C. 1985. Accuracy of recumbent height measurement. *J. Parenter. Enteral Nutr.* 9, 712-715.

Gocha, T. P., Vercellotti, G., McCormick, L. E., & Van Deest, T. L. 2013. Formulae for estimating skeletal height in modern south-east Asians. *J. Forensic Sci.* 58, 1279-1283.

Hens, S. M., Konigsberg, L. W., & Jungers, W. L. 2000. Estimating stature in fossil hominids: Which regression model and reference sample to use? *J. Hum. Evol.* 38, 767-784.

Holliday, T. W., & Ruff, C. B. 1997. Ecogeographical patterning and stature prediction in fossil hominids: Comment on M.R. Feldesman and R.L. Fountain, American Journal of Physical Anthropology (1996) 100:207-224. *Am. J. Phys. Anthropol.* 103, 137-140.

Ingalls, N. W. 1927. Studies on the femur. III. The effects of maceration and drying in the White and Negro. *Am. J. Phys. Anthropol.* 10, 297-321.

Jantz, R. L., Hunt, D. R., & Meadows, L. 1994. Maximum length of the tibia: How did Trotter measure it? *Am. J. Phys. Anthropol.* 93, 525-528.

Jantz, R. L., Hunt, D. R., & Meadows, L. 1995. The measure and mismeasure of the tibia: implications for stature estimation. *J. Forensic Sci.* 40, 758-761.

Jantz, R. L., Jantz, L. M., & Devlin, J. L. 2016. Secular changes in the postcranial skeleton of American whites. *Hum. Biol.* 88, 65-75.

Kate, B. R., & Mujumdar, R. D. 1976. Stature estimation from femur and humerus by regression and autometry. *Acta Anatomica* 94, 311-320.

Katzmarzyk, P. T., & Leonard, W. R. 1998. Climatic influences on human body size and proportions: Ecological adaptations and secular trends. *Am. J. Phys. Anthropol.* 106, 483-503.

Kinra, S., Radha Krishna, K., Kuper, H., Rameshwar Sarma, K., Prabhakaran, P., Gupta, V., Walia, G. K., Bhogadi, S., Kulkarni, B., Kumar, A., Aggarwal, A., Gupta, R., Prabhakaran, D., Reddy, K. S., Davey Smith, G., Ben-Shlomo, Y., & Ebrahim, S. 2014. Cohort profile: Andhra Pradesh Children and Parents Study (APCAPS). *Int. J. Epidemiol.* 43(5), 1417-1424.

Kolte, P., & Bansal, P. 1974. Determination of regression formulae for reconstruction of stature from long bones of upper limb in Maharashtrians of Marathwada region. *J. Anat. Soc. India* 23, 6-11.

Konigsberg, L. W., Hens, S. M., Jantz, L. M., & Jungers, W. L. 1998. Stature estimation and calibration: Bayesian and maximum likelihood perspectives in physical anthropology. *Yrbk. Phys. Anthropol.* 41, 65-92.

Kumar, M. A., & Reddy, C. K. 2016. Anthropometric study of femur in Krishna district of AP. *Scholars J. Appl. Med. Sci.* 4, 3822-3825.

Lukacs, J. R., Pal, J. N., & Nelson, G. C. 2014. Stature in Holocene foragers of north India. *Am. J. Phys. Anthropol.* 153, 408-416.

Lundy, J. K. 1985. The mathematical versus anatomical methods of stature estimation from long bones. *Am. J. Forensic Med. Pathol.* 6, 73-76.

Maijanen, H., & Niskanen, M. 2010. New regression equations for stature estimation for medieval Scandinavians. *Int. J. Osteoarchaeol.* 20, 472-480.

Manouvrier, M. 1893. La détermination de la taille d'aprés les grands os des membres. *Bull. Mem. Soc. Anthropol. Paris* 4, 347-402.

Martin, R., & Saller, K. 1957. *Lehrbuch der anthropologie*. Stuttgart: Fischer.

Meadows, L., & Jantz, R. L. 1995. Allometric secular change in the long bones from the 1800s to the present. *J. Forensic Sci.* 40, 762-767.

Meshram, M. M., Rahule, A. S., & Bashir, M. 2014. Stature estimation from the length of humerus in Vidarbha region of Maharashtra. *Medico-Legal Update* 14, 127.

Nat, B. S. 1931. Estimation of stature from long bones in Indians of the united provinces: A medico-legal inquiry in anthropometry. *Indian J. Med. Res.* 18, 1245-1253.

Nath, S., & Badkur, P. 2002. Reconstruction of stature from long bone lengths. *The Anthropologist* Special Issue 1, 109-114.

Pablos, A., Gómez-Olivencia, A., García-Pérez, A., Martínez, I., Lorenzo, C., & Arsuaga, J. L. 2013. From toe to head: Use of robust regression methods in stature estimation based on foot remains. *Forensic Sci. Int.* 226: 299, e1 - e7.

Palmer, C. E. 1932. The relationship of erect body length to supine body length. *Hum. Biol.* 4, 262-271.

Pan, N. 1924. Length of long bones and their proportion to body height in Hindus. *J. Anat.* 58, 374-378.

Patil, T. L., Gawhale, K. S., & Muzumdar, R. D. 1983. Reconstruction of stature from long bones of both upper and lower limbs. *J. Anat. Soc. India* 32, 111-118.

Pearson, K. 1899. Mathematical contributions to the theory of evolution. V. On the reconstruction of the stature of prehistoric races. *Proc. R. Soc. Lond. B Biol. Sci. A Math. Phys. Sci.* 192, 169-244.

Perkins, J. M., Khan, K. T., Smith, G. D., & Subramanian, S. V. 2011. Patterns and trends of adult height in India in 2005–2006. *Econ. Hum. Biol.* 9, 184-193.

Pomeroy, E., & Stock, J. T. 2012. Estimation of stature and body mass from the skeleton among coastal and mid-altitude Andean populations. *Am. J. Phys. Anthropol.* 147, 264-279.

R Core Team. 2016. R: A language and environment for statistical computing. Vienna, Austria: https://www.R-project.org/: R Foundation for Statistical Computing.

Rasband, W. S. 1997-2016. ImageJ. Bethesda, Maryland, USA: U.S. National Institutes of Health, http://imagej.nih.gov/ij/.

Raxter, M. H., Auerbach, B. M., & Ruff, C. B. 2006. Revision of the Fully technique for estimating statures. *Am. J. Phys. Anthropol.* 130, 374-384.

Raxter, M. H., Ruff, C. B., & Auerbach, B. M. 2007. Technical note: Revised Fully stature estimation technique. *Am. J. Phys. Anthropol.* 133, 817-818.

Raxter, M. H., Ruff, C. B., Azab, A., Erfan, M., Soliman, M., & El-Sawaf, A. 2008. Stature estimation in ancient Egyptians: A new technique based on anatomical reconstruction of stature. *Am. J. Phys. Anthropol.* 136, 147-155.

Roberts, D. F. 1978. *Climate and human variability*. Menlo Park, CA: Cummings.

Ruff, C. 2002. Variation in human body size and shape. *Ann. Rev. Anthropol.* 31, 211-232.

Ruff, C. B., Holt, B. M., Niskanen, M., Sladék, V., Berner, M., Garofalo, E., Garvin, H. M., Hora, M., Maijanen, H., Niinimäki, S., Salo, K., Schuplerová, E., & Tompkins, D. 2012. Stature and body mass estimation from skeletal remains in the European Holocene. *Am. J. Phys. Anthropol.* 148, 601-617.

Ruff, C.B., Niskanen, M., Junno, J.-A., & Jamison, P. 2005. Body mass prediction from stature and bi-iliac breadth in two high latitude populations, with application to earlier higher latitude humans. *J. Hum. Evol.* 48, 381-392.

Ruff, C.B., Raxter, M.H., & Auerbach, B.M. 2012. Comment on Bidmos and Manger, “New soft tissue correction factors for stature estimation: Results from magnetic resonance imaging” [Forensic Sci. Int. 214 (2012) 212.e1–212.e7]. *Forensic Sci. Int.* 222: e42-e43.

Ruff, C. B., Scott, W. W., & Liu, A. Y. 1991. Articular and diaphyseal remodeling of the proximal femur with changes in body mass in adults. *Am. J. Phys. Anthropol.* 86, 397-413.

Shome, S., Roy, P., Pal, M., & Bharati, P. 2014. Variation of adult heights and weights in India: State & zonewise analysis. *Hum. Biol. Rev.* 3, 242-257.

Siddiqui, M. A. H., & Shah, M. A. 1944. Estimation of stature from long bones of Punjabis. *Indian J. Med. Res.* 32, 105-108.

Sierp, I., & Henneberg, M. 2016. Reconstruction of body height from the skeleton: Testing a dozen different methods for consistency of their results. *Anthropol. Anz.* 73, 7-21.

Sjøvold, T. 1990. Estimation of stature from long bones utilizing the line of organic correlation. *Hum. Evol.* 5, 431-447.

Smith, R. J. 1984. Allometric scaling in comparative biology: Problems of concept and method. *Am. J. Physiol. Regul. Integr. Comp. Physiol.* 246, R152-R160.

Smith, R. J. 2002. Estimation of body mass in paleontology. *J. Hum. Evol.* 43, 271-287.

Smith, R. J. 2009. Use and misuse of the reduced major axis for line-fitting. *Am. J. Phys. Anthropol.* 140, 476-486.

Stevenson, P. H. 1929. On racial differences in stature long bone regression formulae, with special reference to stature reconstruction formulae for the Chinese. *Biometrika* 21, 303-321.

Trinkaus, E. 1981. Neanderthal limb proportions and cold adaptation. In: Stringer, C. B., editor. *Aspects of human evolution* (pp. 187-224). London: Taylor and Francis.

Trotter, M. 1970. Estimation of stature from intact long bones. In: Stewart, T. D., editor. *Personal identification in mass disasters* (pp. 71-83). Washington: Smithsonian Institution.

Trotter, M., & Gleser, G. C. 1952. Estimation of stature from long bones of American Whites and Negroes. *Am. J. Phys. Anthropol.* 10, 463-514.

Trotter, M., & Gleser, G. C. 1958. A re-evaluation of estimation of stature based on measurements of stature taken during life and of long bones after death. *Am. J. Phys. Anthropol.* 16, 79-123.

Trotter, M., & Gleser, G. C. 1977. Corrigenda to "Estimation of stature from long limb bones of American Whites and Negroes," American Journal Physical Anthropology (1952). *Am. J. Phys. Anthropol.* 47, 355-356.

Ulijaszek, S. J., & J. A. Lourie. 1994. Intra- and inter-observer error in anthropometric measurement. In: Ulijaszek, S. J., & Mascie-Taylor, C. G. N. editors. *Anthropometry: The Individual and the Population* (pp. 30-55). Cambridge: Cambridge University Press.

Venables, W. N., & Ripley, B. D. 2002. *Modern applied statistics with S*. New York: Springer.

Table 1. Intra- and inter-observer reliability statistics for bone length measurements derived from whole body DXA scans. TEM = Technical error of measurement, R = coefficient of reliability.

Bone	Side	Intra-observer			Inter-observer		
		TEM (mm)	%TEM	R	TEM (mm)	%TEM	R
Humerus	R	1.7	0.6	0.99	5.3	1.8	0.93
	L	2.4	0.8	0.99	5.3	1.8	0.93
Ulna	R	2.0	0.8	0.99	6.1	2.4	0.88
	L	2.4	0.9	0.99	5.5	2.2	0.91
Femur	R	2.2	0.5	1.00	6.1	1.4	0.96
	L	2.8	0.7	0.99	6.6	1.5	0.95
Tibia	R	2.0	0.6	1.00	5.3	1.5	0.95
	L	1.8	0.5	1.00	5.7	1.6	0.94
Fibula	R	3.3	0.9	1.00	8.1	2.3	0.89
	L	2.3	0.3	1.00	7.4	2.1	0.90

Table 2. Summary statistics on age, height and bone measurements of the study sample. Min. = minimum, Max. = Maximum. XLH = maximum humerus length; XLU = maximum ulna length; BLF = Bicondylar femur length; XLF = maximum femur length (estimated from bicondylar femur length for Nat's dataset as described in the text); CLT = complete tibia length; XLFi = maximum fibula length.

Variable	Females					Males					Nat (1931) Upper limb					Nat (1931) Lower limb				
	N	**Mean**	**SD**	**Min.**	**Max.**	**N**	**Mean**	**SD**	**Min.**	**Max.**	**N**	**Mean**	**SD**	**Min.**	**Max.**	**N**	**Mean**	**SD**	**Min.**	**Max.**
Age	78	23	1.36	20	26	78	22.5	1.29	20	25										
Height	78	153.9	6.47	138	166	78	166.9	6.64	147	180	50	163.5	6.4	150.5	173.9	40	160.6	8.14	147.4	174.7
XLH	78	278	13.68	247	311	78	303.8	15.39	268	332	50	306.2	14.5	274	334					
XLU	77	236.2	12.48	202	264	78	259.6	12.73	224	290	50	258.0	12.8	223	280					
Ulna/Humerus ratio	77	84.9	3.03	78.4	92.5	78	85.5	2.94	78.3	91.8	50	84.3	2.42	79.1	90.6					
XLF*	78	405.8	20.81	353	456	78	445.1	22.54	379	491						40	437.4	22.4	393	478
CLT	78	345.1	19.09	290	391	78	372.5	19.87	318	431						40	359.6	29.1	317	387
XLFi	78	337.9	18.15	289	387	77	366.9	19.5	308	421						40	358.4	18.4	309	385
Tibia/Femur ratio	78	85.1	2.1	79.5	88.7	78	83.7	2.07	79.7	88.4						40	82.2	1.65	77.1	85.4

Table 3. OLS regression equations for stature estimation. Bone measurements are in mm. SEE = standard error of estimate, PE = prediction error (observed – predicted stature). All models and terms in the models significant at $p < 0.001$. XLH = maximum humerus length; XLU = maximum ulna length; XLF = maximum femur length; CLT = complete tibia length; XLFi = maximum fibula length.

Estimate based on	Sex	Equation: Stature (cm) =	Adjusted R^2	SEE (cm)	%SEE	Mean (minimum, maximum) PE (cm)	Mean (minimum, maximum) %PE	Median |%PE|
Humerus	Female	48.850 + 0.365 * XLH	0.63	3.9	2.5	0.0 (-12.1, 9.1)	0.0 (-7.7, 5.9)	1.8
	Male	58.953 + 0.343 * XLH	0.67	3.8	2.3	0.0 (-8.3, 8.1)	0.0 (-5.3, 4.8)	1.5
Ulna	Female	62.523 + 0.375 * XLU	0.58	4.1	2.7	0.0 (-8.7, 10.0)	0.0 (-5.6, 6.5)	1.9
	Male	56.701 + 0.410 * XLU	0.66	3.9	2.3	0.0 (-8.7, 8.2)	0.0 (-5.1, 4.8)	1.6
Femur	Female	42.384 + 0.266 * XLF	0.78	3.1	2.0	0.0 (-8.9, 8.1)	0.0 (-6.0, 5.5)	1.1
	Male	51.482 + 0.251 * XLF	0.77	3.2	1.9	0.0 (-6.5, 7.6)	0.0 (-3.9, 4.6)	1.3
Tibia	Female	51.880 + 0.286 * CLT	0.87	3.2	2.1	0.0 (-7.4, 8.8)	0.0 (-4.9, 5.7)	1.3
	Male	53.516 + 0.294 * CLT	0.83	2.8	1.6	0.0 (-7.8, 6.0)	0.0 (-4.6, 3.5)	1.2
Fibula	Female	47.510 + 0.304 * XLFi	0.78	3.1	2.0	0.0 (-7.4, 9.0)	0.0 (-4.4, 5.8)	1.4
	Male	52.744 + 0.301 * XLFi	0.82	2.8	1.7	0.0 (-8.4, 7.0)	0.0 (-4.9, 4.0)	1.0
Femur + Tibia	Female	40.796 + 0.157 * XL F + 0.133 * CLT	0.81	2.8	1.8	0.0 (-7.1, 7.4)	0.0 (-4.8, 5.0)	1.0
	Male	46.462 + 0.097 * XLF + 0.196 * CLT	0.85	2.6	1.5	0.0 (-6.3, 5.9)	0.0 (-3.7, 3.4)	0.9

Table 4. RMA regression equations for stature estimation. Bone measurements are in mm. SEE = standard error of estimate, PE = prediction error (observed – predicted stature). All models and terms in the models significant at p<0.001.XLH = maximum humerus length; XLU = maximum ulna length; XLF = maximum femur length; CLT = complete tibia length; XLFi = maximum fibula length.

Estimate based on	**Sex**	**Equation: Stature (cm) =**	**SEE (cm)**	**%SEE**	**Mean (minimum, maximum) PE (cm)**	**Mean (minimum, maximum) %PE**	**Median |%PE|**
Humerus	Female	34.550 + 0.489 * XLH	4.1	2.5	0.0 (-13.2, 9.0)	0.0 (-8.3, 5.9)	1.8
	Male	35.872 + 0.417 * XLH	4.0	2.4	0.0 (-8.4, 7.9)	0.0 (-4.8, 4.8)	1.4
Ulna	Female	34.550 + 0.489 * XLU	4.3	2.7	0.0 (-8.9, 11.8)	0.0 (-5.8, 8.3)	1.7
	Male	31.558 + 0.504 * XLU	4.0	2.5	0.0 (-9.6, 8.3)	0.0 (-5.6, 5.1)	1.5
Femur	Female	27.677 + 0.301 * XLF	3.1	1.9	0.0 (-8.3, 8.9)	0.0 (-5.6, 6.0)	1.3
	Male	35.873 + 0.284 * XLF	3.2	2.0	0.0 (-7.0, 7.7)	0.0 (-4.0, 4.6)	1.2
Tibia	Female	36.870 + 0.328 * CLT	3.3	2.0	0.0 (-7.5, 8.8)	0.0 (-4.6, 5.7)	1.4
	Male	42.451 + 0.323 * CLT	2.8	1.7	0.0 (-8.2, 5.7)	0.0 (-4.8, 3.5)	1.3
Fibula	Female	33.385 + 0.345 * XLFi	3.1	1.9	0.0 (-7.6, 8.8)	0.0 (-4.6, 5.7)	1.4
	Male	41.354 + 0.331 * XLFi	2.8	1.7	0.0 (-8.8, 6.4)	0.0 (-5.1, 3.7)	1.0

Table 5. Robust regression equations for stature estimation. Bone measurements are in mm. SEE = standard error of estimate, PE = prediction error (observed – predicted stature). All models and terms in the models significant at $p < 0.001$. XLH = maximum humerus length; XLU = maximum ulna length; XLF = maximum femur length; CLT = complete tibia length; XLFi = maximum fibula length.

Estimate based on	Sex	Equation: Stature (cm) =	SEE (cm)	%SEE	Mean (minimum, maximum) PE (cm)	Mean (minimum, maximum) %PE	Median |%PE|
Humerus	Female	47.426 + 0.370 * XLH	3.9	4.1	-0.1 (-12.2, 9.0)	0.0 (-7.7, 5.8)	1.8
	Male	60.298 + 0.339 * XLH	3.7	3.8	-0.1 (-8.5, 8.1)	0.0 (-5.5, 4.8)	1.6
Ulna	Female	58.999 + 0.388 * XLU	4.1	2.0	0.2 (-8.5, 10.2)	0.1 (-5.5, 6.7)	1.9
	Male	56.495 + 0.411 * XLU	3.9	2.3	0.1 (-8.6, 8.2)	0.1 (-5.1, 4.9)	1.6
Femur	Female	41.781 + 0.267 * XLF	3.1	2.1	-0.1 (-9.0, 8.0)	-0.1 (-6.0, 5.4)	1.1
	Male	51.285 + 0.251 * XLF	3.2	1.9	0.2 (-6.4, 7.8)	0.1 (-3.8, 4.7)	1.2
Tibia	Female	52.002 + 0.285 * CLT	3.2	2.0	0.0 (-7.4, 8.9)	0.0 (-4.9, 5.7)	1.3
	Male	53.037 + 0.295 * CLT	2.8	1.6	0.0 (-7.9, 5.9)	0.0 (-4.6, 3.4)	1.2
Fibula	Female	45.944 + 0.309 * XLFi	3.1	2.0	0.1 (-7.6, 9.0)	0.0 (-4.5, 5.8)	1.4
	Male	54.062 + 0.297 * XLFi	2.7	1.6	0.0 (-8.3, 7.0)	0.0 (-4.9, 4.1)	1.1
Femur + tibia	Sex	39.514 + 0.160 * XLF + 0.133 * CLT	2.8	1.8	0.0 (-7.1, 7.5)	0.0 (-4.8, 5.1)	1.0
	Female	46.824 + 0.095 * XLF + 0.197 * CLT	2.5	1.5	0.0 (-6.2, 5.9)	0.0 (-3.7, 3.4)	0.9

Table 6. Prediction errors using published stature estimation equations on Nat's (1931) dataset.

Estimate based on	Mean (minimum, maximum) PE (cm)	Mean (minimum, maximum) %PE	Median |%PE|	t-test p value	Correlation (estimate vs. PE)	
					r	p
Trotter and Gleser American White (Trotter 1970)						
Humerus	-1.2 (-8.9, 5.8)	-0.8 (-5.5, 3.6)	1.7	**0.02**	**0.56**	**<0.001**
Ulna	-6.0 (-14.3, 1.9)	-3.5 (-8.6, 1.2)	3.5	**<0.001**	**0.43**	**0.005**
Radius	-5.5 (-13.3, 1.1)	-3.2 (-8.1, 0.7)	3.2	**<0.001**	**0.44**	**0.004**
Humerus + Radius	-3.5 (-10.9, 2.2)	-2.1 (-6.7, 1.3)	2.0	**<0.001**	**0.51**	**<0.001**
Femur	-4.9 (-10.9, 0.4)	-3.0 (-6.7, 0.3)	2.7	**<0.001**	**0.85**	**<0.001**
Tibia *	-8.6 (-16.2, -0.9)	-5.1 (-9.7, -0.5)	4.7	**<0.001**	**0.81**	**<0.001**
Fibula	-7.2 (-14.7, 0.9)	-4.3 (-8.9, 0.5)	4.3	**<0.001**	**0.78**	**<0.001**
Femur + Tibia *	-6.3 (-12.9, -0.7)	-3.8 (-7.9, -0.4)	3.5	**<0.001**	**0.84**	**<0.001**
Femur + Fibula	-6.7 (-13.3, -0.8)	-4.0 (-8.1, -0.4)	3.9	**<0.001**	**0.83**	**<0.001**
Trotter and Gleser American Black (Trotter 1970)						
Humerus	-0.1 (-8.1, 6.7)	-0.1 (-5.1, 4.2)	1.8	0.8	**0.63**	**<0.001**
Ulna	0.1 (-8.6, 7.4)	0.1 (-5.4, 4.7)	2.1	0.8	**0.56**	**<0.001**
Radius	0.6 (-7.7, 6.7)	0.3 (-4.8, 4.2)	2.1	0.4	**0.54**	**<0.001**
Humerus + Ulna	-0.2 (-8.3, 5.8)	-0.2 (-5.2, 3.6)	1.7	0.7	**0.60**	**<0.001**
Humerus + Radius	0.1 (-7.7, 5.5)	0.1 (-4.9, 3.4)	1.8	0.8	**0.61**	**<0.001**
Femur	-3.5 (-9.9, 2.3)	-2.2 (-6.1, 1.4)	1.8	**<0.001**	**0.91**	**<0.001**
Tibia *	-4.1 (-12.0, 4.4)	-2.6 (-7.4, 2.6)	2.5	**<0.001**	**0.87**	**<0.001**
Fibula	-3.6 (-11.3, 4.5)	-2.2 (-7.0, 2.7)	2.7	**<0.001**	**0.84**	**<0.001**
Femur + Tibia *	-2.1 (-9.0, 4.5)	-1.3 (-5.6, 2.6)	2.1	**0.002**	**0.90**	**<0.001**
Femur + Fibula	-2.8 (-9.6, 3.4)	-1.8 (-6.0, 2.0)	2.0	**<0.001**	**0.88**	**<0.001**
Feldesman and Fountain (1996)						
Femur Generic	-1.6 (-6.7, 2.9)	-1.0 (-4.2, 1.7)	0.8	**<0.001**	**0.57**	**<0.001**
Femur '2 race' (White-Asian)	-2.8 (-8.1, 1.9)	-1.8 (-5.1, 1.1)	1.6	**<0.001**	**0.68**	**<0.001**
Femur '3 race' (Asian)	-2.5 (-7.6, 1.9)	-1.6 (-4.7, 1.1)	1.3	**<0.001**	**0.53**	**<0.001**

Table 6 Continued

Estimate based on	Mean (minimum, maximum) PE (cm)	Mean (minimum, maximum) %PE	Median |%PE|	t-test p value	Correlation (estimate vs. PE) r	p
Raxter et al. (2008)						
Humerus	0.3 (-8.1, - 6.8)	0.1 (-5.1, - 4.2)	2.0	0.6	**0.72**	**<0.001**
Ulna	-0.2 (-9.4, - 5.0)	-0.2 (-5.8, - 3.1)	2.5	0.7	**0.74**	**<0.001**
Radius	0.5 (-7.8, - 5.6)	0.3 (-4.9, - 3.5)	2.0	0.3	**0.72**	**<0.001**
Femur	-2.0 (-8.2, 3.5)	-1.3 (-5.2,- 2.1)	1.7	**<0.001**	**0.88**	**<0.001**
Tibia	-1.5 (-9.1,- 6.1)	-1.0 (-5.7,- 3.7)	2.3	**0.03**	**0.80**	**<0.001**
Femur + tibia	-1.7 (-8.4,- 4.0)	-1.1 (-5.3,- 2.4)	1.8	**0.004**	**0.85**	**>0.001**
Nath and Badkur (2002)						
Humerus	-1.5 (-11.5, 4.2)	-0.9 (-7.0, 2.5)	1.7	**0.04**	**0.93**	**<0.001**
Ulna	-1.8 (-12.4, 2.7)	-1.1 (-7.6, 1.7)	2.2	**0.02**	**0.93**	**<0.001**
Radius	-1.5 (-11.9, 2.9)	-0.9 (-7.3, 1.8)	2.1	**0.05**	**0.93**	**<0.001**
Femur	-5.3 (-12.5, 2.7)	-3.2 (-7.7, 1.6)	2.6	**<0.001**	**0.97**	**<0.001**
Tibia	-2.1 (-10.3, 7.4)	-1.4 (-6.4, 4.4)	2.5	**0.01**	**0.93**	**<0.001**
Fibula	-4.7 (-12.9, 4.8)	-2.9 (-7.8, 2.9)	2.7	**<0.001**	**0.92**	**<0.001**
Patil et al. (1983)						
Humerus	1.7 (-7.1, 8.1)	1.1 (-4.5, 5.0)	2.6	**0.004**	**0.79**	**<0.001**
Radius	-1.0 (-9.4, 5.0)	-0.6 (-5.9, 3.1)	2.0	0.1	**0.58**	**<0.001**
Ulna	-2.9 (-11.9, 4.0)	-1.7 (-7.3, 2.5)	1.9	**<0.001**	**0.61**	**<0.001**
Femur	-1.9 (-8.6, 4.5)	-1.2 (-5.4, 2.6)	2.4	**0.006**	**0.93**	**<0.001**
Tibia	-3.5 (-11.4, 4.8)	-2.2 (-7.0, 2.8)	2.7	**<0.001**	**0.86**	**<0.001**
Fibula	-4.9 (-12.8, 3.9)	-3.0 (-7.8, 2.3)	2.8	**<0.001**	**0.86**	**<0.001**
Kolte and Bansal (1974)						
Humerus	1.2 (-7.8, 7.4)	0.7 (-4.9, 4.6)	2.3	0.06	**0.81**	**<0.001**
Radius	1.6 (-6.8, 7.6)	1.0 (-4.3, 4.8)	2.2	**0.01**	**0.59**	**<0.001**
Ulna	1.2 (-7.7, 8.3)	0.7 (-4.8, 5.2)	2.2	0.07	**0.59**	**<0.001**

Table 6 Continued

Estimate based on	Mean (minimum, maximum) PE (cm)	Mean (minimum, maximum) %PE	Median |%PE|	t-test p value	Correlation (estimate vs. PE)	
					r	p
Other						
Kate and Mujumdar (1976) Humerus	1.2 (-5.7, 8.7)	0.8 (-3.6, 5.4)	1.7	**0.02**	**0.35**	**0.02**
Kate and Mujumdar (1976) Femur	-3.7 (-9.4, 1.3)	-2.3 (-5.9, 0.8)	2.1	**<0.001**	**0.79**	**<0.001**
Meshram et al. (2014) Humerus	7.4 (0.5, 14.8)	4.7 (0.3, 9.7)	4.7	**<0.001**	**0.35**	**0.02**
Kumar et al. (2016) Femur	-0.9 (-8.2, 7.1)	-0.6 (-5.1, 4.2)	2.7	0.3	**0.97**	**<0.001**

* Tibia measurements from Trotter and Gleser's various publications are known to overestimate stature do to misreporting of the method for measuring the tibia. This is discussed further in the body of the text.

Table 7. Recommended ordinary least squares regression equations for stature estimation from South Asian skeletons generated in this study, in order of preference (standard error of estimate). Bone measurements are in mm. SEE = standard error of estimate. XLH = maximum humerus length; XLU = maximum ulna length; XLF = maximum femur length; CLT = complete tibia length; XLFi = maximum fibula length.

Estimate based on	Equation: Stature (cm) =	SEE (cm)
Females		
Femur + Tibia	40.796 + 0.157 * XL F + 0.133 * CLT	2.8
Femur	42.384 + 0.266 * XLF	3.1
Fibula	47.510 + 0.304 * XLFi	3.1
Tibia	51.880 + 0.286 * CLT	3.2
Humerus	48.850 + 0.365 * XLH	3.9
Ulna	62.523 + 0.375 * XLU	4.1
Males		
Femur + Tibia	46.462 + 0.097 * XLF + 0.196 * CLT	2.6
Tibia	53.516 + 0.294 * CLT	2.8
Fibula	52.744 + 0.301 * XLFi	2.8
Femur	51.482 + 0.251 * XLF	3.2
Humerus	58.953 + 0.343 * XLH	3.8
Ulna	56.701 + 0.410 * XLU	3.9

Figure 1: Example whole body DXA image used in this study

Figure 2. Mean percent standard error of estimates (%SEE) and median percent prediction error (%PE) for regression equations derived using ordinary least squares (OLS), reduced major axis (RMA) and robust regression techniques for females (above) and males (below).

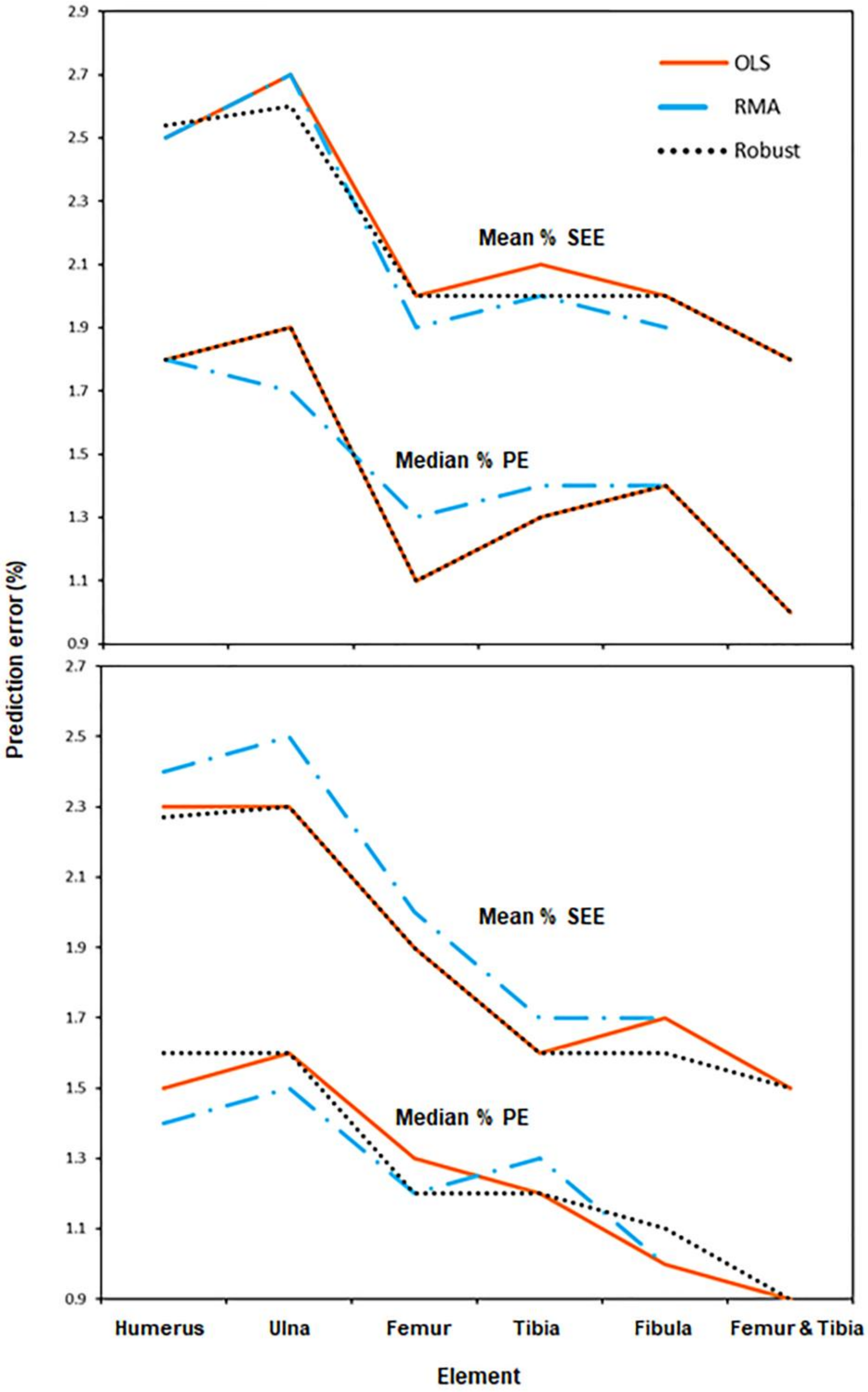
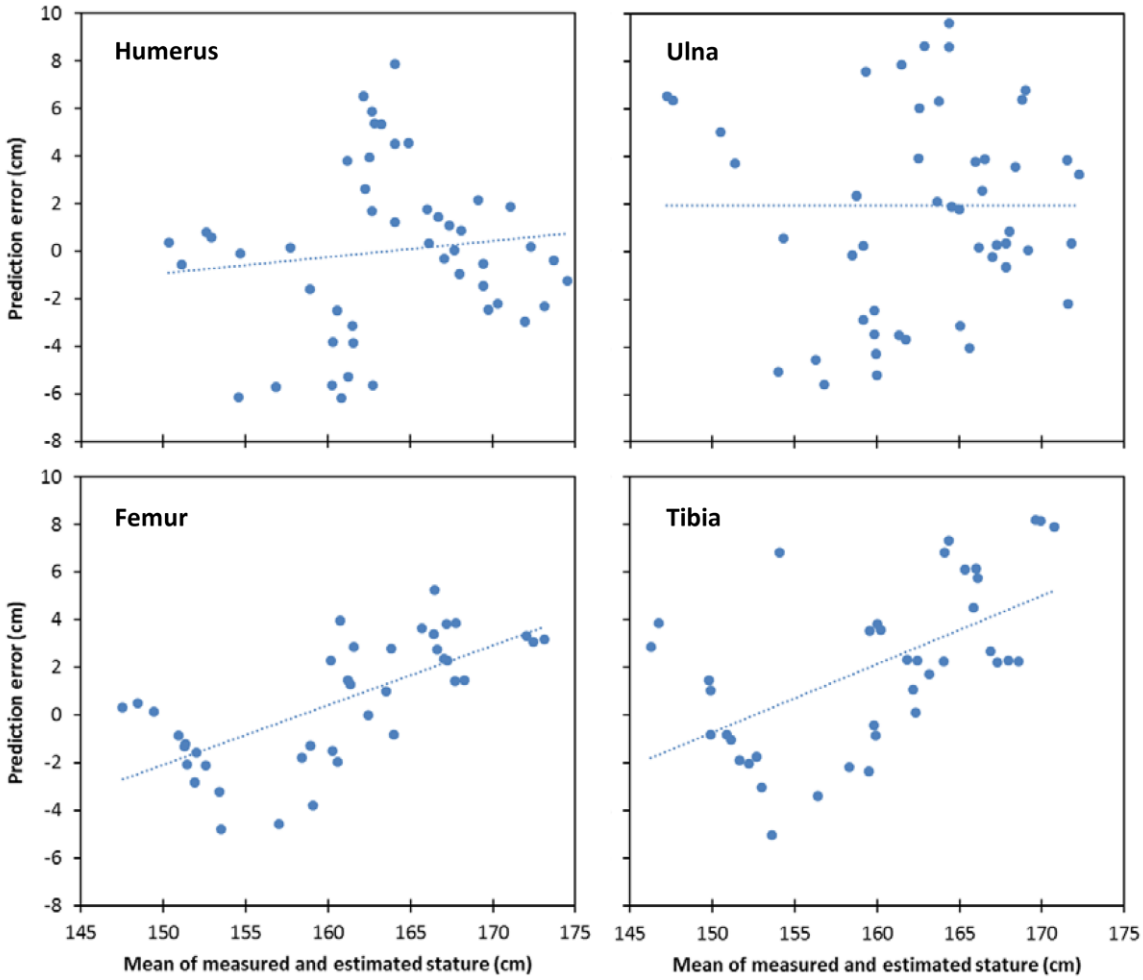


Figure 3. Example Bland-Altman plots of prediction error against true stature for RMA regression equations derived in this study when applied to data from Nat (1931).



Stature estimation equations for South Asian skeletons based on DXA scans of contemporary adults

Emma Pomeroy[1], Veena Mushrif-Tripathy[2], Jonathan C. K. Wells[3], Bharati Kulkarni[4], Sanjay Kinra[5] and Jay T. Stock[6]

[1] School of Natural Sciences and Psychology, Liverpool John Moores University, UK
[2] Deccan College Postgraduate and Research Institute, Pune, India
[3] UCL Great Ormond Street Institute of Child Health, UCL, UK
[4] National Institute of Nutrition, Hyderabad, India
[5] Department of Non-communicable Disease Epidemiology, London School of Hygiene and Tropical Medicine, London, UK
[6] ADaPt Project, PAVE Research Group, Department of Archaeology and Anthropology, University of Cambridge, UK

Supplementary Information

Supplementary Table 1. Prediction errors (PEs) from applying the ordinary least squares (OLS), reduced major axis (RMA) and robust regression equations in Tables 3-5 to males of known stature reported by Nat (1931), and p values for paired t-test comparing measured and estimated values. N = 50 for upper limb, 40 for lower limb. Bold indicates significant differences between the true and estimated statures by paired t-test or significant correlation between the estimate and prediction error (p < 0.05).

Estimate based on	Mean (minimum, maximum) PE (cm)	Mean (minimum, maximum) %PE	Median |%PE|	t-test p value	Correlation (mean of measured and estimated vs. PE)	
					r	p
OLS						
Humerus	-0.4 (-7.6, 6.8)	-0.2 (-4.8, 4.2)	1.4	0.4	**0.43**	**0.005**
Ulna	1.0 (-6.9, 9.6)	0.7 (-4.3, 6.1)	2.1	0.09	0.30	0.06
Femur	0.3 (-5.6, 5.4)	0.1 (-3.5, 3.3)	1.7	0.6	**0.78**	**<0.001**
Tibia	1.4 (-5.9, 8.2)	0.8 (-3.8, 4.9)	1.7	**0.02**	**0.69**	**<0.001**
Fibula	0.0 (-7.3, 7.5)	0.0 (-4.6, 4.5)	1.8	1.0	**0.69**	**<0.001**
Femur & tibia	1.3 (-5.3, 6.6)	0.7 (-3.4, 4.0)	1.6	**0.02**	**0.60**	**<0.001**
RMA						
Humerus	0.0 (-6.2, 7.9)	0.0 (-3.9, 4.9)	1.3	1.0	0.11	0.48
Ulna	1.9 (-5.6, 11.9)	1.2 (-3.5, 7.7)	2.3	**0.004**	0.00	1.0
Femur	0.5 (-4.8, 5.3)	0.3 (-3.1, 3.2)	1.4	0.2	**0.68**	**<0.001**
Tibia	2.0 (-5.0, 8.2)	1.3 (-3.2, 4.9)	1.5	**<0.001**	**0.57**	**<0.001**
Fibula	0.7 (-6.4, 7.6)	0.4 (-4.1, 4.5)	1.6	0.3	**0.58**	**<0.001**
Robust						
Humerus	-0.6 (-7.8, 6.7)	-0.3 (-4.9, 4.1)	1.5	0.3	**0.45**	**0.004**
Ulna	1.0 (-6.9, 9.5)	0.6 (-4.4, 6.1)	2.1	0.1	0.29	0.06
Femur	0.4 (-5.4, 5.6)	0.2 (-3.4, 3.4)	1.7	0.4	**0.82**	**<0.001**
Tibia	1.5 (-5.8, 8.3)	0.9 (-3.7, 5.0)	1.7	**0.01**	**0.68**	**<0.001**
Fibula	0.1 (-7.2, 7.7)	0.0 (-4.6, 4.6)	1.8	0.8	**0.70**	**<0.001**
Femur & tibia	1.4 (-5.2, 6.8)	0.8 (-3.3, 4.1)	1.7	**0.008**	**0.74**	**<0.001**