Methods for Estimating Missing Human Skeletal Element Osteometric Dimensions Employed in the Revised Fully Technique for Estimating Stature

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ABSTRACT One of the greatest limitations to the application of the revised Fully anatomical stature estimation method is the inability to measure some of the skeletal elements required in its calculation. These element dimensions cannot be obtained due to taphonomic factors, incomplete excavation, or disease processes, and result in missing data. This study examines methods of imputing these missing dimensions using observable Fully measurements from the skeleton and the accuracy of incorporating these missing element estimations into anatomical stature reconstruction. These are further assessed against stature estimations obtained from mathematical regression formulae for the lower limb bones (femur and tibia). Two thousand seven hundred and seventeen North and South American indigenous skeletons were measured, and subsets of these with observable Fully dimensions were used to simulate missing elements and create estimation methods and equations. Comparisons were made directly between anatomically reconstructed statures and mathematically derived statures, as well as with anatomically derived statures with imputed missing dimensions. These analyses demonstrate that, while mathematical stature estimations are more accurate, anatomical statures incorporating missing dimensions are not appreciably less accurate and are more precise. The anatomical stature estimation method using imputed missing dimensions is supported. Missing element estimation, however, is limited to the vertebral column (only when lumbar vertebrae are present) and to talocalcaneal height (only when femora and tibiae are present). Crania, entire vertebral columns, and femoral or tibial lengths cannot be reliably estimated. Further discussion of the applicability of these methods is discussed. Am J Phys Anthropol 145:67–80, 2011. ©2011 Wiley-Liss, Inc.

Recent studies (Raxter et al., 2006, 2007; Raxter et al., 2008; Auerbach and Ruff, 2010; Kurki et al., 2010) have demonstrated the utility of using Fully's (1956) anatomical method to estimate living stature from skeletal remains. In this estimation technique, the superoinferior dimensions of osteological elements contributing directly to stature are summed and a "soft tissue correction" is added to yield an approximation of living stature. Raxter et al. (2006) revisited the method as outlined by Fully, and made revisions and clarifications to the osteometric methods. In addition, Raxter et al. (2006, 2007) developed a new soft tissue correction that is continuous—as opposed to Fully's discrete correction—and accounts for stature decreases coinciding with older age.

Perhaps the greatest limitation to applying this method to skeletal remains, especially in archaeological samples, is the incidence of missing or nonmeasurable elements. There are a number of factors that contribute to the variability in preservation and use of archaeological human remains for research (Boddington, 1987; Henderson, 1987). Further discussion on the differential preservation of remains and the practical effects on sampling can be found in a number of other publications (e.g., Waldron, 1987; Galloway et al., 1996; Stojanowski et al., 2002). Even though it is statistically preferential to not estimate missing dimensions, using only the most complete skeletons artificially biases sample analyses to geographic regions where taphonomic conditions, cultural practices, and excavation techniques preserved skeletons in their entirety (Holt and Benfer, 2000). In the case of rare modern human samples of great antiquity (such as early Holocene samples), for example, the estimation of stature is often desired for comparability with other skeletons despite fragmentary preservation (e.g., Auerbach, in press). The researcher may either choose to limit analyses to only those measurements that were observable at the time of data collection, or estimate the measurements of the missing bones using the measurements from the available bones. The former choice is more statistically conservative, as the only error present is accountable measurement error, while the latter is subject to compounded error arising from measurement error in the estimator and estimation error arising from uncertainties in both the variance of the estimators and the criterion.

This article focuses on developing methods for the instances when missing element dimensions in the anatomical stature method must be estimated, as well as

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ascertaining the limitations in the use of these estimates. It also assesses the point where it is more conservative to estimate stature using mathematical (regression) methods instead of the anatomical method with estimated measurements. The study concludes with recommendations for the appropriate application of the Fully technique to samples not possessing all of the necessary elements.

Past methods

Despite the existence of a broad literature on imputing missing data, the accuracy, and utility of missing element measurement estimations employed in anatomical stature estimation have not been studied extensively. Fully and Pineau (1960) developed equations for the estimation of the total vertebral column length using regions of vertebrae. Lundy (1985) devised a method for estimating individual vertebral heights as a percentage of total vertebral column length, using all other vertebrae in the vertebral column as estimators. The downside of these two methods is their dependency on almost completely intact vertebral columns, which are infrequently or inconsistently available in archaeological samples, for use as a reference sample by which to estimate the missing regions or individual vertebrae. Sciulli et al. (1990), in developing regression equations for stature estimation, used archaeological skeletons missing nonadjacent vertebrae. They imputed these missing vertebral heights by averaging adjacent vertebrae, which yielded results comparable with those of Lundy (1985), but did not depend on completely intact vertebral regions.

Auerbach et al. (2005) developed missing element equations for estimating all revised Fully technique (Raxter et al., 2006) measurements on a limited sample of Terry Collection skeletons. These were tested by estimating simulated missing elements from known elements, followed by applying the revised Fully technique incorporating various combinations of estimated missing measurements. This article builds on the analyses developed by Auerbach et al. (2005) by employing a larger and more diverse sample, while also creating specific recommendations about the limitations of the employment of the anatomical stature estimation methods when elements are not measurable.

Estimating missing measurements

Several methods are available for approximating missing values when working with incomplete data (Allison, 2002; Little and Rubin, 2002). Asfaw et al. (1999), for example, utilized a multiple regression method to estimate missing long bone measurements for fragmentary remains. Another method was employed by Rhode and Arriaza (2006), in which the mean measurement of a dimension among observable cases in a sample was used as a “stand-in” for the missing measurement. In addition to these, modified expected maximization procedures (Schafer, 1997), bootstrapping of complete data (Little and Rubin, 2002), and various data exclusions based on listwise or pairwise deletions (Holt and Benfer, 2000) may be used. As noted above, however, this article relies on developing methods that directly estimate missing dimensions from known values, accounting for individual variation while minimizing effects that would increase the standard deviation of the estimated stature.

Alternative to the methods listed above, mathematical stature estimation methods based on regression formulae are often utilized with fragmentary remains because few skeletal elements are necessary. For example, estimations from long bone lengths have been commonly used (see Auerbach and Ruff, 2010), though the downside of this approach is that proportions are not always known for the samples under examination. As argued in various studies (Feldesman et al., 1990; Holliday, 1999; Auerbach and Ruff, 2004; Raxter et al., 2008; Auerbach and Ruff, 2010), the matching of body proportions (i.e., crural index and cormic index) between the reference sample and skeletons with statures to be estimated is crucial to ensure the highest possible accuracy. Different patterns of limb allometry, especially in hominins for which we have no complete skeletons, compounds this problem (Hens et al., 2000). It is therefore paramount in these studies to not *a priori* assume any of the proportions of the skeletons in a sample; special attention to this must be employed when predicting missing element measurements used in the anatomical stature estimations. Furthermore, as demonstrated by Raxter et al. (2006), the anatomical stature estimation methods are more accurate and precise than existing mathematical stature estimation techniques. It is therefore important to evaluate whether skeletal dimensions used in the revised Fully anatomical technique may be accurately estimated when missing, and when mathematical methods are statistically preferable for estimating statures from incomplete remains.

It is notable that any missing data imputations rely on criteria associated with data missing at random (e.g., data are not systematically missing because of relative fragility of the element under consideration) and with data missing independent of other factors (e.g., smaller bones or more gracile individuals will, by their nature, preserve fewer observable dimensions). Most bones missing in archaeological contexts are considered randomly occurring, as the various factors influencing their preservation, though predictable, come about by chance. Often, data missing under these circumstances are imputed using the mean measurement for the dimension within a sample. Yet, some elements are more likely to be missing due to size and bone density (Galloway et al., 1996), and therefore using sample means could artificially bias the “stand-in” measurements for missing data. Additionally, dimensions of limb elements—and possibly other bones in the Fully method—have positive allometry (Jantz and Jantz, 1999; Sylvester et al., 2008; Auerbach and Sylvester, in press). For these reasons, methods different than using sample means for the estimation of missing data values are developed in this study.

MATERIALS AND METHODS

Sample and incidence of missing data

The author attempted to measure revised Fully method dimensions from a total sample of 2,717 (1,484 males, 1,233 females) skeletons, representing 123 archaeological sites or aggregated sites from throughout the Holocene in the Americas (Table 1). All skeletons used in this study were adults, determined by complete epiphyseal closure of long bones, vertebrae, and os coxae. Age and sex estimations were determined using os coxae and cranial features (Brooks and Suchey, 1990; Bruzek, 2002; Buckberry and Chamberlain, 2002). Measurements were obtained using a portable osteometric board (accurate

TABLE 1. Total sample measured prior to exclusion due to supernumerary vertebrae (n = 2,717)

Site name[a]	Supplemental information number[b]	Site location[c]	Number measured (♂/♀)
Aleutian Islands (“Pre-Aleut”)	1	Alaska	29 (13/16)
Aleutian Islands (“Neo-Aleut”)	2	Alaska	60 (37/23)
Ikogmiut	3	Alaska	61 (30/31)
Kuskowagamiut	4	Alaska	28 (14/14)
Point Barrow	5	Alaska	29 (20/9)
Point Hope–Ipiutak	6	Alaska	35 (19/16)
Point Hope–Tigara	7	Alaska	44 (22/22)
Canyon del Muerto	8	Arizona	30 (18/12)
Carter Ranch	9	Arizona	16 (9/7)
Grasshopper	10	Arizona	48 (27/21)
Knishba	11	Arizona	25 (13/12)
Point of Pines	12	Arizona	10 (5/5)
Turkey Creek	13	Arizona	8 (4/4)
Pecan Point	14	Arkansas	3 (1/2)
Boytt’s Field	15	Arkansas	2 (2/0)
McClure Place	16	Arkansas	1 (0/1)
Rose, Potter Pl., Lauratown	17	Arkansas	17 (10/7)
Bear Creek & Jones sites	18	California	28 (15/13)
Blossom	19	California	39 (20/19)
Channel Islands (two groups)	20	California	30 (12/18)
Cook	21	California	19 (15/4)
Cuyama Ranch & Tulamnui	22	California	12 (6/6)
Ellis Landing	23	California	19 (12/7)
Hicks, Herzog, Augustine	24	California	17 (8/9)
Karlo	25	California	9 (2/7)
La Jolla	26	California	25 (12/13)
Mustang Mound	27	California	18 (10/8)
Need 1	28	California	27 (15/12)
Point Sal	29	California	25 (17/8)
Ryan Mound	30	California	40 (20/20)
Western Berkeley	31	California	11 (7/4)
Yerba Buena and Bayshore Mound	32	California	12 (10/2)
Yuma III	33	California	8 (4/4)
Ackmen/Lowry Ruin	34	Colorado	13 (6/7)
Yellow Jacket Pueblo	35	Colorado	3 (2/1)
Bayshore Mounds	36	Florida	23 (10/13)
Palmer/Casey Key	37	Florida	45 (22/23)
Tick Island	38	Florida	5 (3/2)
Windover	39	Florida	74 (44/30)
Irene Mound	40	Georgia	32 (13/19)
Albany	41	Illinois	19 (11/8)
Calhoun County	42	Illinois	17 (12/5)
Carrier Mills	43	Illinois	25 (14/11)
Dickson	44	Illinois	53 (26/27)
Elizabeth	45	Illinois	8 (5/3)
Fulton County	46	Illinois	2 (1/1)
Jersey County	47	Illinois	33 (21/12)
Kane	48	Illinois	23 (13/10)
Kuhlman	49	Illinois	14 (8/6)
Modoc Rock Shelter	50	Illinois	17 (7/10)
St. Clair County	51	Illinois	1 (1/0)
Wilson	52	Illinois	8 (6/2)
Indian Knoll	53	Kentucky	61 (31/30)
Brouillette	54	Louisiana	3 (3/0)
Glassell Plantation/Pickett Landing	55	Louisiana	1 (0/1)
Harrelson Landing	56	Louisiana	1 (0/1)
Jones Landing	57	Louisiana	2 (1/1)
Myatts Landing	58	Louisiana	6 (3/3)
Sorrel Bayou Mound	59	Louisiana	5 (3/2)
Ward Place and Bray Landing	60	Louisiana	15 (8/7)
Southeastern Maine	61	Maine	13 (8/5)
Western Cape Cod Bay	62	Massachusetts	26 (13/13)
Winnemucca: Crypt, Cowbone, Chimney	63	Nevada	8 (5/3)
Montague	64	New Jersey	21 (10/11)
Chaco Canyon	65	New Mexico	26 (9/17)
Chamisal	66	New Mexico	13 (7/6)
Gallina Springs	67	New Mexico	12 (8/4)
Hawikuh	68	New Mexico	61 (26/35)

(continued)

TABLE 1. (Continued)

Site name[a]	Supplemental information number[b]	Site location[c]	Number measured (♂/♀)
Mimbres (multiple sites)	69	New Mexico	14 (9/5)
Paa-Ko	70	New Mexico	29 (14/15)
Pottery Mound	71	New Mexico	43 (25/18)
Pueblo Bonito	72	New Mexico	14 (4/10)
Puye Cliff Dwellings	73	New Mexico	40 (17/23)
Fort Ancient/Oregonia	74	Ohio	24 (16/8)
Libben	75	Ohio	52 (25/27)
Madisonville	76	Ohio	40 (20/20)
Mobridge	77	South Dakota	41 (27/14)
Larson	78	South Dakota	41 (21/20)
Cheyenne River	79	South Dakota	26 (15/11)
Sully	80	South Dakota	20 (12/8)
Black Widow Ridge, Anton Rygh, Medicine Crow, Charles Mix	81	South Dakota	7 (0/7)
Averbuch	82	Tennessee	55 (27/28)
Cherry	83	Tennessee	20 (15/5)
Ebenezer	84	Tennessee	17 (12/5)
Eva	85	Tennessee	32 (19/13)
Hiwassee	86	Tennessee	40 (20/20)
Ledbetter Landing	87	Tennessee	17 (13/4)
Ledford Island	88	Tennessee	47 (24/23)
Thompson Village	89	Tennessee	26 (13/13)
Toqua	90	Tennessee	37 (18/19)
Caplen	91	Texas	15 (8/7)
Ernest Whitte	92	Texas	17 (10/7)
Loeve Fox	93	Texas	19 (12/7)
Mitchell Ridge	94	Texas	20 (11/9)
Caldwell Village	95	Utah	9 (5/4)
Duna Leyenda	96	Utah	6 (4/2)
Evans Site/Median Village	97	Utah	10 (5/5)
Glen Canyon	98	Utah	78 (45/33)
Polley-Secrest	99	Utah	8 (6/2)
Bladwin	100	British Columbia	6 (5/1)
Boardwalk	101	British Columbia	29 (20/9)
Dodge Island	102	British Columbia	6 (4/2)
Fort Rupert	103	British Columbia	14 (8/6)
Garden Island	104	British Columbia	9 (4/5)
Hammond	105	British Columbia	6 (4/2)
Kamloops	106	British Columbia	10 (6/4)
Lachane	107	British Columbia	12 (10/2)
Lillooet Valley	108	British Columbia	5 (3/2)
Nanaimo	109	British Columbia	11 (8/3)
Nimpkish	110	British Columbia	10 (6/4)
North Sannich	111	British Columbia	14 (9/5)
Antler Plain/Souris River Mounds	112	Manitoba	15 (9/6)
Fort Prince of Wales	113	Manitoba	3 (1/2)
Snowflake	114	Manitoba	9 (6/3)
Chesterfield Inlet	115	Nunavut	24 (15/9)
Sadlermiut	116	Nunavut	57 (30/27)
Donaldson	117	Ontario	11 (5/6)
Altar de Sacrificios	118	Guatemala	15 (10/5)
Punta Anllulla: Hacienda Ayalán	119	Ecuador	13 (6/7)
Ancón	120	Peru	51 (28/23)
Aramburú	121	Peru	10 (5/5)
Nasca sites	122	Peru	25 (14/11)
Cerro Azul	123	Peru	14 (7/7)
Total sample	–	–	2,717 (1,484/1,233)

[a] Some sites are aggregates of smaller, temporally and geographically proximate sites. See Appendix I of Auerbach (2007).
[b] This number is the identification number used in the site information provided in Appendix I (Auerbach, 2007).
[c] Modern location within state, province, or nation.

to 0.5 mm) produced by Paleo-Tech Concepts, Inc., Mitutoyo digital calipers (accurate to 0.01 mm), and Paleo-Tech spreading calipers (accurate to the nearest millimeter). Portions of the data taken from this sample have been utilized elsewhere (Auerbach, 2007; Auerbach and Raxter, 2008; Auerbach and Ruff, 2010; Auerbach, 2010, 2011; Auerbach, in press; Auerbach and Sylvester, in press). Additional information about this sample-including antiquity, site locations, and archaeological information-may be found in the Appendix I of Auerbach (2007).

The osteometric dimensions used in this study and their abbreviations are listed in Table 2, and descriptions

TABLE 2. Measurements and missing element frequency in the total sample after exclusions (n = 2,683)

Dimension	Measurement abbreviation	Measurement error (mm) [%]	Number missing		Percent missing	
			Males	Females	Males	Females
Basion-bregma height	BBH	0.08 mm [0.06%]	492	353	33.54%	29.03%
Complete cervical vertebrae			**781**	**664**	**53.24**	**54.61**
C2 maximum height	C2	0.10 [0.29]	508	407	34.63	33.47
C3 maximum height	C3	0.10 [0.74]	547	456	37.29	37.50
C4 maximum height	C4	0.14 [1.20]	549	446	37.42	36.68
C5 maximum height	C5	0.08 [0.67]	531	434	36.20	35.69
C6 maximum height	C6	0.07 [0.54]	488	384	33.27	31.58
C7 maximum height	C7	0.07 [0.50]	481	372	32.79	30.59
Complete thoracic vertebrae			**805**	**675**	**54.87**	**55.51**
T1 maximum height	T1	0.07 [0.46]	465	339	31.70	27.88
T2 maximum height	T2	0.05 [0.29]	449	377	30.61	31.00
T3 maximum height	T3	0.03 [0.16]	476	363	32.45	29.85
T4 maximum height	T4	0.07 [0.41]	489	371	33.33	30.51
T5 maximum height	T5	0.07 [0.39]	480	367	32.72	30.18
T6 maximum height	T6	0.08 [0.44]	481	363	32.79	29.85
T7 maximum height	T7	0.14 [0.70]	464	359	31.63	29.52
T8 maximum height	T8	0.05 [0.27]	449	358	30.61	29.44
T9 maximum height	T9	0.09 [0.44]	438	362	29.86	29.77
T10 maximum height	T10	0.05 [0.25]	425	370	28.97	30.43
T11 maximum height	T11	0.15 [0.67]	462	380	31.49	31.25
T12 maximum height	T12	0.07 [0.28]	401	342	27.33	28.13
Complete lumbar vertebrae			**561**	**451**	**38.24**	**37.09**
L1 maximum height	L1	0.09 [0.31]	389	301	26.52	24.75
L2 maximum height	L2	0.12 [0.48]	411	292	28.02	24.01
L3 maximum height	L3	0.08 [0.32]	408	318	27.81	26.15
L4 maximum height	L4	0.08 [0.30]	400	308	27.27	25.33
L5 maximum height	L5	0.05 [0.14]	373	288	25.43	23.68
S1 maximum height	S1	0.15 [0.50]	341	244	23.24	20.01
Femur bicondylar length	FBL	0.63 [0.15]	174	155	11.86	12.75
Tibia "Fully" length	TFL	0.46 [0.13]	235	199	16.02	16.37
Talus and calcaneus	TCH	0.33 [0.52]	451	351	30.74	28.87

of these may be found in the Appendix of Raxter et al. (2006). All skeletons presenting supernumerary vertebrae were excluded (cf. Raxter and Ruff, 2010). With the removal of these skeletons, the total sample used in this analysis is 2,683 skeletons (1,467 males, 1,216 females). In addition to the Fully technique measurements, femoral and tibial maximum lengths were taken, as they were used in missing data estimation methods. All lower limb lengths were taken bilaterally when possible, and the two sides were averaged for use in this analysis, justified by the minimal directional asymmetry found in lower limb lengths (Auerbach and Ruff, 2006). Skeletons preserving femoral and tibial dimensions were preferentially selected in this study, and so there is a sample bias in the frequency of these bones. Generally, only in the case of rare, small samples, were skeletons measured even when lacking femora and/or tibiae. In the case of all measurements taken, measurement errors were all determined to be below 2%, and so are regarded to be highly reliable and not systematically biased. These measurement errors were calculated from three independent bouts of repeated measures, and calculated as the mean absolute deviation from the average of the bouts for each individual; percentages were calculated as the mean error among individuals divided by the average for each dimension. Mean measurement errors for all dimensions are reported in Table 2. It is worth noting that, in some instances (e.g., BBH); the measurement errors are smaller than the accuracy of the measuring device employed in taking the dimension.

It is important to establish the frequency of missing elements in an archaeological sample prior to developing methods for the estimation of missing osteometric measurements. Table 2 presents the total number and percentage of the total sample lacking osteometric dimensions for each element. In the case of long bones, if one side was present, the element was regarded as not missing. The instance of complete vertebral regions (i.e., cervical, thoracic or lumbar) is listed in the table (bold text) in addition to the individual vertebrae. For the purposes of this study, entire missing elements and elements not measurable due to trauma, pathology, or erosion were regarded equally; damaged or pathological bones effectively result in missing osteometric data.

Statistics

In order to determine the accuracy and precision of estimated skeletal dimensions, missing elements were simulated using individual skeletons in which these dimensions could be measured. The most appropriate subsample of the total skeletal sample was used in approximating missing element measurements. For example, when estimating missing vertebral elements, only those skeletons with complete vertebral columns were used. Differences between estimated dimensions and observed measurements were assessed statistically using paired t-tests. The accuracy and precision of each method was further compared between the estimated dimension and the known measurement, from which standard errors of the estimate were computed.

Previous studies have established significant proportional difference between the thigh and leg, as well as between the lower limb and total stature, among human

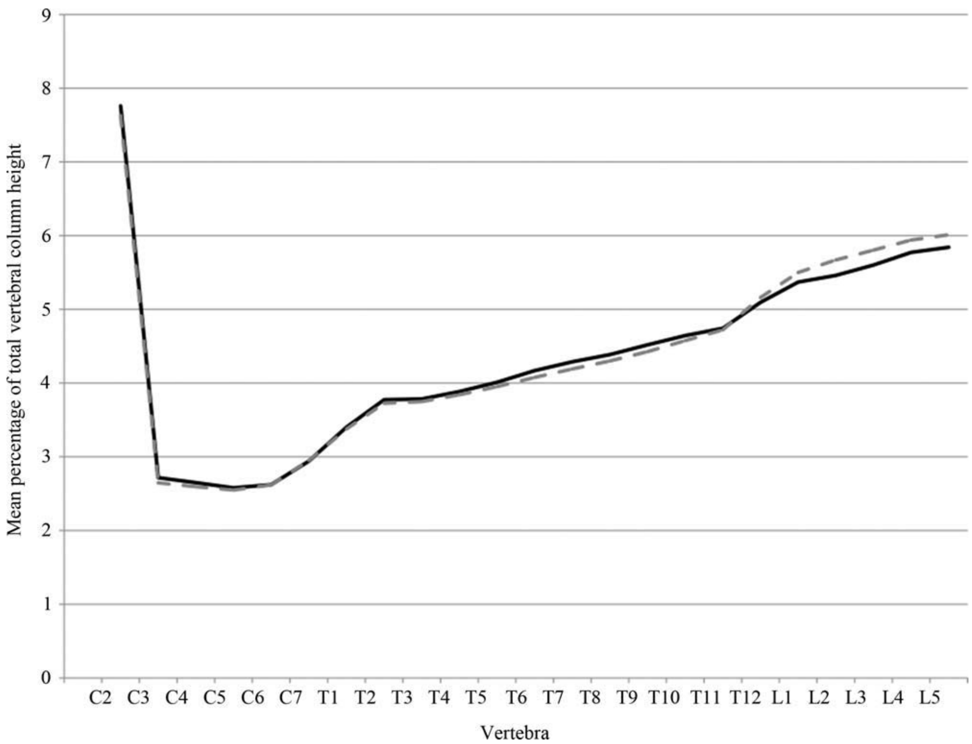

Fig. 1. The average percentage of total vertebral column length (C2 through L5) of each vertebral centrum height, calculated from all individuals with completely intact vertebral columns (n = 839). Females are represented by the dashed gray line, and males are represented by the solid black line.

groups in the Americas (Stinson, 1990; King, 2007; Auerbach and Ruff, 2010; Jantz et al., 2010). The relative contributions of the cranium and of vertebral dimensions likely also differ between groups as well as males and females. Thus, before performing any analyses, tests were conducted to determine significant sample differences and sexual dimorphism in the proportions of the portions of the skeleton under examination. These assessments were made within the subsample examined for each skeletal portion: the cranium, the vertebral column, and the lower limbs. In all cases, proportions were calculated between the dimension to be estimated and total stature or segmental measurements. Basion-bregma height (BBH) was estimated from all postcranial dimensions or a combination of them, and so required a subsample possessing all of these dimensions (total n = 656; 369 males, 287 females). In the case of individual vertebral heights, other vertebrae were used as estimators, and so the relative heights of individual vertebrae to total vertebral column heights were examined (total n = 839; 466 males, 373 females). As noted above, significant differences are known to exist among groups in the relative proportions of the femur and tibia, including in the sample used here (see Auerbach and Ruff, 2010), so sex differences were not assessed for femoral or tibial proportions as these would have to be applied on a group-by-group basis. Talocalcaneal height (TCH) estimated from tibial and femoral lengths, however, take this proportional difference into account, and so sexual dimorphism in this dimension was assessed (total n = 1,881; 1,016 males, 865 females).

Proportions generally violate the requirements of parametric statistics (Zar, 2010), and so these comparisons were run using nonparametric Kruskal-Wallis tests and Mann-Whitney U-tests. When differences existed among the samples, these were noted and general estimation methods were not attempted, as formulae would need to be specific to geographic regions or to individual samples. General methods for estimation were developed when significant differences were found between males and females but not among samples.

Estimation methods that were not significantly different from the observed dimensions, in addition to yielding the smallest estimation errors and least systematic biases, were chosen for further assessment. Upon determining which method was the most accurate for estimating any given dimension or set of dimensions, the anatomical statures using imputed dimensions were simulated using the subset of the sample with all elements present. Resulting statures were then compared with the empirically determined anatomical stature estimations. This was undertaken to ascertain when it would be accurate and practical to estimate sections of the skeleton. Comparisons of anatomical stature estimations with imputed missing elements were also made with statures estimated mathematically using lower limb elements, based on equations published in Auerbach and Ruff (2010). In addition, a practical worked example of the application of the best methods is presented at the end of this paper within the Conclusions.

All statistics were calculated using Stata SE 10.1 for Macintosh and Microsoft Excel 2008 for Macintosh.

RESULTS

On the whole, up to one-third of the sample lacks measurements for any individual Fully technique element (Table 2), and approximately one-fifth of the total

TABLE 3. Mean maximum vertebral heights and mean estimation errors of estimations using the mean of adjacent vertebrae

	Mean maximum centrum height (mm)			Mean estimation error (mm) [Std. Error][b]	
Vertebra[a]	All (839)	Males (466)	Females (373)	Males	Females
C1	10.67	11.12	10.11	N/A	N/A
C2	35.69	36.97	34.12	N/A	N/A
C3	12.48	12.97	11.88	N/A	N/A
C4	12.21	12.66	11.65	−0.008 [0.035]	−0.012 [0.032]
C5	11.94	12.32	11.46	−0.268 [0.033]	−0.244 [0.033]
C6	12.18	12.53	11.76	−0.651 [0.032]	−0.590 [0.031]
C7	13.67	14.03	13.23	−0.340 [0.032]	−0.217 [0.031]
T1	15.73	16.22	15.14	0.206 [0.033]	0.177 [0.030]
T2	17.41	17.99	16.70	0.864 [0.031]	0.731 [0.033]
T3	17.48	18.03	16.79	−0.208 [0.032]	−0.161 [0.029]
T4	17.92	18.49	17.21	−0.069 [0.030]	−0.034 [0.025]
T5	18.47	19.11	17.69	−0.070 [0.029]	−0.041 [0.029]
T6	19.15	19.87	18.26	0.095 [0.029]	0.023 [0.035]
T7	19.69	20.44	18.78	0.058 [0.029]	0.016 [0.034]
T8	20.16	20.90	19.27	−0.080 [0.029]	−0.044 [0.034]
T9	20.76	21.51	19.84	−0.002 [0.028]	−0.048 [0.033]
T10	21.41	22.13	20.52	0.049 [0.036]	−0.004 [0.031]
T11	22.00	22.65	21.20	−0.562 [0.051]	−0.640 [0.037]
T12	23.78	24.30	23.16	0.164 [0.044]	0.224 [0.040]
L1	25.19	25.61	24.67	0.441 [0.041]	0.360 [0.041]
L2	25.78	26.05	25.47	−0.084 [0.035]	−0.088 [0.039]
L3	26.42	26.71	26.06	−0.087 [0.036]	−0.002 [0.045]
L4	27.16	27.56	26.66	0.251 [0.048]	0.125 [0.044]
L5	27.50	27.90	27.01	N/A	N/A

[a] Bolded vertebrae indicate vertebral heights that are able to be estimated reliably from the average of adjacent vertebral heights.
[b] Shaded cells indicate vertebral heights with estimation errors within measurement error for the dimension.

sample (547 skeletons; 314 males, 233 females) possesses all of the necessary dimensions for Fully stature estimations. Only marginally more skeletons possess complete vertebral columns ($n = 839$). A higher proportion of males are complete (21.2%) than females (19.1%), likely due to the greater overall size of male bones. The smallest elements, namely cervical vertebrae, have the highest incidence of absence. However, the data reported in Table 2 are not representative of the true occurrence of missing elements in archaeological samples (cf. Waldron, 1987). Instead, as noted above, this is representative of a sample given the basic selection criteria (with some exceptions) of measurable femora and tibiae.

Sex and group differences in proportions

Significant differences occur between males and females in the proportions for most dimensions. Mann-Whitney *U*-tests reveal that males' BBHs are proportionally shorter than females relative to total skeletal stature (males = 9.30%; females = 9.58%) ($z = -6.599$; $P < 0.01$). Similarly, the mean relative proportion of each vertebral centrum height to total vertebral column length significantly differs ($P < 0.01$) between males and females in all vertebrae except C5, C6, C7, T1, and T11. The relative proportions of vertebral heights to total vertebral column length are shown in Figure 1 by sex, and mean vertebral centrum heights within complete vertebral columns are listed in Table 3 in the total sample and by sex. Finally, TCH, relative to the combined length of the femur and tibia, is significantly higher in males than females (males = 8.33%; females = 8.08%) ($z = 6.352$; $P < 0.01$). Given these collective results, all missing element estimations were developed separately by sex.

Group differences among sites were examined for the same dimensions by sex. Kruskal-Wallis tests indicate that BBH significantly differs among groups, both among males and among females ($P < 0.01$). This may be in part due to neurocranial modifications within samples from the Pacific Northwest, Southwest, Southeast, and Peru. Excluding all crania that demonstrate signs of modification, however, does not change the significant differences among groups. The proportion of skeletal stature represented by total vertebral column height significantly varies among groups within each sex ($P < 0.01$), and so attention is instead focused on proportional differences in estimating missing individual vertebrae. Vertebral heights relative to total vertebral column length significantly differ among groups only for C2 through C5, as well as T2 through T4. These differences, though statistically significant, generally amount to under 0.5% (all under 1 mm) for each vertebra when comparing between the means of extreme groups. In contrast, mean group differences in BBH exceed 1.5 cm. For this reason, the group differences in the proportions of individual vertebrae are considered statistically, but not biologically significant. Although TCH does significantly differ among groups, the mean difference between groups amounts to under 0.75% (less than 1 mm), a result not considered biologically significant. Therefore, methods for estimating individual missing vertebrae, vertebral regions (but not the entire vertebral column from nonvertebral elements), and missing tarsals are developed below by sex, while methods for estimating BBH, total vertebral length (estimated from nonvertebral elements), and the lengths of the femur or tibia are not, as these require group-specific formulae.

Cranium estimation

Given the significant group differences in the relative contribution of BBH to skeletal stature, no attempt is made to develop a general estimation formula for this

TABLE 4. Position of vertebrae, based on height, that do not fall close to 50% of the height difference between adjacent vertebrae, and heights relative to superior and inferior vertebral heights

Estimated vertebra	Mean percent position relative to height difference between superior and inferior vertebrae	Mean difference between height estimated using percent position and actual height (mm) (%SEE)	Percentage of mean vertebral centrum height relative to superior vertebral centrum height[a]	Percentage of mean vertebral centrum height relative to inferior vertebral centrum height[a]	Mean difference between actual height and best-performing height estimated as a percentage of adjacent vertebrae[a] (mm) (%SEE)
Males					
C2	N/A	N/A	N/A	**286.77%**	−0.370 (5.76%)
C3	98.81%	0.015 (9.87%)	**35.14%**	102.75	0.035 (8.56)
C6	26.61	0.674 (10.89)	101.90	**89.35**	0.010 (6.14)
T2	117.63	−0.432 (6.65)	111.11	**99.87**	0.001 (4.33)
T11	24.78	1.061 (6.37)	102.42	**93.35**	0.155 (5.09)
L1	70.82	2.657 (8.37)	**105.52**	98.42	−0.142 (4.22)
L5	N/A	N/A	**101.36**	N/A	0.018 (5.60)
Females					
C2	N/A	N/A	N/A	**289.04%**	−0.067 (6.20%)
C3	99.08%	0.018 (8.70%)	**34.89**	102.07	−0.063 (8.53)
C6	25.31	0.770 (10.86)	102.90	**88.98**	−0.046 (5.53)
T2	118.97	−0.454 (6.36)	110.42	**99.52**	−0.043 (4.27)
T11	19.94	1.201 (6.29)	103.40	**91.64**	−0.248 (3.60)
L1	64.50	2.993 (8.36)	**106.65**	96.96	0.125 (3.61)
L5	N/A	N/A	**101.36**	N/A	−0.022 (4.11)

[a] Best-performing estimator is in bold text.

dimension. In fact, even using regionally constrained samples wherein proportions do not significantly differ, postcranial measurements predict BBH poorly. For example, using only males from western Alaska, a multiple regression employing all of the postcranial dimensions as predictors and BBH as the criterion yields a low correlation ($r = 0.393$) with a standard error of the estimate of 5.79 mm (4.30%, which is much larger than the measurement error of 0.6% for BBH). Thus, any estimation using postcrania yields imprecise results for BBH.

Vertebrae estimation

Missing individual vertebrae. As noted in the Introduction, Sciulli et al. (1990) estimated missing vertebral heights by averaging existing adjacent vertebrae. This method is logical, as vertebral heights generally increase inferiorly, but is also limited because it assumes a serial equal linearity in vertebral height increase. Although this is the trend for most vertebrae, there are important exceptions that prevent the use of this method.

Table 3 reports the mean estimation errors for vertebral maximum heights estimated using adjacent vertebrae. Mean estimation errors with shaded cells in the table indicate estimations for which the mean estimation error is less than measurement error for that vertebra. Despite significant differences between males and females in the relative contribution of individual vertebrae to vertebral column length, the estimation errors for the averaging technique follow do not differ between the sexes. C5, C7, T1, T3, T12, and L4 have estimation errors greater than measurement errors for those dimensions, but their estimation errors are smaller than 1/3 of a millimeter. As these are biologically negligible errors, it was decided to allow for the estimation of these elements from adjacent vertebrae. The remaining vertebrae—namely C6, T2, T11, and L1—have mean estimation errors are close to or greater than 0.5 mm, which is more than measurement error. Although these individually are negligible potential errors in relation to overall stature, estimations of any number of these in combination could result in considerable compounded error. In addition, C2 falls at the end of the (measured) vertebral column, and so is not eligible to be estimated by averaging adjacent vertebrae. Although L5 could be estimated from adjacent vertebrae, the height of S1 is variable among groups and L5 is not intermediate in height between its adjacent vertebrae. (No attempt to estimate missing S1 centrum height is attempted due to its proportional differences among groups.) Therefore, other methods are necessary to estimate these vertebrae.

Estimating the heights of the exceptional vertebrae relative to the heights of adjacent vertebrae is an option. One method is to examine the percent position of these vertebrae relative to the height difference between their superior and inferior vertebrae. (See the Appendix for discussion of an alternative not considered here.) Averaging adjacent vertebrae to estimate a missing vertebral height assumes that the intermediate vertebral centrum height is close to halfway (i.e., 50%) between the heights of the vertebra superior and the vertebra inferior to it. Table 4 presents the mean height of these vertebrae as a percentage of the height difference of the superior and inferior vertebrae. This is termed the "percent position." For example, C6 has an incremental height close to 20% of the total height difference between C5 and C7; hence, this is why averaging C5 and C7 tends to overestimate the height of C6. These percent positions were calculated as:

$$\frac{X_S - X_E}{X_S - X_I}$$

X_S is the height of the superior vertebral centrum height, X_E is the height of the vertebrae to be estimated, and X_I is the height of the inferior vertebra. Taking the mean of all of the percent positions, this number was then multiplied by the absolute value of $X_S - X_I$, the answer of which was then subtracted from X_S (except for

TABLE 5. Best performing multiple regression equations estimating missing vertebral heights not estimated by averaging adjacent vertebrae

Estimated vertebra	Most effective estimator vertebrae	Number of applicable cases in total male sample (n = 1467)	Estimation equation (all known measurements in mm)	Mean difference between estimated and actual height (mm)	SEE (%SEE)
Males					
C2	C3, C7	60	0.592(C3) + 0.625(C7) + 20.588	−0.070	2.131 (5.75%)
C3	C2, C4, C5	37	0.064(C2) + 0.545(C4) + 0.274(C5) + 0.308	0.025	0.796 (6.13)
C6	C5, C7	32	0.454(C5) + 0.477(C7) + 0.235	0.003	0.645 (5.14)
T2	T1, T3, T6	16	0.425(T1) + 0.448(T3) + 0.098(T6) + 1.092	−0.022	0.617 (3.42)
T11	T9, T10, T12	50	0.234(T9) + 0.346(T10) + 0.325(T12) + 2.078	−0.014	1.056 (4.65)
L1	T12, L2, L3	15	0.342(T12) + 0.399(L2) + 0.192(L3) + 1.789	−0.007	0.828 (3.23)
L5	L3, L4	29	0.372(L3) + 0.532(L4) + 3.322	0.014	1.365 (4.88)
Females					
C2	C3, C7	45	0.589(C3) + 0.525(C7) + 20.170	0.003	2.063 (6.05%)
C3	C2, C4, C5	43	0.066(C2) + 0.612(C4) + 0.228(C5) – 0.119	−0.001	0.679 (5.72)
C6	C5, C7	35	0.402(C5) + 0.474(C7) + 0.871	0.007	0.566 (4.81)
T2	T1, T3, T6	29	0.419(T1) + 0.364(T3) + 0.188(T6) + 0.807	0.002	0.619 (3.70)
T11	T9, T10, T12	49	0.072(T9) + 0.398(T10) + 0.395(T12) + 2.437	0.018	0.680 (3.20)
L1	T12, L2, L3	21	0.488(T12) + 0.320(L2) + 0.124(L3) + 1.990	0.001	0.770 (3.12)
L5	L3, L4	28	0.184(L3) + 0.788(L4) + 1.168	0.041	1.123 (4.16)

T2, where it is added due to an average percent position over 100%) to give the estimated height of the missing element. This method, unlike the averaging method (which assumes a percent position of 50%), also allows for the estimation of C3. The resulting estimates are generally less accurate than those obtained using the assumed percent position of 50% (reported in Table 3). Moreover, the percent standard errors of the estimate are high, as is mean measurement difference for the lower vertebrae.

A related alternative would be to calculate the heights of missing elements as a percentage of the vertebral height of either the superior or the inferior vertebra. In these cases, the ratio of the vertebral centrum height to the superior or inferior vertebral centrum height was calculated as a percentage (reported in Table 4), and then the mean percentages were used to calculate the height of the simulated missing vertebrae. For example, the centrum of C2 among females is, on average, 289.04% of the height of the centrum of C3. C3, C6, T2, T11, and L1 were estimated using both the superior and inferior vertebrae, and the more accurate estimator was selected (Table 4). C2 was only estimated from C3, and L5 only from L4. When using this method, the mean differences between the estimated vertebrae and the actual vertebrae were considerably smaller than any of the other methods attempted.

One final option for estimating the heights of individual vertebrae is by using a multiple regression formula, estimating the height of missing elements based on those of known vertebrae. Various permutations of these formulae could be devised, so a stepwise regression was used to determine which vertebrae served as the best predictors of the seven vertebrae not estimated using the average of adjacent vertebrae. The resulting equations are presented for males and females in Table 5. On the whole, these equations yield the most accurate method for estimating missing vertebral height measurements for these seven vertebrae, but their application to the sample is rare. Even where estimators in the multiple regression equations that are themselves estimated were permitted (e.g., a T6 estimated using the averaging of adjacent vertebrae, which is then used to estimate T2), risking compounded error, there are very few instances in which the multiple regression equations may be employed practically.

Missing vertebral regions. All of these preceding methods are applicable for the estimation of single vertebrae, and generally assume a vertebral column that is mostly intact. As shown in Table 3, though, at least half of the sample is lacking complete regions of vertebrae, with multiple adjacent cervical and thoracic vertebrae commonly missing or unobservable. Thus, methods are also needed for estimating regions of the vertebral column length in the absence of multiple vertebrae.

Regression formulae have the potential for estimating missing regions using extant vertebral regions. Skeletons hardly ever possess all thoracic vertebrae while missing multiple lumbar vertebrae, or all cervical vertebrae while missing multiple thoracic or lumbar vertebrae (there are none meeting these criteria in the total sample). Therefore, two methods for estimating vertebral column length with only missing cervical or missing cervical and thoracic vertebrae were tested: estimating missing regions and adding them to observable vertebral regions, or estimating total vertebral column length from the intact region(s) alone. There are no significant differences between males and females in the proportion of each vertebral region (cervical, thoracic and lumbar) to total vertebral column length, though individual vertebrae comprise different proportions; equations were generated with sexes combined. In all instances, in order to avoid compounded error, only nonestimated vertebral heights were incorporated.

Table 6 reports the equations and performance of regression methods for estimating missing vertebral regions. Two options were tested in the case of missing cervical vertebral regions: (1) estimating the cervical region, and adding it to the known thoracic and lumbar region measurements to determine the complete vertebral column; (2) estimating the entire vertebral column length from the thoracic and lumbar regions. The latter method yielded more accurate estimations (Table 6), with a smaller standard error of the estimate (SEE) and confidence intervals that are not negatively skewed. In

TABLE 6. *Regression formulae for estimating missing section or total vertebral column length (combined sex)*

Estimated vertebral section	Estimator(s)	Applicable cases in sample (n = 2683)	Estimation equation (all known measurements in mm)	SEE (%SEE)	Mean difference between estimated and actual column length (mm)	95% confidence intervals	
						Lower	Upper
Cervical	Thoracic and lumbar sections	1084	0.295(Thoracics) + 0.179(Lumbars) + 5.481	4.860 (4.95%)	−1.39[a]	−2.29	−0.49
Vertebral column*	Thoracic and lumbar sections	1084	1.279(Thoracics) + 1.072(Lumbars) + 22.024	12.814 (2.77%)	−0.75	−0.97	0.82
Cervical and thoracic	Lumbar section	1671	1.639 (Lumbars) + 114.481	18.544 (5.61%)	−0.034[a]	−1.33	1.26
Vertebral column*	Lumbar section	1671	2.639(Lumbars) + 114.480	18.644 (4.03%)	−0.033	−1.33	1.26

[a] This is the difference between the total actual vertebral column length and the vertebral column length determined from estimated section(s) and the known (estimator) section(s).
* Preferred method.

the case of missing thoracic and cervical regions, two similar approaches were tested using the lumbar vertebral region as the estimator. Again, the regression equation estimating complete vertebral column, rather than the missing region, performed more accurately. In this case, however, the difference between the two options is more marginal; only in the standard errors of the estimate are there differences, mostly because in the first equation, the error is for a smaller total measurement (thoracic and cervical regions, as opposed to the entire vertebral column).

Lower limb estimation

Femur and tibia lengths. Group differences in crural and cormic indices make estimations of the femur and tibia from each other or from other dimensions (e.g., vertebral column length) prone to high amounts of error were an equation for general use employed. Group-specific equations may be created as needed for estimating the length of the tibia from femoral length, or vice versa, using ordinary least squares regression. However, as the proportions of any given group cannot be anticipated from the data used in this study, such equations are not presented.

The lengths of the femur and tibia employed by the Fully technique, however, may be estimated using maximum lengths of each element. Femoral maximum length (FML) and femoral bicondylar length (FBL) are highly correlated (r = 0.998) and are not sexually dimorphic. Similarly, tibial maximum length (TML) and tibial “Fully” length (TFL) have high correlations (r = 0.989) and this relationship does not differ between males and females. Using OLS regression, the following equations may be used in both sexes (FML and TML estimation are provided for reference):

$$\mathrm{FBL} = 0.995 \times \mathrm{FML} - 1.557\ (n = 2440; \%\mathrm{SEE} = 0.46\%)$$

$$\mathrm{FML} = 1.000 \times \mathrm{FBL} + 3.597\ (n = 2440; \%\mathrm{SEE} = 0.45\%)$$

$$\mathrm{TFL} = 0.982 \times \mathrm{TML} + 2.686\ (n = 2344; \%\mathrm{SEE} = 1.10\%)$$

$$\mathrm{TML} = 0.996 \times \mathrm{TFL} + 5.164\ (n = 2344; \%\mathrm{SEE} = 1.09\%)$$

Talocalcaneal height. Estimation of missing tarsal height (TCH) is a frequently encountered necessity; among the elements used in the Fully method, only cranial BBH and vertebral heights are more frequently missing (Table 2). The group-specific proportional variation that limits estimations of femoral and tibial length, either from each other or from other dimensions, do not apply to the estimation of talocalcaneal height if both femoral and tibial lengths are known and used as estimators. As there is significant sexual dimorphism in this measurement ($P < 0.01$; mean male TCH = 65.78 mm, n = 1012; mean female TCH = 59.49 mm, n = 865), all calculations must be sex-specific:

$$\text{Males: } 0.100 \times \mathrm{FML} - 0.018 \times \mathrm{TML} + 28.775\ (\mathrm{SEE} = 3.35; \%\mathrm{SEE} = 5.1\%)$$

$$\text{Females: } 0.074 \times \mathrm{FML} + 0.004 \times \mathrm{TML} + 27.745\ (\mathrm{SEE} = 3.26; \%\mathrm{SEE} = 5.47\%)$$

The resulting multiple regression equations are not highly precise estimators. Percent SEEs for both equations are an order of magnitude greater than observed measurement error. However, these equations yield a 95% confidence interval of −0.13 to 0.17 mm, which is minimal in comparison with most of the measurement errors encountered in estimating other dimensions.

Comparison with multiple regression estimations of stature

Table 7 presents the results of comparisons between statures estimated using the anatomical method with permutations of anatomically estimated statures with imputed dimensions and with the mathematically estimated statures using the formulae developed by Auerbach and Ruff (2010). The 547 skeletons in the sample not missing any elements were used for comparison, and varying numbers of skeletons with all necessary dimensions were utilized in the other assessments (see Table 7). Although it was established above that multiple regression estimations of cranial height are inaccurate, its simulated absence is still included in Table 7 to assess the inaccuracy in estimating stature anatomically with a missing skull. In addition, in order to examine the effects of compounded error, skeletons with incomplete vertebral sections that can be completed by estimating the heights of individual vertebrae—either by averaging adjacent vertebrae or as a percentage of adjacent vertebral heights—are also assessed.

Results indicate minimal average errors for most of the estimation methods used in comparison with empirically determined anatomical stature estimations. All calculations with missing element dimensions tend to overestimate stature. Although most anatomical stature estimations with imputed dimensions are statistically different, only estimations incorporating missing cranial height have average estimation errors over 1 cm. In addition, even though mathematical stature estimation using the femur and tibia has among the lowest mean difference, all of the anatomical stature estimations with imputed measurements have lower standard errors of the estimate.

DISCUSSION

This study demonstrates utility in imputing the dimensions of unobservable elements and applying them to anatomical stature estimation. Anatomical stature reconstructions using imputed vertebral or tarsal dimensions yield stature estimations that are slightly less accurate but more precise than mathematical regression stature estimations from femoral and tibial length. All estimations using imputed missing element dimensions are generally accurate to within 0.5 cm of statures estimated with all elements present (except including cranial height estimations). Moreover, the inclusion of individually estimated vertebral heights in lumbar or thoracic regression equations for estimating total vertebral column length did not introduce notable compounded error into the estimations; the larger sample sizes of these comparisons actually reduced the standard errors of the estimate. This is important, as it allows for a sizeable portion (up to 1,321 out of 2,683 individuals, or 49.23%) of the sample to be eligible for anatomical stature estimations despite missing vertebrae and tarsals.

Furthermore, the methodology developed herein has practical application. As discussed by others (e.g., Waldron,

TABLE 7. Comparisons of complete skeletons with anatomical stature estimations against anatomical stature estimations with simulated imputed missing element dimensions and with mathematically estimated statures (from Auerbach and Ruff, 2010)

	Mathematical stature estimation	Anatomical stature reconstructions using estimations described in Results									
		Cranium only missing[a]	Cervical vertebrae only missing		Cervical and thoracic vertebrae only missing		Tarsals only missing	Cervical vertebrae and tarsals missing		Cervical and thoracic vertebrae and tarsals missing	
			A	B	A	B		A	B	A	B
Number of applicable cases in total sample	547	656	679	982	940	1151	606	765	1099	1073	1321
Mean difference from complete anatomical stature estimation (cm)	0.09	3.09*	0.14*	0.10*	0.18*	0.10*	0.05	0.19*	0.12*	0.23*	0.13*
95% CI	−0.10–0.27	2.95–3.06	0.10–0.19	0.06–0.13	0.06–0.29	0.01–0.20	0.02–0.08	0.14–0.25	0.08–0.17	0.10–0.35	0.03–0.23
SEE	2.26	3.09	0.56	0.54	1.40	1.42	0.38	0.73	0.71	1.50	1.53

For estimations requiring the imputation of vertebral regions, column "A" designates the use of regions measured without estimating individual missing vertebrae, and column "B" designates regions that incorporate individually missing vertebrae in their calculation. (E.g., all lumbar vertebrae are present in a skeleton used in "A," but L2 would be estimated and used in totaling lumbar height in additional skeletons utilized in column "B.")

[a] Estimated using all vertebral elements, femur and tibial length.

* Significantly different from mathematically estimated stature in paired *t*-test ($P < 0.05$).

1987), the elements that most often need to be estimated are also those to which these formulae apply: cervical and thoracic vertebrae, as well as the talus and calcaneus. These are elements that likely are missing as a consequence of low mass (due to trabecular relative to cortical content), fragility, and small size, in addition to incomplete excavation methods. Direct measurement of these elements is always preferred, but these are also among the more difficult dimensions to measure in the revised Fully method—especially due to taphonomic damage or pathology—and so it may be preferable to estimate these dimensions from other measurements than attempt to mitigate for damage or disease.

Overall, the results show that estimations of individual vertebral heights from either averaging adjacent centra heights or using a percentage of adjacent centra heights (in the case of exceptional vertebrae) are accurate within measurement error. It may be more statistically conservative, however, to estimate vertebral column length from lumbar vertebrae when multiple nonadjacent cervical or thoracic vertebrae are missing. In fact, Fully and Pineau (1960) reached the same solution under different logic in their study. This is despite the lack of notable differences when including or excluding individually imputed vertebral heights in the vertebral column estimations reported in Table 7. In addition, using the regression equations from Table 6 to estimate vertebral column length requires less computational steps (and therefore reduces the chances of unexplained error).

There are important limitations to the estimation of missing dimensions when trying to apply the revised Fully stature estimation method. Cranial height cannot be reliably estimated from postcranial dimensions, and so the anatomical method cannot be applied when skeletons are found without skulls. The estimation of the height of the vertebral column may be attempted when only lumbar vertebrae are present, though missing individual lumbar vertebral heights may be estimated before using total lumbar height to estimate vertebral column length. Also, as they require a priori knowledge of proportions, vertebral column length cannot be estimated using lower limb bones, and femora and tibiae cannot be estimated from each other or intact vertebral columns.

The inability to estimate basion-bregma height is notable, as it implies that the size of the superoinferior cranial dimension is independent from the height of the postcranial skeleton. The amount of independent variance in cranial dimensions relative to postcranial dimensions awaits further research. However, this may indicate greater independence between the skull and postcrania than among postcranial dimensions.

This study also further emphasizes the limitations to the practical application of the anatomical stature estimation method. Mathematical regression formulae estimating stature from femora and tibiae will generally yield stature estimations as accurate any of the anatomical estimation methods with imputed missing element dimensions; however, the mathematical stature estimations were more accurate but less precise. This, though, depends on whether good mathematical stature estimation equations exist for a given sample. As all of the individuals examined between both stature estimation methods in Table 7 were part of the larger sample used to create the mathematical regression stature estimation formulae in Auerbach and Ruff (2010), it is not surprising that the equations performed so well. Indeed, were Trotter and Gleser's (1958) formulae used instead, all of the anatomical stature estimations with missing dimensions imputed are both more accurate and precise (results not shown). Thus, the estimation of missing vertebral and tarsal measurements will be most useful in situations where these few elements are all that prevent the estimation of stature in skeletons for which no good stature estimation equation using long bones exists.

The behavior of the methods developed to estimate individual vertebrae require additional attention. Approximating the heights of most vertebrae can be achieved employing Sciulli et al.'s (1990) 50% averaging solution. The vertebrae for which this method is inaccurate—C2, C3, C6, T2, T11, L1, and L5—generally fall close to transitional areas of the vertebral column. Reasons for this pattern are beyond the scope of this study, though it may be related to the anterior curvature of the spine; these vertebrae generally fall near the maxima of these curves. However, the poor estimation of the heights of these vertebrae using their "percent positions" (Table 4) indicates a great amount of variation in the relative height of exceptional vertebrae to adjacent vertebrae. This, in turn, could relate to variable amounts of curvature present among individuals. That this pattern is not observed in the vertebrae nearest to the maximum of posterior curvature (around T7) is interesting and worth analysis in future studies.

Multiple methods for estimating missing dimensions were reviewed in the Introduction but not used in this study. However, it is not an implied argument of this article that those methods would be inappropriate or impractical, though all have inherent assumptions about which should be understood before employing them. Arguably, Bayesian methods, which were not considered in this study, may prove better at resolving the problem of obtaining missing element dimensions. Other methods would be highly limited in application: using an average of observed dimensions within a sample to "stand-in" for a missing measurement may be appropriate, but only when there is little variance in a sample or the individual with the missing dimension would fall near to the sample mean. For this reason, the methods in this article that rely on imputing dimensions from other dimensions within a skeleton are preferred, as they assume only that individuals fall near to the slope of the formulae devised (and within the range of the equations developed).

How universally may the missing element imputation methods be applied to human populations outside of the Americas, or indigenous New World populations not sampled? As examined by the author elsewhere (Auerbach, 2007), the groups sampled from the Americas and used in this study have as great a range of variation in body proportions-brachial, crural, and cormic indices-as those observed by Ruff (1994) and Holliday (1997, 1999) in African and European samples. Without performing comparisons similar to those reported in this study on Old World human samples, however, there is unknown error in using the formulae presented here on samples from outside the Americas. For instance, as none of the groups included in this study are pygmoid peoples who have been shown to differ substantially from other human groups in the prediction of other dimensions (Kurki et al., 2010; Auerbach and Ruff, 2004)—caution should be exercised in trying to apply these methods to very small-bodied groups. Yet, the methods explained in the present study are applicable to devising methods for imputing missing dimensions in any human group, and readers are encouraged to use the described methodology in creating new, sample-appropriate equations when the presented equations' application is dubious.

CONCLUSIONS

As shown by Raxter et al. (2006), anatomical stature estimations are more reliable than mathematical stature estimations, especially when body and limb proportions of the sample used to create the mathematical regression formulae are not the same as the groups for which stature is estimated. Missing element dimensions are one of the greatest impediments to the successful application of anatomical stature estimation. This study has expanded the potential sample to which the revised Fully method may be applied, however, by providing guidelines and formulae for imputing missing skeletal dimensions. In conclusion, the following guidelines are suggested for estimating missing measurements:

- The estimation of cranial height cannot be performed accurately using any combination of postcranial dimensions as estimators. Furthermore, the proportion of cranial height relative to postcranial skeletal height varies significantly among human groups, so any equation developed would be population-specific. For this reason, anatomical stature estimation should not be attempted on skeletons with missing or nonmeasurable skulls.
- Vertebral centra heights may be estimated by averaging adjacent vertebral heights except for the following vertebrae: C2, C3, C6, T2, T11, L1, and L5. These vertebral heights are best imputed by calculating a percentage of the height of one of the adjacent vertebrae (see Table 4); a practical worked example of this method is presented below. Alternatively, multiple regression formulae may be employed (Table 5), though the practical application of these formulae is greatly limited.
- In the case multiple cervical and thoracic vertebrae are missing, it is recommended that the entire length of the vertebral column be estimated using formulae presented in Table 6. Missing individual vertebrae may be estimated to complete lumbar and thoracic vertebral sections as necessary before using the regression formulae without resulting in substantially higher estimation errors, though this is statistically less conservative.
- No attempt should be made to estimate vertebral column length from lower limb dimensions unless the proportions of the sample under examination are known and homogenous. The same logic applies to estimating femoral length from tibial length, or vice versa.
- Tibial and femoral physiological length may be estimated accurately from measured maximum lengths of these bones, respectively.
- Talocalcaneal height may be imputed from femoral and tibial length, as this takes the proportions of the individual into account within the estimation.

Worked example: applying the method with missing vertebrae

A brief example of how to apply the missing dimension estimation for individual vertebrae described in Table 4 is presented here for practical reference. A male skeleton yields the following measurements (see Table 2 for abbreviations): BBH = 126 mm; C2 = MISSING; C3 = 11.96 mm; C4 = 11.19 mm; C5 = 11.31 mm; C6 = 11.30 mm; C7 = 13.30 mm; T1 = 14.96 mm; T2 = MISSING; T3 = 16.69; T4 = 16.89; T5 = 17.84; T6 = 18.23; T7 = 19.05; T8 = 19.87; T9 = 20.30; T10 = 20.58; T11 = MISSING; T12 = 22.93 mm; L1 = 24.57 mm; L2 = 25.34 mm; L3 = MISSING; L4 = 26.98 mm; L5 = 27.51 mm; S1 = 28.39; FBL = 375 mm; TFL = 315 mm; TCH = 63.5 mm. The maximum heights of C2, T2, T11, and L3 will need to be estimated. C2 is estimated as 286.77% of the height of C3: 11.96 mm × 2.8677 = 34.30 mm. Likewise, T2 is estimated to be 16.67 mm (99.87% of the height of T3) and T11 is estimated to be 21.41 mm (93.35% the height of T12). L3 may be reliably estimated as the mean of the heights of L2 and L4: 26.16 mm.

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APPENDIX

One alternative approach for estimating missing vertebrae not discussed in the main text is Lundy's (1985) method, wherein each vertebra centrum height's mean percentage of total vertebral column length is determined, and then applied to determine the height of a missing vertebral centrum height (X_E):

$$\%X = \frac{X_K}{V_T}$$

$$X_E = \left(\frac{V_K}{100 - \%X}\right) - V_K$$

X_K is the known vertebral height, V_T is the known total vertebral column length, $\%X$ is the percent of total vertebral column length made by X_K, and V_K is the total vertebral column length without the missing vertebra. $\%X$ is calculated for an entire sample and then applied to individuals with missing vertebrae in need of estimation (X_E).

This method was tested on the vertebrae not estimated using the averaging technique (C2, C3, C6, T2, T11, L1, and L5). Among males, in two instances-C3 and C6-the resulting estimates were not significantly different from the actual vertebral centra heights (C3: p = 0.914; C6: p = 0.689). The mean difference between the estimations and actual measurements of the other five vertebrae ranged from −0.62 to −2.05 mm. Similar results were obtained for the female sample. This technique, then, performs poorly as a means of estimating missing vertebral measurements compared with measurement error for these vertebrae. Moreover, its application is limited; the method requires that all vertebrae except the missing vertebra are present.

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