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Juvenile body mass estimation: A methodological evaluation☆

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Two attempts have been made to develop body mass prediction formulae specifically for immature remains: Ruff (Ruff, C.C., 2007, Body size prediction from juvenile skeletal remains. American Journal Physical Anthropology 133, 698–716) and Robbins et al. (Robbins, G., Sciulli, P.W., Blatt, S.H., 2010. Estimating body mass in subadult human skeletons. American Journal Physical Anthropology 143, 146–150). While both were developed from the same reference population, they differ in their independent variable selection: Ruff (2008) used measures of metaphyseal and articular surface size to predict body mass in immature remains, whereas Robbins et al. (2010) relied on cross-sectional properties. Both methods perform well on independent testing samples; however, differences between the two methods exist in the predicted values. This research evaluates the differences in the body mass estimates from these two methods in seven geographically diverse skeletal samples under the age of 18 ($n = 461$). The purpose of this analysis is not to assess which method performs with greater accuracy or precision; instead, differences between the two methods are used as a heuristic device to focus attention on the unique challenges affecting the prediction of immature body mass estimates in particular. The two methods differ by population only in some cases, which may be a reflection of activity variation or nutritional status. In addition, cross-sectional properties almost always produce higher estimates than metaphyseal surface size across all age categories. This highlights the difficulty in teasing apart information related to body mass from that relevant to loading, particularly when the original reference population is urban/industrial.

1. Introduction

The estimation of adult body mass from skeletal remains has played a critical role in the anthropological analyses of past populations, and a variety of methods are available to researchers for these purposes. The diversity of methods available for adult estimation can be loosely grouped into two categories: "mechanical" methods, which depend on the functional relationship between a given measurement and body mass, and "morphometric" methods, which reconstruct body mass more directly from skeletal remains (Auerbach and Ruff, 2004). Most of these methods rely on estimation from the postcranium, as this is widely agreed to provide the highest accuracy (Elliott et al., 2014). "Mechanical" methods have relied on both articular surface size at the knee and hip, and long bone cross-sectional size (Ruff et al., 1991; McHenry, 1992; Grine et al., 1995). "Morphometric" methods approach body mass estimation by modeling the body as a cylinder with a diameter of bi-iliac breadth (Ruff, 1994; Ruff et al., 1997).

While many studies have generated body mass prediction formulae for adults, relatively fewer analyses have focused on body mass prediction in immature individuals. Such formulae for juveniles are essential, as many studies of health and growth in immature populations rely on some measure of body size (as reviewed in Bogin, 1999; Lewis, 2007). However, formulae generated to predict body mass in adults are generally unsuitable for application to immature remains for several reasons. Many adult equations rely on measurements of articular size or bi-illiac breadth, both of which are difficult if not impossible to measure on unfused immature postcrania. In addition, formulae designed to predict body mass using an adult reference sample will generally overestimate body mass in juveniles, due to relatively larger epiphyses compared to shaft size in growing individuals (Ruff, 2007). Furthermore, general approximations of body size using long bone length are difficult during growth due to allometrically changing relationships between body length and body mass across ontogeny.

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Fortunately, two studies have produced body mass estimation formulae specifically for prediction in immature remains (Ruff, 2007; Robbins et al., 2010). While both studies rely on “mechanical” prediction, Ruff (2007) based his estimation formulae on femoral head size and distal femoral metaphyseal breath measurements, whereas Robbins et al. (2010) used measurements derived from cross-sectional geometry, specifically femoral midshaft polar second moment of area (J). The theoretical justifications for the use of either of these measurements are well established. Measurements of articular surface size are relatively unaffected by activity patterns during life (Lieberman et al., 2001), correlate well with body mass (Jungers, 1988; Ruff, 1990; Godfrey et al., 1991), and results from estimation techniques based on them compare favorably with body mass estimates from “morphometric” body mass estimation techniques (Auerbach and Ruff, 2004). However, body mass, particularly in immature individuals, correlates very well with long bone cross-sectional size and is the primary determinant of bone strength in the growing lower limb (van der Meulen et al., 1993, 1996; Moro et al., 1996; Ruff, 2003b).

Despite their focus on different, at least partially independent variables to predict body mass, the two studies lend themselves to convenient comparison for several reasons. First, both are based on the same longitudinal reference sample derived from the Denver Growth Study (McCammon, 1970). Second, both developed age-specific formulae for prediction that used the same age categories. Third, both analyses used the same basic methodology, least squares regression, to generate their formulae.

Through a comparison of these two methods, it is possible to shed light on several larger issues and questions within biological anthropology. First, it is unclear whether articular surface area and diaphyseal measurements are equally appropriate in their ability to predict body mass. While the relationship between bone strength and body mass during growth is well documented, properties of the diaphysis are likely to be strongly affected by activities engaged in during life, even in immature individuals (Cowgill, 2010), whereas articular surface area appears to be less responsive to changes in loading (Lieberman et al., 2001). It is uncertain, however, how the relative environmental plasticity of these areas interact with their ability to be used as the independent variable in body mass prediction. Second, it is unclear if these differences in environmental plasticity affect body mass estimates the same way across developmental ages, subsistence strategies, and time periods. For example, if both the diaphyses and articular surface are present, should one technique be used above the other in all age categories, or does appropriateness of the technique vary with developmental age? Also, does the activity level and/or subsistence strategy of the target population affect the accuracy of the two methods, given that the original sample both methods were developed on, the Denver Growth Study (McCammon, 1970), is a modern, urban group unlikely to be engaging in extensive activity at any age? Last, does the time period of the target sample/individual influence the results? Late Pleistocene juveniles, for example, show the higher levels of diaphyseal robusticity typical of Late Pleistocene adults (Trinkaus and Ruff, 1996; Trinkaus et al., 2002a, b; Cowgill et al., 2007; Cowgill, 2010), and methods based on a Holocene, urban sample may provide inaccurate results.

It is impossible to evaluate the true accuracy of both methods without an independent sample of immature individuals for which body mass, articular surface size, and cross-sectional geometry are known. Unfortunately, such immature samples are very difficult to acquire, even with the use of data from clinical sources. However, given the broader theoretical issues detailed above, this research compares immature body mass estimates produced via Ruff's (2007) Articular Surface Measurement Method (ASMM) and the Diaphyseal Measurement Method (DMM) of Robbins et al. (2010) in an attempt to explore the compatibility of the methods, as well as to evaluate basic biological mechanisms acting on the skeleton during growth. Differences related to age and population were evaluated in a large, diverse sample of immature individuals, to identify any differences between the two methods that varied systematically with age and group membership. Based on these results, recommendations can be made for appropriate application of the two methods in archaeological, paleontological, and applied forensic contexts.

2. Materials and methods

2.1. Materials

The primary data for this analysis consisted of femoral diaphyseal cross-sectional properties and articular metrics from seven Holocene human skeletal samples (Table 1; Cowgill, 2010). Two sets of body mass estimates were produced from a total of 461 immature individuals between the ages of 0.5 and 17.5 years. The seven samples were selected to represent the broadest possible range of historical and archaeological time periods, geographic locations, and subsistence strategies. Previous research has shown that factors such as latitude and subsistence activities affect individuals across much of the human life span, so the diversity of morphology present in the adults in these populations is likely to influence the immature individuals as well (Cowgill et al., 2012). Individuals displaying indicators of obvious developmental pathology were excluded, although observations of non-specific developmental stress (Harris lines, cribra orbitalia, porotic hyperostosis) were not considered grounds for exclusion.

While details of the comparative sample have been published elsewhere (Cowgill, 2010) and are summarized in Table 1, they are discussed at greater length here for additional clarity. The California

Table 1
Sample description, size, date, and location.

Sample	Original location	Approximate time period[a]	*n*	Sample location
California Amerindian	Northern California	500–4600 BP	74	Phoebe Hearst Museum at the University of California, Berkeley (Berkeley, CA)
Dart	Johannesburg, South Africa	20th century	66	School of Medicine, University of Witwatersrand (Johannesburg, South Africa)
Indian Knoll	Green River, Kentucky	4143–6415 BP	80	University of Kentucky, Lexington (Lexington, KY)
Kulubnarti	Batn el Hajar, Upper Nubia	Medieval (6th–14th century)	96	University of Colorado, Boulder (Boulder, CO)
Luis Lopes	Lisbon, Portugal	20th century	46	Bocage Museum (Lisbon, Portugal)
Mistihalj	Bosnia-Herzegovina	Medieval (15th century)	45	Peabody Museum at Harvard University (Cambridge, MA)
Point Hope	Point Hope, Alaska	300–2100 BP	54	American Museum of Natural History (New York, NY)

[a] BP = Before present.

Amerindian sample used in this analysis is derived from 28 sites in the Alameda, Sacramento, and San Joaquin counties of north-central California, primarily clustered along the San Francisco Bay and the Sacramento and San Joaquin River valleys. California Amerindians of this area are best characterized as pre-contact, semi-sedentary, foraging populations, reliant on deer, elk, antelope, fishing, and extensive exploitation of acorns. Indian Knoll is an Archaic Period shell-midden site located on the Green River in Kentucky (Webb, 1946). Individuals from Indian Knoll were likely semi-sedentary with prolonged residences at seasonally occupied sites, who experienced relatively high population densities and relied heavily on a narrow spectrum of essential resources, such as deer, turkey, mussels, nuts, and a variety of locally collected plant materials (Winters, 1974). The site of Kulubnarti is located in Upper Nubia in the Batn el Hajar region, approximately 130 km south of Wadi Halfa, where two medieval Christian cemeteries containing 406 burials were excavated in 1979. With marginal subsistence levels, individuals traditionally lived in small villages, participated in small scale agriculture, and likely suffered from chronic nutritional difficulty combined with bouts of infectious disease during growth (Van Gerven et al., 1995). Mistihalj is a medieval burial site located on the border between Bosnia-Herzegovina and Montenegro. The remains at Mistihalj are culturally associated with the Vlakhs, an indigenous Balkan ethnic group, who engaged primarily in breeding sheep, horses, mules, and cattle, and who migrated seasonally over varied terrain (Alexeeva et al., 2003). The Dart Collection is an ethnically mixed, native African cadaver sample derived from hospitals in the Transvaal region in South Africa (Saunders and DeVito, 1991). Approximately 74% of all individuals died prior to 1950, and approximately 92% of the individuals within this sample are Bantu-speaking South African Blacks. Due to the diversity of this region, it is difficult to classify this sample area as exclusively rural or urban. The Luis Lopes skeletal collection consists of 20th century Portuguese from several cemeteries in Lisbon. In general, the sample is best categorized as an urban population of low to middle socioeconomic status (Cardoso, 2005). The site of Point Hope, Alaska, is situated on a peninsula in the Chuckchi Sea, approximately 200 km north of the Arctic Circle (Larsen and Rainey, 1948). Earlier periods of the Point Hope stratigraphic sequence are characterized by a reliance on caribou hunting, whereas later cultural horizons indicate a more extensive dependence on the exploitation of maritime resources such as walruses, seals, and whales (Larson and Rainey, 1948; Rainey, 1971). Immature skeletal remains from the multiple cultural periods excavated at Point Hope were combined into a single sample for this analysis, as previous analyses of Point Hope adults and immature individuals found little biomechanical difference between the early and late periods at this site (Cowgill, 2014; Shackelford, 2014).

Age was undocumented for six of the seven samples used in this study, and crown and root formation evaluated from lateral mandibular radiographs was used whenever dental and postcranial remains were reliably associated. Crown and root formation was assessed following the developmental standards set by Smith (1991) for permanent dentition and Liversidge and Molleson (2004) for deciduous dentition. Each set of dentition was scored twice on two consecutive days, and individual teeth that produced different formation stage scores were evaluated a third time to resolve inconsistencies. When no dentition was directly associated with the postcranial remains, chronological age was predicted from within-sample least squares regression of femoral, tibial, or humeral length on age for each of the comparative samples in order to maximize sample size (Cowgill, 2010). By developing age prediction equations specific to each sample, difficulties arising from the application of a formula developed on individuals differing in body size or proportions to an archaeological target sample are partially mitigated. Given the well-known difficulties of determining sex in immature samples (Cunningham et al., 2000), this was not attempted here and both males and females are analyzed together.

2.2. Methods

2.2.1. Body mass estimation methods Both of the formulae for generating body mass estimates used in this analysis are based on body masses and radiographic measurements from the Denver Growth Sample study, which was a longitudinal study carried out between 1927 and 1967 (McCammon, 1970). The formulae are based on a sub-sample of 20 individuals from this study, 10 male and 10 female, who are predominantly of northern European ancestry and middle to upper-middle class socioeconomic status. Both studies include least squares formulae for yearly intervals that are centered on the whole year (i.e., equations for 6 year olds apply to individuals between 5.5 and 6.5 years of age). Both studies also used percent standard error of the estimate (standard error of the estimate divided by mean body mass for that age group), which permits comparison of relative error across different size ranges, to evaluate the effectiveness of the formula. Percent standard error of the estimate is similar between the two methods, ranging between 5.0% and 19.1% for Ruff (2007) and 5.9% and 16.9% for Robbins et al. (2010) for raw measurements.

Ruff (2007) generated formulae based on maximum superoinferior femoral head breadth and maximum mediolateral distal femoral metaphyseal breadth. Formulae using distal femoral metaphyseal breadth are available for individuals between 1 and 12 years of age, and formulae based on femoral head breadth are available between ages 7 and 17, with the raw formula for ages 15 and 16 not achieving significance. Robbins et al. (2010) generated formulae based on femoral midshaft (45.5% of bone length from the distal end—see below) polar second moment of area, using diaphyseal external diameter and cortical thickness to reconstruct the cross-section (O'Neill and Ruff, 2004). The formula for the 16 year old age category was non-significant. Ruff (2007) also calculated formulae based on log-transformed data, but those based on raw data are used here to be comparable to raw data formulae from Robbins et al. (2010).

It should be noted that there is a third method for estimating body mass in immature individuals that uses the same sample and an alternate regression model, panel regression (Robbins Schug et al., 2013). In the development of this method, the authors found that the resulting formula performed equally well when compared to the previous age-structured, least squares method. I have elected not to include the panel regression method in my comparisons here, as the primary focus of this paper is to explore differences in accuracy across different regions of the femur and how those differences may or may not inform issues in growth and remodeling. Including the panel regressions from Robbins Schug et al. (2013) would add an additional layer of potential statistical effects, which is beyond the scope and aims of this paper.

2.2.2. Comparative samples The same skeletal dimensions were measured in each of the seven comparative samples. All measurements were taken with digital calipers to the nearest 0.1 mm. In order to calculate cross-sectional properties, biomechanical lengths for unfused humeri and femora were measured following Trinkaus et al. (2002a, b). Cross-sectional levels were chosen to best approximate the 50% section level in fused elements. In immature femora, however, 50% of diaphyseal length was calculated as 45.5% of femoral intermetaphyseal length, as this measurement best corresponds to the location of the 50% level in individuals with fused distal femoral epiphyses due to the relatively larger contribution of the distal epiphysis to biomechanical length in fused femora (Ruff, 2003a).

All cross-sectional properties were collected using a method similar to O'Neill and Ruff's (2004) “latex cast method” (LCM) and the method used by Sakaue (1998), which rely on anteroposterior and mediolateral radiographs and external molding. In order to reconstruct the femoral and humeral cross-sections, the external surface of the diaphysis was molded with Cuttersil Putty Plus™ silicone molding putty. Anterior, posterior, medial, and lateral cortical bone thicknesses were measured from radiographs with digital calipers, and measurements were corrected for parallax distortion by comparing external breadths measured on the radiograph with external breaths measured on the element. Once corrected for parallax, the four cortical bone thicknesses were plotted onto the two-dimensional copy of the original mold, and the endosteal contours were interpolated by using the subperiosteal contour as a guide. The resultant sections were enlarged on a digitizing tablet, and the endosteal and periosteal contours digitized. Cross-sectional properties were computed from the sections in a PC-DOS version of SLICE (Nagurka and Hayes, 1980; Eschman, 1992).

2.2.3. Analysis All body mass estimates were based on raw, unlogged measurements. When applying the ASMM, femoral metaphyseal breadth was used on individuals 12 and under, due to the fact that the proximal femoral epiphysis was missing in some individuals in the archaeological samples. In order to evaluate methodological differences in the two techniques related to age, individuals were divided into six age categories encompassing three year intervals: 0.0–2.9 years, 3.0–5.9 years, 6.0–8.9 years, 9.0–11.9 years, 12.0–14.9 years, and 15.0–17.9 years. These age categories were constructed primarily to provide sufficient sample size within categories for statistical analysis. Paired *t*-tests and Cohen's d were used to evaluate differences related to population membership and age between the two methods. When evaluating effect sizes, a Cohen's d of 0.2 is considered a “small” effect size, 0.5 represents a “medium” effect size, and 0.8 a “large” effect size.

3. Results

Body mass means for the two methods by sample and age category are shown in Table 2.

For the comparison of age categories, the results of the paired *t*-tests and Cohen's d are shown in Table 3. Boxplots of raw body mass differences by age category and the percent difference between the two methods by age category are shown in Figure 1. Estimates based on the diaphysis (DMM) are significantly higher in all age categories except one, where articular estimates (ASMM) are non-significantly larger (9.0–11.9 years, $p = 0.163$). All differences show small to moderate effect sizes ranging from 0.27 to 0.49.

For the comparison of samples, the results of paired *t*-tests and Cohen's d are shown in Table 4. Boxplots of raw body mass differences by sample and the percentage difference between the two methods by sample are shown in Figure 2. Three samples (Dart, Mistihalj, Point Hope) are significantly larger using the DMM and one sample (Kulubnarti) is smaller. The effect sizes range from small (0.25) to large (0.98).

4. Discussion

While both body mass estimation techniques for immature individuals perform well based on percent standard error of the estimate, there are statistically significant differences between the two methods that are related to both age and group membership. In comparisons by age group, the DMM produced higher body mass estimates in all ages except between 9.0 and 11.9 years of age, where the ASMM produces non-significantly higher results. This is likely due, in part, to the use of distal femoral metaphyseal breadth rather than femoral head diameter in this age range. While Ruff (2007) presents the options of using either distal femoral metaphyseal breadth or femoral head diameter for the ages between 7 and 13, the proximal femoral epiphysis is occasionally missing from archaeological specimens in this age range. Therefore, predictions from distal femoral metaphyseal breadth were used in this analysis. However, these formulae had the highest percent standard error of the estimate of all of the ASMM formulae, ranging between 14.3% and 16.4%. The large error surrounding estimates in these age categories may be related to the relatively higher estimates from the ASMM in the age category.

In comparisons by population, the DMM produced higher values than the ASMM in three samples and lower values in one. The DMM values are higher in Dart, Mistihalj, and Point Hope, but lower in Kulubnarti. This likely has to do with activity patterns and body mass reduction near the time of death. In particular, Mistihalj and Point Hope are samples of highly active, robust people (Cowgill, 2010). Subsistence reconstructions suggest that those in Mistihalj primarily engaged in breeding sheep, horses, mules, and cattle, and were nomadic pastoralists who migrated seasonally, spending summers in the highland pastures and winters in the warmer costal valleys (Alexeeva et al., 2003). In addition to being highly mobile, individuals at Mistihalj may have traveled over mountainous terrain, which previous studies have shown results in elevated lower limb robusticity (Ruff, 1999). The Point Hope population was also highly active—earlier periods at the site show evidence of caribou hunting and later periods indicate a more extensive

Table 2
Body mass means by method, age category, and sample.[a]

		Californian Amerindian		Dart		Indian Knoll		Kulubnarti		Luis Lopes		Mistihalj		Point Hope	
		ASMM	DMM	ASMM	DMM	ASMM	DMM	ASMM	DMM	ASMM	DMM	ASMM	DMM	ASMM	DMM
0.0–2.9 years	Mean	9.19	9.66	7.22	7.75	9.20	9.37	8.51	8.16	9.14	8.64	9.01	10.37	9.25	9.95
	Std. Deviation	1.84	2.28	1.55	1.97	1.53	2.02	1.76	2.09	1.92	2.96	2.36	3.19	2.15	3.04
3.0–5.9 years	Mean	14.68	14.61	12.86	13.58	12.51	13.37	13.98	13.77	14.14	14.26	14.76	15.49	11.69	13.63
	Std. Deviation	2.21	1.85	1.95	1.12	1.59	1.57	1.52	1.45	1.53	1.18	2.62	1.99	1.17	1.30
6.0–8.9 years	Mean	21.53	21.83	18.77	19.16	20.45	20.95	18.79	18.81	20.07	20.41	20.87	24.35	18.22	21.43
	Std. Deviation	1.82	0.99	3.19	2.91	2.78	2.40	2.67	2.10	3.26	3.42	3.25	4.38	2.32	3.14
9.0–11.9 years	Mean	29.15	25.15	25.87	25.54	25.53	24.70	27.56	23.75	30.42	30.61	27.91	29.82	26.50	28.87
	Std. Deviation	3.44	1.76	3.38	2.92	2.65	2.01	3.26	2.32	5.52	8.82	1.71	3.47	4.40	3.31
12.0–14.9 years	Mean	41.10	41.51	34.37	39.47	35.49	35.04	34.95	33.87	41.24	42.15	40.32	41.31	42.29	45.63
	Std. Deviation	8.21	8.39	8.67	10.87	5.49	5.51	4.04	5.13	8.76	8.96	6.57	8.67	7.32	10.31
15.0–17.9 years	Mean	55.71	58.03	55.72	57.97	50.37	52.61	51.42	52.78	56.17	56.17	59.60	60.02	52.83	56.60
	Std. Deviation	5.35	4.98	4.37	3.36	4.96	2.84	5.34	2.71	4.49	3.38	6.90	5.84	4.23	3.49

[a] ASMM = Articular Surface Measurement Method, DMM = Diaphyseal Measurement Method, Std = standard.

Table 3
Results of paired *t*-tests by age category.[a]

Age category	*n*	Method	Mean	*t*-Value	*p*-Value	Cohen's d
0.0–2.9 years	115	ASMM	8.578	−3.312	0.001	0.308
		DMM	8.890			
3.0–5.9 years	76	ASMM	13.581	−3.403	0.001	0.390
		DMM	14.019			
6.0–8.9 years	78	ASMM	19.784	−4.315	<0.001	0.489
		DMM	20.795			
9.0–11.9 years	69	ASMM	27.340	1.409	0.163	N/A
		DMM	26.717			
12.0–14.9 years	69	ASMM	38.146	−2.263	0.027	0.272
		DMM	39.382			
15.0–17.9 years	54	ASMM	54.602	−3.099	0.003	0.422
		DMM	56.591			

[a] ASMM = Articular Surface Measurement Method, DMM = Diaphyseal Measurement Method.

Table 4
Results of paired *t*-test by population.[a]

Sample	*n*	Method	Mean	*t*-Value	*p*-Value	Cohen's d
Cal. Amerindian	74	ASMM	26.969	−0.255	0.799	N/A
		DMM	27.067			
Dart	66	ASMM	24.119	−4.023	<0.001	0.450
		DMM	25.683			
Indian Knoll	80	ASMM	22.820	−0.866	0.389	N/A
		DMM	23.066			
Kulubnarti	96	ASMM	20.404	2.459	0.016	0.251
		DMM	19.813			
Luis Lopes	46	ASMM	26.006	−0.419	0.677	N/A
		DMM	26.223			
Mistihalj	45	ASMM	22.932	−3.689	0.001	0.550
		DMM	24.551			
Point Hope	54	ASMM	26.457	−7.186	<0.001	0.978
		DMM	29.076			

[a] ASMM = Articular Surface Measurement Method, DMM = Diaphyseal Measurement Method.

dependence on the exploitation of maritime resources such as walruses, seals, and whales (Larsen and Rainey, 1948; Rainey, 1971). In addition, previous studies have shown Point Hope and Mistihalj to have the most robust femora out of the seven samples used here (Cowgill, 2010). However, even when these two samples are removed, the DMM still has significantly higher body mass estimates than the ASMM in all ages except for one (between the 9.0 and 11.9 years; $p < 0.05$). This suggests that even in the absence of highly robust samples, the DMM may produce high body mass estimates in most archaeological samples.

In contrast, one group, Kulubnarti, shows lower estimates of body mass when the DMM is used. During the medieval period, marginal subsistence levels characterized the area, and the site of Kulubnarti experienced increasing economic isolation and hardship. Individuals at medieval Kulubnarti suffered from chronic nutritional difficulty combined with bouts of infectious disease during growth. Incidence of iron deficiency and non-specific developmental stress are extremely high among immature individuals at this site, with 82–94% of all immature crania exhibiting signs of cribra obritalia and all individuals having at least one enamel hypoplasia (Mittler et al., 1992; Van Gerven et al., 1995). In the light of the previously documented growth disturbances and nutritional deficits among the immature individuals at Kulubnarti, it seems plausible that their low levels of femoral robusticity may be related to nutritional stress leading to body mass reduction, which is reflected to a greater extent in diaphyseal dimensions.

Two additional studies provide support for this interpretation. When Lambert et al. (2005) compared tibial strength properties of well-fed growing rats to those of calorically deprived controls, tibial length, mass, area, and cross-sectional moment of inertia were indeed reduced in deprived animals. However, when the reduced structural properties were scaled to the reduced body mass of the deprived sample, this pattern disappeared. Similar arguments can be made for reduced bone mass in anorexics. Galusca et al. (2008) compared cross-sectional properties of the radius and tibia in anorexics to those of very thin women with a BMI range of 12.0–16.5 kg/m^2 but normal fat mass percentages, menstrual cycles, hormonal levels, and energy metabolism. Cortical thickness, total area, and second moments of area of the radial and tibial diaphyses were decreased in both very thin women and longstanding anorexics, leading the authors to suggest that the primary determinant of reduced skeletal mass in these subjects is not nutritional deficit or hormonal changes associated with amenorrhea, but insufficient skeletal load.

Last, there is good evidence that long bone diaphyses may be particularly sensitive to environmental factors during growth. While several studies have documented the correlation between articular surface size and body mass, articular surface areas may not be as sensitive to changes in mechanical loading as diaphyses. Lieberman et al. (2001) compared articular surface areas of

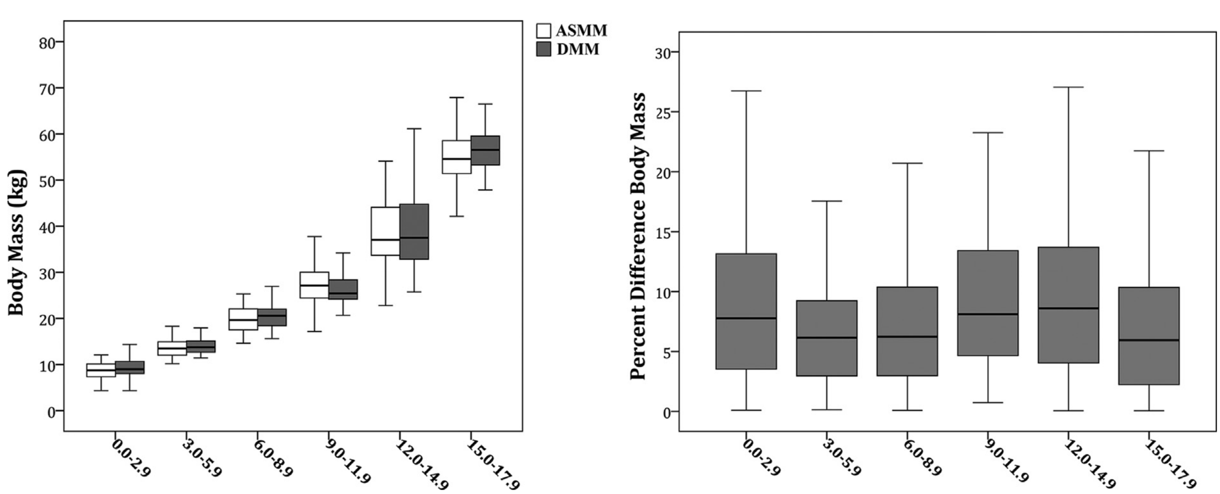

Figure 1. Boxplots of raw body mass differences by age category (x axis) and the percent difference between the two methods by age category. Boxplots show the median value, the interquartile range, minimum, and maximum. Articular Surface Measurement Method (ASMM) shown in white; Diaphyseal Measurement Method (DMM) shown in gray. Percent difference between the two estimates is calculated at |ASMM − DMM|/(ASMM + DMM/2).

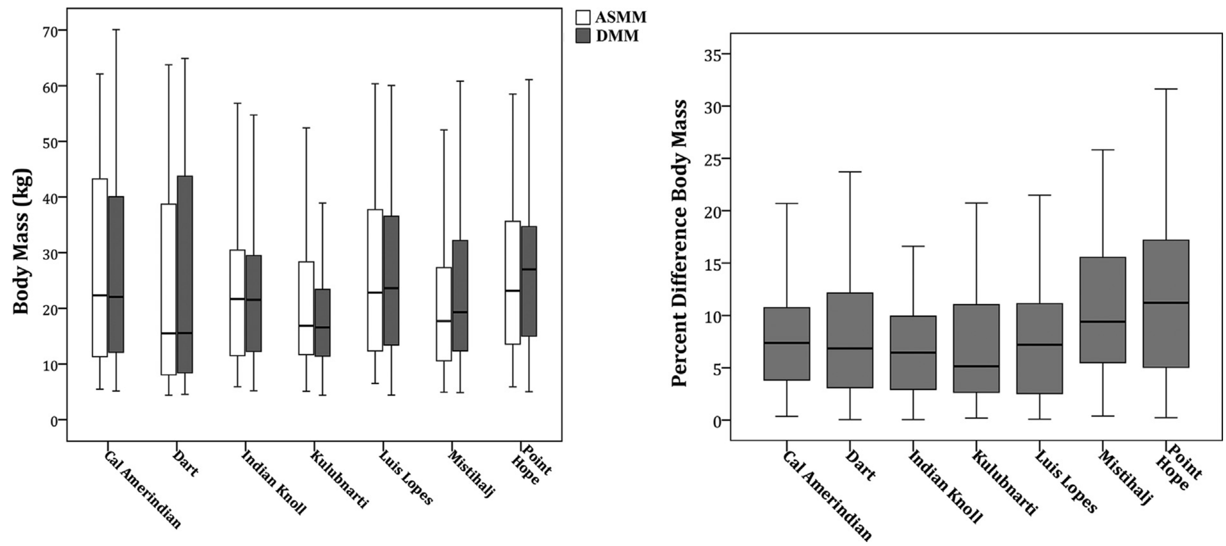

Figure 2. Boxplots of raw body mass differences by sample (x axis) and the percentage difference between the two methods by sample. Boxplots show the median value, the interquartile range, minimum, and maximum. Articular Surface Measurement Method (ASMM) shown in white; Diaphyseal Measurement Method (DMM) shown in gray. Percent difference between the two estimates is calculated at |ASMM − DMM|/(ASMM + DMM/2).

exercised and control sheep and found that, in contrast to immature diaphyseal cross-sectional properties, articular surface areas did not respond to mechanical loading. It is possible that articular surface areas are more tightly constrained by their need to maintain congruence with the opposite joint surface (see also Auerbach and Ruff, 2006). These two lines of evidence suggests that bone diaphyses may be sensitive to shifts in body mass that articular surface measurements are unable to detect. Therefore, while the DMM may over-estimate body mass in active archaeological populations, it may also be sensitive to body mass declines (or increases) near the time of death.

This may make the DMM more appropriate for use when actual body mass near the time of death is necessary. For example, in paleoanthropology or bioarchaeology, a generalized population-wide estimate of body mass may be useful for drawing conclusions regarding changes in body mass over broad periods of time and the relationship of those changes to health, growth, subsistence, or encephalization. Conversely, in forensic analyses, an estimate of body mass that reflects exceptionally low or high body mass may be of more use in providing an accurate image of the deceased for law enforcement. Given this, each researcher should carefully evaluate the ultimate goals of their body mass reconstruction prior to the selection of a particular method.

5. Conclusion

Given that the determination of body mass in immature individuals is important in forensic, bioarchaeological, and paleoanthropological research, it is useful to have estimation formulae that rely on different skeletal elements for contexts where preservation may be suboptimal. However, how different approaches to body mass calculation may influence point estimates must be considered. When selecting an appropriate method for use in bioarchaeological or paleontological samples where childhood activity is likely to be vigorous and create higher biomechanical loads, it is important to consider that methods based on long bone cross-sections may be influenced by bone functional adaptation to elevated loading. Because juvenile body mass estimation techniques, by necessity, have been developed from living industrialized samples, caution should be used when applying such methods to past populations that are non-industrial or where the level of activity is not known a priori. However, the DMM may be useful in some forensic contexts where, due to highly fragmentary and/or damaged remains, methods based on complete articular surfaces are not applicable and the level of activity engaged in by the deceased is probably similar to middle to upper-middle class children in an industrial environment. In contrast, the ASMM is appropriate for bipedal hominins where the scaling relationship between articular surface size and body mass has already been established, and if not confounded by reduced hip joint reaction forces and small femoral head sizes, as has been suggested for australopiths (Ruff, 2015; Ruff et al., 2018). In addition, while exploratory analyses suggest the ASMM works well on individuals of differing body types (Cowgill, 2010), additional testing with individuals of known body mass from diverse populations is necessary for further confirmation.

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