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Juvenile body mass estimation: A methodological evaluation☆

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ABSTRACT

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.

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