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Can we refine body mass estimations based on femoral head breadth?

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ABSTRACT

Femoral head breadth is widely used in body mass estimation in biological anthropology. Earlier research has demonstrated that reduced major axis (RMA) equations perform better than least squares (LS) equations. Although a simple RMA equation to estimate body size from femoral head breadth is sufficient in most cases, our experiments with male skeletons from European data (including late Pleistocene and Holocene skeletal samples) and the Forensic Anthropology Data Bank data (including the W. M. Bass Donated Skeletal Collection sample) show that including femoral length or anatomically estimated stature in an equation with femoral head breadth improves body mass estimation precision. More specifically, although directional bias related to body mass is not reduced within specific samples, the total estimation error range, directional bias related to stature, and temporal fluctuation in estimation error are markedly reduced. The overall body mass estimation precision of individuals representing different temporal periods and ancestry groups (e.g., African and European ancestry) is thus improved.

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1. Introduction

Body mass is the most important indicator of overall body size, due to its correlation with energy requirements, home-range size, social organization, and many life-history variables. In addition, body mass estimations are needed when determining sexual dimorphism, as well as relative brain size, tooth size, and skeletal robusticity (for more complete reviews see [Ruff et al., 2012](#); [Grabowski et al., 2015](#); [Jungers et al., 2016](#)).

Body mass is largely a product of body dimensions determined by underlying skeletal dimensions. Linear skeletal dimensions (e.g., long bone lengths, vertebral body heights) mainly determine stature, and lateral skeletal dimensions (e.g., bi-iliac breadth) determine trunk breadth. Stature, combined with trunk breadth, is thus an important determinant of body mass. Stature estimation accuracy is especially important if stature is included as a predictor variable in body mass estimation.

Stature estimation methods are divided into “mathematical” methods, in which stature is estimated from skeletal dimensions

(most often long bone lengths) using a regression equation or a ratio, and more accurate “anatomical” methods, in which stature is estimated from summed skeletal elements from the cranium to the ankle (see reviews in [Lundy, 1985](#); [Raxter et al., 2006](#); [Ruff et al., 2012](#); [Niskanen et al., 2013](#)). Of the anatomical equations, Eq. (1) of [Raxter et al. \(2006\)](#) is currently the most commonly used (e.g., [Raxter et al., 2008](#); [Vercellotti et al., 2009](#); [Auerbach and Ruff, 2010](#); [Maijanen and Niskanen, 2010](#); [Ruff et al., 2012](#)).

Estimating body mass is not as straightforward and accurate as estimating stature. There are more “dimensions” included and much more variation in the soft tissue mass-skeletal size relationship between individuals, as well as within individuals. Furthermore, as reviewed by [Jungers et al. \(2016\)](#), there are differences in opinion about the best predictor variables and the most appropriate reference samples used.

There are two main categories of body mass estimation: the “morphometric” approach and the “mechanical” approach ([Auerbach and Ruff, 2004](#)). In morphometric body mass estimation, body mass is estimated from estimated or even measured body dimensions, for example, from stature and bi-iliac breadth ([Ruff et al., 1991, 2005](#); [Ruff, 1994, 2000](#)). Morphometrically derived body masses from stature and bi-iliac breadth exhibit little or no

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systematic error related to these predictor variables, but biacromial shoulder breadth relative to bi-iliac breadth and relative sitting height affect estimation precision. Body mass tends to be underestimated if biacromial shoulder breadth is relatively broad and relative sitting height is high, and vice versa (Ruff, 2000; Ruff et al., 2005). Accuracy of the morphometric method naturally partly depends on the accuracy of stature estimation.

In mechanical body mass estimation, body mass is estimated from skeletal dimensions that mechanically support body mass. Femoral head breadth is most often used because it is often preserved, easy to measure, and has been found to correlate positively with body mass (Ruff et al., 2012 and references therein). There are several regression equations for estimating body mass of humans from this skeletal dimension (Ruff et al., 1991, 2012; McHenry, 1992; Grine et al., 1995).

There is little or no change in joint size and shape with age during adulthood because joint size and shape do not appear to change in response to changes in loading (see Squyres and Ruff, 2015 and references therein). For this reason, femoral head breadth reflects an individual's young adult body mass more closely than later life body mass (Ruff et al., 1991). Young adult body mass data are more appropriate for body mass estimation in archaeological samples, especially due to the current obesity epidemic in industrial countries. Although current young males in their late teens and early twenties have not yet achieved their peak lean body mass, their fat percentages are higher on average than those of highly mobile prehistoric foragers. For example, the traditional Inuit combined strong muscles with low body fat percentage, which resulted in heavier body mass for stature than expected (see Rode and Shephard, 1971). However, as in comparisons between modern elite athletes and normal (sedentary) people, the greater fatness of current young adults and greater muscularity of fully adult past people may cancel each other out in terms of body mass estimation from skeletal dimensions (Ruff, 2000).

Body mass estimates from femoral head breadth and other joint breadths are not as accurate as those derived using the stature and bi-iliac breadth method (but see Elliott et al., 2016a). Femoral head breadth-body mass correlations (male $r = 0.497$; female $r = 0.411$ in Ruff et al., 1991:their Table 2) and knee joint breadth-body mass correlations (male $r = 0.58$; female $r = 0.31$ in Squyres and Ruff, 2015:their Table 3) are lower than correlations between body mass estimates from stature and bi-iliac breadth and body mass. In this latter case, for younger adults (20–39 years) with healthy fat percentages (Schaffer, 2016:Table 2), correlations range from $r = 0.717$ to $r = 0.720$ in males and $r = 0.549$ to $r = 0.661$ in females. In the case of males, these correlations are about as strong as correlations between stature and forearm long bone lengths in Trotter and Gleser (1958:their Table 4).

Due to assuming unbiased results for estimating body mass from stature and bi-iliac breadth, these estimates have been used as proxies of body mass in a kind of “hybrid” approach to generate regression equations to estimate body mass from femoral head breadth (e.g., Ruff et al., 2012). Using the stature and bi-iliac breadth equations in preference to the femoral head equations has been questioned by Elliott et al. (2016a), who found that these equations do not necessarily provide more accurate estimates than the femoral head ones. However, their sample includes many excessively obese and possibly also underweight individuals (see summary data in Elliott et al., 2016a:their Table 1, 2016b:their Tables 1 and 2). Restricting analyses to individuals within the “healthy” BMI range (Squyres and Ruff, 2015) or fat percentage range (Schaffer, 2016) greatly improves estimation accuracy and provides different conclusions on relative performances of the morphometric and mechanical methods (see correlation coefficient values in the previous paragraph).

The overall size of an individual appears to matter in estimating body mass from femoral head breadth. Several researchers have found apparent allometric effects on the body mass-femoral head breadth size relationship and have recommended the application of different equations in different body size ranges (e.g., Auerbach and Ruff, 2004; Kurki et al., 2010; Ruff, 2010). For example, Auerbach and Ruff (2004) found that body masses estimated from femoral head breadth tend to be larger than body masses estimated from stature and bi-iliac breadth in small individuals, but smaller in large individuals. Assuming unbiased results for estimating body mass from stature and bi-iliac breadth, body mass estimates from femoral head breadth tend to be overestimations in short and/or narrow-bodied individuals and underestimations in tall and/or broad-bodied individuals.

The above size-related trends are driven in part by stature variation. Stature is not only an important determinant of body mass, but it also affects proportional relationships of different skeletal elements and thus body proportions. For example, temporal stature changes are associated with considerable changes in limb length and biacromial shoulder breadth (based on shifts in clavicular lengths), but lesser shifts in femoral head breadth and especially in bi-iliac breadth (see Niskanen et al., 2018b).

Differences in body proportions between current human populations adapted to different climates and between different past populations inhabiting the same general region also matter in estimating body mass from stature and bi-iliac breadth or from femoral head breadth. For example, Americans of African and European ancestry do not differ in stature, body mass, and lean body mass (computed from fat percentage and total body mass), but the former have slightly smaller femoral head breadths combined with longer long bones (especially those of distal limb segments), slightly broader biacromial breadths, and considerably narrower bi-iliac breadths (on osteometrics see Spradley and Jantz, 2011:their Tables 7 and 8; on anthropometrics see Schaffer, 2016:their Table 1). Similarly, considerable differences in the proportional relationships of skeletal dimensions between the Neandertals and their early Upper Paleolithic (EUP) successors in Europe indicate very different body shapes. More specifically, the former had absolutely and relatively much shorter limbs, as well as somewhat larger femoral heads and broader bi-iliac breadths (see Holliday, 1995). There has also been temporal and geographic fluctuation in body proportions in Europe since the EUP (Niskanen et al., 2018b). For example, the middle Neolithic foragers associated with the Pitted Ware culture in Scandinavia had absolutely and relatively shorter limbs and relatively broader bi-iliac breadths than other Neolithics (Niskanen et al., 2018a). It is possible that the above temporal and geographic fluctuation in body proportions have effects on body mass estimation.

In this study, we investigate whether body mass estimations from femoral head breadth could be improved by including femoral length or estimated stature in a body mass estimation equation with femoral head breadth. That is, body mass is estimated from femoral head breadth and a linear dimension, analogous to estimating body mass from bi-iliac breadth and stature, which provides accurate estimates for individuals with different body proportions (see Ruff et al., 2005).

2. Material and methods

2.1. Study samples

Three skeletal samples were included in this study: a sample of European male skeletons, a sample of W.M. Bass Donated Collection males of European ancestry, and a sample of males of European and African ancestry from the Forensic Anthropology Data Bank. The

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