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Assessing the accuracy of body mass estimation equations from pelvic and femoral variables among modern British women of known mass

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ABSTRACT

Femoral head diameter is commonly used to estimate body mass from the skeleton. The three most frequently employed methods, designed by Ruff, Grine, and McHenry, were developed using different populations to address different research questions. They were not specifically designed for application to female remains, and their accuracy for this purpose has rarely been assessed or compared in living populations. This study analyzes the accuracy of these methods using a sample of modern British women through the use of pelvic CT scans ($n = 97$) and corresponding information about the individuals' known height and weight. Results showed that all methods provided reasonably accurate body mass estimates (average percent prediction errors under 20%) for the normal weight and overweight subsamples, but were inaccurate for the obese and underweight subsamples (average percent prediction errors over 20%). When women of all body mass categories were combined, the methods provided reasonable estimates (average percent prediction errors between 16 and 18%). The results demonstrate that different methods provide more accurate results within specific body mass index (BMI) ranges. The McHenry Equation provided the most accurate estimation for women of small body size, while the original Ruff Equation is most likely to be accurate if the individual was obese or severely obese. The refined Ruff Equation was the most accurate predictor of body mass on average for the entire sample, indicating that it should be utilized when there is no knowledge of the individual's body size or if the individual is assumed to be of a normal body size. The study also revealed a correlation between pubis length and body mass, and an equation for body mass estimation using pubis length was accurate in a dummy sample, suggesting that pubis length can also be used to acquire reliable body mass estimates. This has implications for how we interpret body mass in fossil hominins and has particular relevance to the interpretation of the long pubic ramus that is characteristic of Neandertals.

1. Introduction

The ability to accurately estimate human body mass from skeletal remains is an important task for paleoanthropologists, archeologists, and forensic scientists (Auerbach and Ruff, 2004). Knowledge about an organism's body size gives significant insight into its ecological, behavioral, and life history traits (Calder, 1984; Schmidt-Nielsen, 1984; Damuth and MacFadden, 1990; Smith et al., 1996). Accurately estimating body mass also has implications for the study of human evolution due to the fact that size estimates are used to extrapolate other information about an organism's anatomy and life history. Because body size and allometric relationships have an important bearing on many aspects of an organism's existence, paleoanthropologists often infer characteristics of fossil hominins such as their relative lifespan, social structure, and diet (Wood and Collard, 1999; Ruff, 2002; Sciulli and Blatt, 2008; Kurki et al., 2010; Reynolds and Gallagher, 2012) on the basis of body mass estimates. Estimates of body mass are also beneficial when comparing intra and inter-specific features of hominins such as relative limb size, tooth size, and cranial capacity (Smith and Jungers, 1997; Rightmire, 2004; DeSilva and Lesnik, 2008). However, body mass estimates for *Homo* have varied greatly, with as much as 50% difference in size estimation for the same individual (McHenry, 1976, 1992; Feldesman and Lundy, 1988; Rightmire,

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1988; Hartwig-Scherer, 1993; Aiello and Wood, 1994; Kappleman and Kappleman, 1996; Will and Stock, 2015). This discrepancy demonstrates the need for more precise methods of body mass estimation with smaller margins for error.

Multiple methods of body mass estimation in humans and hominins have been calculated that utilize femoral head diameter as an independent variable in regression equations (Ruff et al., 1991; McHenry, 1992; Grine et al., 1995), but their accuracy has rarely been re-assessed or compared in living populations. On the occasions when these equations have been tested, it is typical that they are more accurate in male samples than in female samples, thus showing the need for enhancing the accuracy of body mass estimation methods for females (Lorkiewicz-Muszyńska et al., 2013; Elliott et al., 2016). This study therefore assesses the accuracy of three body mass estimation equations based on femoral head diameter (FMHD) in a sample of pelvic computed tomography (CT) scans of modern women of known mass.

The Ruff Equation (Ruff et al., 1991), derived from a study of 80 living subjects in North America, is likely the most frequently used equation of the three discussed here. The individuals were outpatients at Johns Hopkins Hospital in Baltimore, Maryland, USA, and they ranged in age from 24 to 81 years, with a mean of 52 years. Males and females were nearly equally divided, with 41 males and 39 females. Mean weight of the total sample was 76.7 kg, and mean weight of the female subsample was 72.4 kg. Because many individuals in the sample were overweight, the authors concluded that the body mass estimation equations they calculated were likely to overestimate body mass in preindustrial or preagricultural populations by a margin of roughly 10%. They therefore concluded that 10% should be subtracted from the estimate "to account for the increased adiposity of very recent U.S. adult populations" (Ruff et al., 1991:411). This results in the final sex-specific equation for females:

$$\text{Body mass} = (2.426 \times \text{FMHD} - 35.1) \times 0.90$$

The original and amended versions of the Ruff Equation will be assessed in this study and will be referred to as the Original Ruff Equation and the Refined Ruff Equation henceforth. Both versions of the equation will be assessed in order to compare their accuracy in subsamples of differing BMI ranges and to determine whether the authors were correct in asserting that the original equation would be best suited for modern samples.

The McHenry Equation was published in a study of body size and proportions in early hominids (McHenry, 1992). The human sample used was composed of skeletons from cadavers of North Americans of mixed ancestry, as well as museum specimens including "6 skeletons of the diminutive Khoisan people and 2 African Pygmies" (further identification of the specific populations the "Pygmy" sample came from was not provided in the original manuscript). McHenry estimated each specimen's body weight by first calculating stature from humeral, femoral, and tibial lengths by Olivier's (1976) standards and deriving weight from a power curve by Jungers and Stern (1983). McHenry measured multiple variables and performed least squares regression in order to determine their relationship to body weight and create regression equations for body mass estimation that could be utilized in the fossil sample. McHenry's equation for predicting body mass from femoral head diameter in both sexes is:

$$\text{Body mass} = 2.239 \times \text{FMHD} - 39.9$$

The Grine Equation was developed as part of a study of the Berg Aukas fossil *Homo* femur (Grine et al., 1995). Grine et al. (1995) estimated the body size of the individual based on the femoral head diameter by utilizing a sample of 10 sex-specific means of large-bodied humans, including African Americans, European Americans, and Native Americans, from data collected for a separate study (Jungers, 1988). A large-bodied sample was chosen due to the fact that the femur itself was large, with a femoral head diameter larger than any other found in the hominin fossil record at the time. The equation that results from the linear regression performed is not female specific and was reported as:

$$\text{Body mass} = 2.268 \times \text{FMHD} - 36.5$$

Little is known about the accuracy of the Ruff, Grine, and McHenry Equations, especially with regard to female samples. The aim of this study is therefore to test the accuracy of these equations in a modern female sample and compare their accuracy across subsamples of BMI ranges to determine which equations are best suited to individuals, particularly female individuals, that are believed or known to be large or small bodied. Two additional aims of this study are to determine whether pelvic and proximal femur metrics other than femoral head diameter provide equal or better estimates of body mass for females, and to develop new body mass estimation equations based on these potential metrics.

2. Methods

The collection of pelvic CT scans utilized in this study was acquired in a previous study (Poole et al., 2010). Female volunteers between the age of 20 and 90 were recruited in order to analyze the structure of the femoral neck in women of various ages. One hundred twenty-five women volunteered and fulfilled the inclusion criteria, but twenty declined to participate (84% compliance rate). Additionally, five participants were excluded from the sample after the CT scanning was completed. Study participants were volunteers who attended Addenbrooke's Hospital in Cambridge, UK, for a routine clinical CT scan (including the abdomen and pelvis) for purposes unrelated to skeletal disease and who were otherwise healthy. The participants consented to a hip quantitative computed tomographic (QCT) scan that involved both proximal femora, ranging beyond the pelvic scan to extend 2 cm distally to the lesser trochanter. Body mass was recorded at the time of the CT scan. The Cambridgeshire Regional Ethics Committee approved the study, and subjects were recruited according to the Declaration of Helsinki. The sample used in the current study includes pelvic CT scans from 97 individuals, with the remaining three CT scans unable to be included due to unavailable data. Descriptive and demographic parameters of the study participants are provided in Table 1. The scans are currently held at Addenbrooke's Hospital in Cambridge, UK.

Computed tomography measurements were taken in Avizo Fire, and estimated values of body mass were calculated for each individual using the measurement of the femoral head diameter in the equations by Ruff, Grine, and McHenry. For each estimation equation, the means of actual body mass and estimated body mass were compared using an independent samples *t*-test in IBM SPSS Statistics 21. The results were considered statistically significant when $p < 0.05$. Percent error of the estimate was also taken for each individual by using the formula (estimated weight—actual weight)/actual weight.

The process of comparing actual weight and estimated weight and calculating percent errors was completed for the entire sample ($n = 97$) and was then repeated for the subsamples of specific BMI ranges to compare the rates of error between subsamples of underweight (BMI below 18.5), normal weight (18.5–24.9), overweight (25–29.9), obese (30–39.9), and severely obese (BMI greater than 40), as defined by the UK National Health Service.