Estimating Body Mass in Subadult Human Skeletons

Gwen Robbins,¹ Paul W. Sciulli,² and Samantha H. Blatt²

¹Department of Anthropology, Appalachian State University, Boone, NC 28608
²Department of Anthropology, The Ohio State University, Columbus, OH 43201

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ABSTRACT  Methods for estimating body mass from the subadult skeleton are often required for research in biological or forensic anthropology. There are currently only two methods for estimating body mass in subadults: the width of the distal femur metaphysis is useful for individuals 1–12 years of age and the femoral head is useful for older subadults. This article provides age-structured formulas for estimating subadult body mass using midshaft femur cross-sectional geometry (polar second moments of area). The formulas were developed using data from the Denver Growth Study and their accuracy was examined using an independent sample from Franklin County, Ohio. Body mass estimates from the midshaft were compared with estimates from the width of the distal metaphysis of the femur. Results indicate that accuracy and bias of estimates from the midshaft and the distal end of the femur are similar for this contemporary cadaver sample. While clinical research has demonstrated that body mass is one principle factor shaping cross-sectional geometry of the subadult midshaft femur, clearly other biomechanical forces, such as activity level, also play a role. Thus formulas for estimating body mass from femoral measurements should be tested on subadult populations from diverse ecological and cultural circumstances to better understand the relationship between body mass, activity, diet, and morphology during ontogeny. Am J Phys Anthropol 143:146–150, 2010. © 2010 Wiley-Liss, Inc.

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*Correspondence to: Gwen Robbins, Department of Anthropology, 416 Sanford Hall, 225 Locust Street, Appalachian State University, Boone, NC 28607. E-mail: Robbinsgm@appstate.edu

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Biological anthropologists who seek to understand human biological variation from an evolutionary or bi-cultural perspective often require methods to estimate body shape and size from subadult human skeletal material. Forensic anthropologists similarly require accurate and precise estimates of stature and body mass (or weight) from the skeletal remains of human children to aid in personal identification. While there are several methods available for estimating stature from subadult bones (Telkka et al., 1982; Himes et al., 1977; Feldesman, 1992; Ruff, 2007) there are fewer published methods for accurately estimating body mass from the subadult skeleton. Ruff (2007) provides methods to estimate body mass in subadults using the width of the distal metaphysis of the femur in children less than 12 years of age and using the femoral head for older juvenile and adolescent individuals.

The femur articular surfaces yield accurate estimates of body mass because it is clear that body mass is the base load to which the lower appendicular skeleton is subject during life (Ruff et al., 1993; Ruff, 2000, 2002a, 2005a). Research has also shown a strong correlation between body weight and femoral midshaft bone mass throughout human ontogeny (Van Der Meulen et al., 1993, 1996; Moro et al., 1996; Sumner and Andriacchi, 1996; Ruff, 2003a, b, 2005a; Ruff et al., 2006) with body mass and activity level acting in synergy to shape the acquisition of bone mass early during ontogeny (Ruff, 2003a, b, 2005a). The goals of this article are thus to investigate the relationship between body mass and femoral midshaft geometry (polar second moment of area, J) in samples of modern human subadults and to provide equations for estimating subadult body mass. The present approach can supplement previous methods when the femur distal metaphysis or femur head is not available.

MATERIALS AND METHODS

A set of age-structured least squares regression formulas for predicting subadult body mass from femur midshaft cross-sectional geometry (polar second moment of area) were developed using a longitudinal sample of measurements from 20 well-nourished, active juveniles 2 months to 17 years of age selected from a database compiled by the Denver Child Research Council from 1941 to 1967, and used in several previous studies (Ruff, 2003a, b, 2005a, 2007). Permission to use these data for this project was obtained from Richard Siervogel, current Director of the Lifespan Health research Center at Wright State University. Ruff measured femur lengths, external diaphyseal diameter, and cortical bone thicknesses (at 45.5% of diaphyseal length) from the Denver sample anteroposterior radiographs (Ruff, 2003a, b). Medullary diameter (M) was calculated as diaphyseal external diameter (T) minus combined cortical thickness, and torsional rigidity, J, as (O’Neill and Ruff 2004) \( \pi/32 \times (T^4 - M^4) \), assuming a cylindrical model. Magnification error was corrected as described previously. An intraobserver measurement error of 3.1% for J was reported (Ruff, 2007).
The Denver data were originally collected at 2, 4, 6, and 12 months for the first year of life and at 6 month intervals through the age of 17 years (although more often annually after age 14 years). Here only data for 2 months (referred to as age category “0”) and at annual intervals from 1 to 17 years of age were used to derive estimation equations. Results are intended to apply to individuals at ±6 months from these ages, e.g., the 1-year-old formula applies to individuals 6 months to 17.5 months. The “0” year formula applies to individuals under 6 months of age. Missing data points (2.3% of total sample) were estimated using linear interpolation such that each age category initially contained 20 individuals (following Ruff, 2007). The only exception was the “0” year age category, which contained 15 individuals. Based on comparisons of BMI (body mass index, weight/height\(^2\)) to national standards (Must et al., 1991), one female at ages 4–8 and one male at ages 6–8 were eliminated as extreme positive outliers, following Ruff (2007). Thus, age categories 4 and 5 had a final sample size of 19 individuals and age categories 6–8 had a sample size of 18 individuals.

The formulas were tested on an independent sample from the Franklin County, Ohio Coroner’s office (Pfau and Sciulli, 1994; Sciulli, 1994; Sciulli and Blatt, 2008). This sample consists of 186 subadult individuals, 0.04–20 years of age, who died between July 1, 1990 and June 30, 1991. Long bones were radiographed shortly after death (Pfau and Sciulli, 1994; Sciulli and Blatt, 2008). Dates of birth, death, sex, ancestry, weight, and stature were obtained from previous medical records. The sample includes European-American and African-American males and females. Blatt collected the following measurements from the radiographs: femur midshaft breadth and external diaphyseal and medullary breadths (at 50% of diaphyseal length). Twenty individuals (17.8%) were measured on two separate occasions and these measurements were compared for intraobserver error. The mean standard deviation was ±0.12 mm for the midshaft diameter and ±0.47 mm for the medulla. Following Ruff (2007), Blatt calculated polar second moments of area (\(J\)) using the method described above.

### Results

Least squares regression formulas, by age class, for predicting body mass from \(J\) in the Denver sample are shown in Table 1. Results of one-way ANOVA’s demonstrate that torsional rigidity is a significant predictor of body mass. The %SEE was compared for the formulas from the midshaft with the published formulas for estimating body mass from the width of the distal metaphysis (ages 1–12) and the femoral head (ages 7–17; Ruff, 2007).

### Abbreviations

- **BMI**: body mass index
- **CI**: confidence interval
- **FH**: Femoral Head
- **J**: polar second moments of area
- **MET**: metaphysis
- **MS**: midshaft
- **SEE**: standard error of the estimate
- **%SEE**: percent standard error of the estimate

### Table 1. Equations for predicting body mass (kg) from femoral second moments of area (\(J\)), (raw data)

<table>
<thead>
<tr>
<th>Age</th>
<th>Body mass</th>
<th>BMI Slope</th>
<th>Intercept</th>
<th>(F)</th>
<th>(P)</th>
<th>SEE(^a) %SEE(^b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>4.52</td>
<td>3.8</td>
<td>0.003</td>
<td>3.454</td>
<td>0.086</td>
<td>0.27</td>
</tr>
<tr>
<td>1</td>
<td>9.05</td>
<td>7.1</td>
<td>0.002</td>
<td>15.40</td>
<td>0.001</td>
<td>0.61</td>
</tr>
<tr>
<td>2</td>
<td>11.59</td>
<td>8.1</td>
<td>0.002</td>
<td>16.96</td>
<td>0.001</td>
<td>0.68</td>
</tr>
<tr>
<td>3</td>
<td>13.57</td>
<td>10.5</td>
<td>0.001</td>
<td>8.44</td>
<td>0.009</td>
<td>0.92</td>
</tr>
<tr>
<td>4</td>
<td>15.45</td>
<td>11.4</td>
<td>0.001</td>
<td>13.45</td>
<td>0.002</td>
<td>1.00</td>
</tr>
<tr>
<td>5</td>
<td>17.25</td>
<td>12.8</td>
<td>0.001</td>
<td>14.94</td>
<td>0.001</td>
<td>1.06</td>
</tr>
<tr>
<td>6</td>
<td>19.25</td>
<td>14.2</td>
<td>0.001</td>
<td>15.83</td>
<td>0.001</td>
<td>1.23</td>
</tr>
<tr>
<td>7</td>
<td>21.72</td>
<td>15.8</td>
<td>0.001</td>
<td>15.10</td>
<td>0.001</td>
<td>1.58</td>
</tr>
<tr>
<td>8</td>
<td>24.25</td>
<td>16.0</td>
<td>0.001</td>
<td>19.85</td>
<td>&lt;0.001</td>
<td>1.75</td>
</tr>
<tr>
<td>9</td>
<td>28.70</td>
<td>17.1</td>
<td>0.001</td>
<td>7.430</td>
<td>0.014</td>
<td>11.13</td>
</tr>
<tr>
<td>10</td>
<td>31.87</td>
<td>16.3</td>
<td>0.001</td>
<td>8.81</td>
<td>0.009</td>
<td>5.05</td>
</tr>
<tr>
<td>11</td>
<td>35.87</td>
<td>18.4</td>
<td>0.001</td>
<td>8.70</td>
<td>0.009</td>
<td>6.06</td>
</tr>
<tr>
<td>12</td>
<td>39.53</td>
<td>19.2</td>
<td>0.001</td>
<td>12.24</td>
<td>0.005</td>
<td>6.48</td>
</tr>
<tr>
<td>13</td>
<td>44.44</td>
<td>21.1</td>
<td>0.001</td>
<td>16.89</td>
<td>0.001</td>
<td>7.00</td>
</tr>
<tr>
<td>14</td>
<td>49.89</td>
<td>30.4</td>
<td>0.001</td>
<td>8.505</td>
<td>0.010</td>
<td>7.29</td>
</tr>
<tr>
<td>15</td>
<td>53.92</td>
<td>36.6</td>
<td>0.001</td>
<td>9.463</td>
<td>0.007</td>
<td>6.41</td>
</tr>
<tr>
<td>16</td>
<td>59.16</td>
<td>45.8</td>
<td>0.000</td>
<td>3.815</td>
<td>0.067</td>
<td>8.13</td>
</tr>
<tr>
<td>17</td>
<td>59.93</td>
<td>46.2</td>
<td>0.000</td>
<td>6.244</td>
<td>0.023</td>
<td>7.84</td>
</tr>
</tbody>
</table>

\(^a\) SEE = \(\frac{\sqrt{\sum(Y−\hat{Y})^2}}{n−2}\) where \(Y\) = observed value of the dependent variable based on the given \(X\), \(\hat{Y}\) = predicted value of the dependent variable \(Y\) based on the given \(X\), \(n−2\) = degrees of freedom for the independent variable.

\(^b\) %SEE = SEE/mean body mass (kg) in a given age category.
body mass in all age categories except age categories 0 (P = 0.086) and 16 (P = 0.067). Midshaft femur J appears to be a very good predictor of body mass in age categories 1–8 with mean SEE of 1.01 kg for these age categories (range is 0.61–1.75 kg) and %SEE’s between 5.9 and 7.2%. Body mass can be predicted from J with less accuracy and precision for the older age categories 9–17. The mean SEE increases greatly to 6.48 (range is 4.11–8.43 kg) and %SEE increases to 14.3–16.9%.

The %SEE is provided in Table 2 for three methods of estimating body mass using the Denver growth study data: J, the width of the distal metaphysis, and the femoral head (Ruff, 2007). The %SEE for formulas using both raw and log-transformed data are given for Ruff’s formulas, as presented in the original publication. The midshaft and the distal end of the femur have consistently strong scaling relationships with body mass for age categories 1–8 and both techniques provide body mass estimates with similar %SEE’s. J yields the most precise estimates for age categories 1, 6, and 8. The distal metaphysis performs better than J in age categories 2, 3, and 7, although in age category 7, the femoral head performs better than either J or the distal metaphysis. In the late juvenile years (9–12), both J and the distal metaphysis demonstrate increasing variance in the scaling relationship with body mass, and lower %SEE’s. The equations for the femoral head (log-transformed) provide the most precise estimates for age categories 9–12 and 17. J is the most precise predictor for individuals in age categories 13–15 while precision is about equal for J and the femoral head in age category 16.

For the independent test sample (n = 112) of 1- to 15-year-olds from Franklin County, Ohio, the average bias, or mean directional difference between the observed and expected values, using the femoral J formulas is 0.6 kg (SE = 0.6 kg; Table 3). When four individuals are removed because their body mass index is outside the 95% confidence limits for age (following Sciulli and Blatt, 2008), the mean bias is 0.3 kg (SE = 1.0 kg). When the sample is analyzed by sex, the formulas tend to underestimate slightly body mass in males (Bias = −0.5 kg) and overestimate in females (Bias = 0.8 kg). The accuracy of the estimates from J is 3.1 kg and accuracy improves when the four outliers are removed, ranging from 2.5 to 2.8 kg in the subsamples considered. The results of this analysis indicate that the formulas for estimating body mass from J are useful for subadults up to 15 years of age if the distal femur or femoral head are not available.

Accuracy and bias were compared for a subset of Ohio individuals in age categories 1–8 (n = 38) using formulas based on J and the distal metaphysis (Table 4). Estimates derived from the two methods do not appear to differ greatly in accuracy or bias. Four individuals who fall outside the 95% CI for body mass index (BMI) for age were removed from the sample and accuracy and bias improved for both the midshaft and the bone end formulas. Because accuracy and precision were improved when outliers were removed, it suggests that both methods are limited for individuals with high BMI. The 95% confidence intervals for all comparisons overlap and thus it appears that both methods are similarly useful for estimating body mass in the Ohio sample.
TABLE 4. Comparison of accuracy and bias in formulas for body mass estimation in the Franklin, Ohio population 1- to 8-years old

<table>
<thead>
<tr>
<th>Age</th>
<th>Sex</th>
<th>Ancestry</th>
<th>N</th>
<th>MET</th>
<th>95% CI</th>
<th>MS</th>
<th>95% CI</th>
<th>MET</th>
<th>95% CI</th>
<th>Bias</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>1–8</td>
<td>M,F</td>
<td>A,E</td>
<td>35</td>
<td>2.3</td>
<td>1.4–3.2</td>
<td>2.2</td>
<td>1.3–3.1</td>
<td>2.2</td>
<td>1.3–3.3</td>
<td>1.6</td>
<td>0.5–2.7</td>
</tr>
<tr>
<td>1–8</td>
<td>M,F</td>
<td>A,E</td>
<td>34</td>
<td>1.8</td>
<td>1.2–2.4</td>
<td>1.7</td>
<td>1.2–2.2</td>
<td>1.8</td>
<td>1.1–2.5</td>
<td>1.1</td>
<td>0.4–1.8</td>
</tr>
<tr>
<td>1–8</td>
<td>M</td>
<td>A,E</td>
<td>21</td>
<td>2.0</td>
<td>1.3–2.7</td>
<td>1.8</td>
<td>1.2–2.4</td>
<td>2.0</td>
<td>1.2–2.7</td>
<td>1.8</td>
<td>1.1–2.5</td>
</tr>
<tr>
<td>1–8</td>
<td>M</td>
<td>E</td>
<td>18</td>
<td>2.1</td>
<td>1.3–2.9</td>
<td>2.1</td>
<td>1.5–2.7</td>
<td>2.1</td>
<td>1.3–2.9</td>
<td>2.1</td>
<td>1.5–2.7</td>
</tr>
<tr>
<td>1–8</td>
<td>F</td>
<td>A,E</td>
<td>14</td>
<td>1.6</td>
<td>0.6–2.7</td>
<td>1.5</td>
<td>0.7–2.2</td>
<td>1.3</td>
<td>0.1–2.5</td>
<td>0.6</td>
<td>0.5–1.7</td>
</tr>
<tr>
<td>1–8</td>
<td>F</td>
<td>E</td>
<td>10</td>
<td>1.9</td>
<td>0.5–3.3</td>
<td>1.7</td>
<td>0.6–2.8</td>
<td>1.5</td>
<td>−0.2–3.2</td>
<td>0.8</td>
<td>−0.7–2.3</td>
</tr>
</tbody>
</table>

*Accuracy = observed body mass − estimated body mass.

**Bias = observed body mass − estimated body mass.**

**Note:** Includes four individuals with BMI > 95th percentile (one individual each in age categories 2, 5, and 7).

**DISCUSSION AND CONCLUSIONS**

This article provides a set of equations for estimating body mass from the human subadult femoral midshaft, derived from the modern Denver Growth Study sample. Precision (%SEE) of the formulas is similar to that shown previously in the same sample based on femoral distal metaphyseal and femoral head breadths (Ruff, 2007). When tested on a different contemporary cadaveric sample, accuracy and bias of the new equations are reasonable (2.5–3 kg and ± 0.8 kg, respectively), and are comparable to estimates based on the femoral distal metaphysis in individuals 1–8 years of age. Thus, in cases where the bone ends are damaged or unavailable and the midshaft can still be located or approximated, polar second moments of area (J) can be used to predict body mass for subadult human skeletons. In older age categories (9–17 years) body mass estimates from the midshaft femur are generally less accurate and precise than those from the femoral head and that measure is thus the preferred method for those age categories. This result is to be expected given that we know hormones, activity, and diet play an increasingly large role in bone mass acquisition during older ages. In addition, changes in the shape of the midshaft cross section during adolescence affect the accuracy of estimates for J in these older age categories.

Least-squares regression was used in this analysis primarily to make comparisons with formulas published previously. The increasing variance in the residuals with age for equations based on both the femur midshaft and the distal metaphysis indicates that regression may not be the most appropriate statistical technique for these data. Regression also suffers from a centrist tendency which may contribute to the amount of error for the individual predictions (Lucy and Pollard, 1995). This centrist tendency might be one reason that formulas for estimating body mass considered here fail to predict accurately body mass for individuals outside the 95% confidence interval of BMI for age. This was identified as a major limitation in a previous publication (Sciulli and Blatt, 2008) and our results indicate that obese individuals are also a major limitation of the formulas provided here. A different approach, such as ARIMA analysis (AutoRegressive Integrated Moving Average; Box and Jenkins, 1970) could potentially yield more accurate estimates for body mass from the femur measures. This and other statistical methods are another avenue for future investigation.

There are some important differences among the Denver and Ohio samples used in this analysis. The Ohio sample includes African-American individuals (25%) whereas the Denver growth study included only European-Americans. A significant number of right limb bones were measured in the Ohio cadaver sample, rather than all left side as in the Denver sample. In addition, the midshaft measures were made at 50% diaphyseal length in the Ohio sample as opposed to 45.5% diaphyseal length in the Denver sample, a difference that could result in errors of body mass estimation for the target sample if midshaft measures differ in the two locations. The femur midshaft measurements from the Ohio sample are derived from radiographs of children who died and the sample includes individuals from a wider range of economic statuses, with diseases and traumatic injuries that were probably not present in the Denver sample. As was previously pointed out by Sciulli and Blatt (2008), in general the developmental circumstances and measurement procedures for the Ohio sample probably correspond more closely to those of forensic skeletal samples and therefore the Ohio sample is an appropriate choice for testing methods of body mass estimation for that purpose.

It is clear that there is a close relationship between bone cross-sectional geometry and body mass given clinical and biomechanical studies which have repeatedly demonstrated a strong relationship between these two variables during growth and development (Ruff and Runestad, 1992; Van Der Meulen et al., 1993; Carter et al., 1996; Moro et al., 1996; Ruff, 1997, 1998, 2000, 2002a, 2003a; Pearson and Lieberman, 2004; Wescott, 2006). It is also clear that body mass and activity are not independent in bipedal organisms and both affect the shape of the cross section of the bone and the velocity of bone mass acquisition in the femur beginning early in infancy (Ruff, 2003a, b, 2005a). It is difficult to tease out influences on bone cross sections from body mass, activity levels, muscularity, nutritional status, and hormonal changes, all of which are significant in determining adolescent and adult midshaft robusticity. Articular dimensions, in contrast, seem to be less environmentally plastic (Trinkaus et al., 1994; Lieberman et al., 2001). For this reason, methods for estimating body mass from articular surfaces have generally been preferred over methods based on diaphyseal breadths (McHenry, 1991, 1992, 1994; Ruff et al., 1997; McHenry and Coffing, 2000; Brown et al., 2004; Rosenberg et al., 2006; Ruff, 2010).

The formulas presented here perform well in tests on a contemporary cadaver sample from Ohio and ought to be applicable to contemporary populations with similar
activity levels and lifestyles. The accuracy of these formulas is comparable to previously published techniques for the distal end of the femur for individuals 1–8 years of age and thus these formulas provide an alternative for use in cases where the femur distal metaphyses are damaged. The midshaft formulas are not as accurate as those for the head of the femur for older juveniles and adolescents; however, they may be used in situations where the femoral head is not preserved or is not clearly associated with a particular individual. However, body mass estimation methods for subadults based on measures of the femur should also be tested on populations from diverse climates, latitudes, activity patterns, diets, and biocultural stress levels (Lieberman et al., 2004; Pearson and Lieberman, 2004; Ruff et al., 2006) to evaluate their general applicability.

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LITERATURE CITED


