Estimating body mass in subadult human skeletons

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Abstract:

Methods for estimating body mass from the human 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.

Keywords: femur | geometry | body mass

Article:

Biological anthropologists who seek to understand human biological variation from an evolutionary or bio-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

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children to aid in personal identification. While there are several methods available for estimating stature from subadult bones (Telkka et al., 1962; 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, b, 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.

Abbreviations	
BMI	body max 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

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 17.59 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 distal metaphyseal 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.

Statistical methods

Least squares (LS) regression was used to generate age-structured formulas for predicting body mass from polar second moments of area (*J*). Although there are other statistical methods that are appropriate for these data, one of our goals was to evaluate the usefulness of the midshaft for estimating body mass for subadults in comparison with other methods published previously (Ruff, 2007). Standard errors of the estimates (SEE) were calculated to measure the precision of the predictions for each formula. The percent standard error of the estimate (%SEE) was calculated by dividing the SEE by the mean body mass (kg) for each age category (following Ruff, 2007). This measure allows a comparison of the precision of the estimates from these formulas across different age categories despite differences in average 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).

The accuracy of body mass estimates was examined using an independent sample of children of known body mass from Franklin County, Ohio. Body mass was first estimated for 112 individuals 1–15 years of age. Accuracy and bias were measured for the body mass estimates made from the midshaft. Accuracy was defined as the absolute value of the difference between observed and predicted body mass and bias is the signed difference between observed and predicted (Sciulli and Blatt, 2008). Body mass estimates for 38 individuals in age categories 1–8 (0.5–8.49 years) were also compared using the formulas for the midshaft developed in this article and the formulas for the distal metaphyseal breadth published previously (Ruff, 2007). Older individuals were not included in this comparison because measurement error increases in the midshaft and the distal femur after 9 years; thus the femoral head method (with slightly smaller errors in this age range) would be preferred but that measurement is not available from the radiographs of the Ohio cadavers. Accuracy and bias were also compared for 34 Ohio individuals remaining after four outliers with high BMI (above the 95th percentile for age) were removed. This was done because obese individuals were problematic in a previous test of the formulas for the bone end (Sciulli and Blatt, 2008). Data were also examined by sex (males n = 21, females n = 13) and Caucasian males (n = 17) and females (n = 10) were analyzed separately (following Sciulli and Blatt, 2008).

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 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%.

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

Age	Body mass	BMI	Intercept	Slope	*F*	*P*	SEE[a]	%SEE[b]
0	4.52	15	3.8	0.003	3.454	0.086	0.27	6.0
1	9.05	17	7.1	0.002	15.40	0.001	0.61	6.7
2	11.59	16	8.1	0.002	16.96	0.001	0.68	5.9
3	13.57	15	10.5	0.001	8.44	0.009	0.92	6.8
4	15.45	15	11.4	0.001	13.45	0.002	1.00	6.5
5	17.25	15	12.8	0.001	14.94	0.001	1.06	6.1
6	19.25	15	14.2	0.001	15.83	0.001	1.23	6.4
7	21.72	15	15.8	0.001	15.10	0.001	1.38	6.4
8	24.25	15	16.0	0.001	19.85	<0.0001	1.75	7.2
9	28.70	16	17.1	0.001	7.430	0.014	4.11	14.3
10	31.87	17	16.3	0.001	8.81	0.009	5.05	15.84
11	35.87	17	18.4	0.001	8.70	0.009	6.06	16.89
12	39.53	18	19.2	0.001	12.24	0.003	6.48	16.39
13	44.44	18	21.1	0.001	16.89	0.001	7.00	15.75
14	49.89	19	30.4	0.001	8.505	0.010	7.29	14.61
15	53.92	20	36.6	0.001	9.463	0.007	6.41	11.88
16	59.16	20	45.8	0.000	3.815	0.067	8.13	13.74
17	59.93	21	46.2	0.000	6.244	0.023	7.84	12.76

[a] SEE $= S_{Y-Y} = \sqrt{\frac{\Sigma(Y-Y)^2}{n-2}}$ 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.

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.

Table 2. Comparison of %SEE for body mass predictions from the bone end and the midshaft for the Denver Growth Study population

		%SEE					
		Midshaft (MS)	**Metaphysis (MET)**		**Femoral head (FH)**		**Method with the lowest %SEE**
Age (yrs)	**Body mass (kg)**	**Natural**	**Natural**	**Log**	**Natural**	**Log**	
1	9.05	6.7	7.2	7.1	–	–	MS
2	11.59	5.9	5.0	4.8	–	–	log MET
3	13.57	6.8	6.7	4.8	–	–	log MET
4	15.45	6.5	6.9	6.5	–	–	MS, log MET
5	17.25	6.1	6.1	6.2	–	–	MS, MET
6	19.25	6.4	6.6	6.6	–	–	MS
7	21.72	6.4	6.1	6.3	5.9	6.2	FH
8	24.25	7.2	9.0	9.2	7.7	7.9	MS
9	28.70	14.3	15.5	14.4	12.3	11.3	log FH
10	31.87	15.8	16.8	15.8	14.8	13.9	log FH
11	35.87	16.9	19.1	18.0	15.6	14.7	log FH
12	39.53	16.4	18.7	17.6	14.3	13.5	log FH
13	44.44	15.8	–	19.7	17.7	16.7	MS
14	49.89	14.6	–		15.5	14.9	MS
15	53.92	11.9	–		–	–	MS
16	59.16	13.7	–		–	13.6	MS, log FH
17	61.47	12.8	–		11.9	11.4	log FH

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.

Table 3. Accuracy and bias in formulas for body mass estimation from femur midshaft polar second moments of area in the Franklin, Ohio population (ages 1–15 years)

				Accuracy[b]		Bias[c]	
Age (yrs)	**Sex**	**Ancestry[a]**	***N***	**MS (*J*)[d]**	**95%CI**	**MS (*J*)**	**95%CI**
1–15	M,F	A,E	112[e]	3.1	2.0–4.2	0.6	−0.6–1.8
1–15	M,F	A,E	108	2.6	1.8–3.5	0.3	−0.7–1.3
1–15	M	A,E	63	2.6	1.5–3.7	−0.5	−1.8–0.8
1–15	M	E	52	2.5	1.3–3.7	−0.1	−1.5–1.3
1–15	F	A,E	44	2.7	1.4–4.0	0.8	−0.7–2.3
1–15	F	E	32	2.8	1.1–4.5	0.8	−1.2–2.8

[a] E = European ancestry, A = African American ancestry.
[b] Kilograms; Accuracy = | observed body mass − estimated body mass |.
[c] Kilograms; Bias = (observed body mass − estimated body mass).
[d] Femur midshaft polar second moment of area (*J*). From equations (raw data) in Table 1.
[e] Includes four individuals with BMI > 95th percentile (one individual each in age categories 2, 5, and 7).

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

				Accuracy[a]				Bias[b]			
Age	**Sex**	**Ancestry[c]**	***N***	**MET[d]**	**95%CI**	**MS (*J*)[e]**	**95%CI**	**MET**	**95%CI**	**MS (*J*)**	**95%CI**
1–8	M,F	A,E	38[f]	2.3	1.4–3.2	2.2	1.3–3.1	2.2	1.3–3.3	1.6	0.5–2.7
1–8	M,F	A,E	34	1.8	1.2–2.4	1.7	1.2–2.2	1.8	1.1–2.5	1.1	0.4–1.8
1–8	M	A,E	21	2.0	1.3–2.7	1.8	1.2–2.4	2.0	1.3–2.7	1.8	1.1–2.5
1–8	M	E	18	2.1	1.3–2.9	2.1	1.5–2.7	2.1	1.3–2.9	2.1	1.5–2.7
1–8	F	A,E	14	1.6	0.6–2.7	1.5	0.7–2.2	1.3	0.1–2.5	0.6	−0.5–1.7
1–8	F	E	10	1.9	0.5–3.3	1.7	0.6–2.8	1.5	−0.2–3.2	0.8	−0.7–2.3

[a] Kilograms; Accuracy = | observed body mass − estimated body mass |.
[b] Kilograms; Bias = (observed body mass − estimated body mass).
[c] E = European ancestry, A = African American ancestry.
[d] Femur distal metaphysis. From equations (raw data) in Ruff (2007).
[e] Femur midshaft strength (*J*). From equations (raw data) in Table 1.
[f] 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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Supporting Information

Additional Supporting Information may be found online at https://doi.org/10.1002/ajpa.21320.

LITERATURE CITED

Box GEP, Jenkins GM. 1970. *Time Series Analysis: forecasting and control*. San Francisco: Holden-Day. Google Scholar

Brown P, Sutikna T, Morwood MJ, Soejono RP, Jatmiko, Saptomo EW, Awe Due R. 2004. A new small-bodied hominin from the Late Pleistocene of Flores, Indonesia. *Nature* **431**: 1055– 1061. Google Scholar

Carter DR, Van Der Meulen MCH, Beaupre GS. 1996. Mechanical factors in bone growth and development. *Bone* **18**: S5– S10. Google Scholar

Feldesman MR. 1992. Femur stature ratio and estimates of stature in children. *Am J Phys Anthropol* **87**: 447– 459. Google Scholar

Himes JH, Yarbrough C, Martorell R. 1977. Estimation of stature in children from radiographically determined metacarpal length. *J Forensic Sci* **22**: 452– 456. Google Scholar

Lieberman DE, Devlin MJ, Pearson OM. 2001. Articular area responses to mechanical loading: effects of exercise, age, and skeletal location. *Am J Phys Anthropol* **116**: 266– 277. Google Scholar

Lieberman DE, Polk JD, Demes B. 2004. Predicting long bone loading from cross-sectional geometry. *Am J Phys Anthropol* **123**: 156– 171. Google Scholar

Lucy D, Pollard AM. 1995. Further comments on the estimation of error associated with the Gustafson dental age estimation method. *J Forensic Sci* **40**: 222– 227. Google Scholar

McHenry HM. 1991. Petite bodies of the "Robust" Australopithecines. *Am J Phys Anthropol* **86**: 445– 454. Google Scholar

McHenry HM. 1992. Body size and proportions in early hominids. *Am J Phys Anthropol* **87**: 407– 431. Google Scholar

McHenry HM. 1994. Behavioral ecological implications of early hominid body size. *J Hum Evol* **27**: 77– 87. Google Scholar

McHenry HM, Coffing KE. 2000. Australopithecus to *Homo*: transformations of body and mind. *Ann Rev Anthropol* **29**: 125– 166. Google Scholar

Moro M, Van Der Meulen M, Kiratli B, Marcus R, Bachrach LK, Carter DR. 1996. Body mass is the primary determinant of midfemoral bone acquisition during adolescent growth. *Bone* **19**: 519– 526. Google Scholar

Must A, Dalal GE, Dietz WH. 1991. Reference data for obesity: 85th and 95th percentiles of body mass index (Wt/Ht2) and triceps fold thickness. *Am J Clin Nutr* **53**: 839– 846. Google Scholar

O'Neill MC, Ruff CB. 2004. Estimating human long bone cross-sectional geometric properties: a comparison of noninvasive methods. *J Hum Evol* **47**: 221– 235. Google Scholar

Pearson OM, Lieberman DE. 2004. The aging of Wolff's "Law": ontogeny and responses to mechanical loading in cortical bone. *Yearb Phys Anthropol* **47**: 63– 99. Google Scholar

Pfau RO, Sciulli PW. 1994. A method for establishing the age of subadults. *J Forensic* **39**: 165– 176. Google Scholar

Rosenberg KR, Lü Z, Ruff CB. 2006. Body size, body proportions and encephalization in a middle pleistocene archaic human from northern china. *Proc Natl Acad Sci USA* **103**: 3552– 3556. Google Scholar

Ruff CB. 1998. Evolution of the hominid hip. In: E Strasser, J Fleagle, H McHenry, A Rosenberger, editors. *Primate locomotion: recent advances*. New York: Plenum. p 449– 469. Google Scholar

Ruff CB. 2000. Body size, body shape, and long bone strength in modern humans. *J Hum Evol* **38**: 269– 290. Google Scholar

Ruff CB. 2002a. Variation in human body size and shape. *Ann Rev Anthropol* **31**: 211– 232. Google Scholar

Ruff CB. 2002b. Long bone articular and diaphyseal structure in Old World monkeys and apes. I: locomotor effects. *Am J Phys Anthropol* **119**: 305– 342. Google Scholar

Ruff CB. 2003a. Growth in bone strength, body size, and muscle size in a juvenile longitudinal sample. *Bone* **33**: 317– 329. Google Scholar

Ruff CB. 2003b. Ontogenetic adaptation to bipedalism: age changes in femoral to humeral length and strength proportions in humans, with a comparison to baboons. *J Hum Evol* **45**: 317– 349. Google Scholar

Ruff CB. 2005a. Growth tracking of femoral and humeral strength from infancy through late adolescence. *Acta Paediatr* **94**: 1030– 1037. Google Scholar

Ruff CB. 2007. Body size prediction from juvenile skeletal remains. *Am J Phys Anthropol* **133**: 698– 716. Google Scholar

Ruff CB. 2010. Body size and body shape in early hominins—implications of the gona pelvis. *J Hum Evol* **58**: 166– 178. Google Scholar

Ruff CB, Holt B, Trinkaus E. 2006. Who's afraid of the big bad Wolff? “Wolff's law” and bone functional adaptation. *Am J Phys Anthropol* **129**: 484– 498. Google Scholar

Ruff CB, Runestad JA. 1992. Primate limb bone structural adaptations. *Ann Rev Anthropol* **21**: 407– 433. Google Scholar

Ruff CB, Trinkaus E, Holliday TW. 1997. Body mass and encephalization in pleistocene *Homo*. *Nature* **387**: 173– 176. Google Scholar

Ruff CB, Trinkaus E, Walker A, Spencer Larsen C. 1993. Postcranial robusticity in *Homo* I: temporal trends and biomechanical interpretation. *Am J Phys Anthropol* **91**: 21– 53. Google Scholar

Sciulli PW. 1994. Standardization of long bone growth in children. *Int J Osteoarchaeol* **4**: 257– 259. Google Scholar

Sciulli PW, Blatt SH. 2008. Evaluation of stature and body mass prediction. *Am J Phys Anthropol* **136**: 387– 393. Google Scholar

Sumner DR, Andriacchi TP. 1996. Adaptation to differential loading: comparison of growth-related changes in cross-sectional properties of the human femur and humerus. *Bone* **19**: 121– 126. Google Scholar

Telkka A, Palkama A, Virtama P. 1962. Prediction of stature from radiographs of long bones in infants and children. *J Forensic Sci* **7**: 474– 479. Google Scholar

Trinkaus E, Churchill SE, Ruff CB. 1994. Postcranial robusticity in *Homo* II: humeral bilateral asymmetry and bone plasticity. *Am J Phys Anthropol* **93**: 1– 34. Google Scholar

Van Der Meulen M, Ashford MW, Kiratli BJ, Bachrach LK, Carter DR. 1996. Determinants of femoral geometry and structure during adolescent growth. *J Orthoped Res* **14**: 22– 29. Google Scholar

Van Der Meulen MCH, Beaupré GS, Carter DR. 1993. Mechanobiologic influences in long bone cross-sectional growth. *Bone* **14**: 635– 642. Google Scholar

Wescott DJ. 2006. Effect of mobility on femur midshaft external shape and robusticity. *Am J Phys Anthropol* **130**: 201– 213. Google Scholar