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Body Size Prediction From Juvenile Skeletal Remains

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ABSTRACT There are currently no methods for predicting body mass from juvenile skeletal remains and only a very limited number for predicting stature. In this study, stature and body mass prediction equations are generated for each year from 1 to 17 years of age using a subset of the Denver Growth Study sample, followed longitudinally ($n = 20$ individuals, 340 observations). Radiographic measurements of femoral distal metaphyseal and head breadth are used to predict body mass and long bone lengths are used to predict stature. In addition, pelvic bi-iliac breadth and long bone lengths are used to predict body mass in older adolescents. Relative prediction errors are equal to or smaller than those associated with similar adult estimation formulae. Body proportions change continuously throughout growth, necessitating age-specific formulae. Adult formulae overestimate stature and body mass in younger juveniles, but work well in 17-year-olds from the sample, indicating that in terms of body proportions they are representative of the general population. To illustrate use of the techniques, they are applied to the juvenile *Homo erectus* (*ergaster*) KNM-WT 15000 skeleton. New body mass and stature estimates for this specimen are similar to previous estimates derived using other methods. Body mass estimates range from 50 to 53 kg, and stature was probably slightly under 157 cm, although a precise stature estimate is difficult to determine due to differences in linear body proportions between KNM-WT 15000 and the Denver reference sample. Am J Phys Anthropol 133:698–716, 2007. © 2007 Wiley-Liss, Inc.

Accurate estimation of human body size—stature and body mass—from skeletal material is important in a variety of contexts, paleontological, archaeological, and forensic. Many techniques have been developed for estimating adult stature, using a variety of approaches and reference samples (for reviews, see Krogman and Iscan, 1986; Rösing, 1988; Raxter et al., 2006). A number of techniques are also now available for estimating body mass from adult skeletal remains (Auerbach and Ruff, 2004).

In contrast, prediction of body size from juvenile skeletal material has received much less attention. Only a handful of studies have attempted to develop methods for juvenile stature estimation beyond the fetal–perinatal period (Telkka et al., 1962a,b; Olivier, 1969; Himes et al., 1977; Feldesman, 1992), and as discussed in more detail later, each has significant limitations. Apart from a preliminary analysis carried out to estimate the body mass of the 4.5–5-year-old Lagar Velho child (Ruff et al., 2002), there are apparently no previous studies of body mass prediction in juveniles. This is unfortunate, since variation in body size is very commonly used to assess health among modern children, both within and between populations (Eveleth and Tanner, 1990; WHO, 1995). Similar relationships between body size and nutrition, disease, and other environmental factors undoubtedly existed in the past (Johnston and Zimmer, 1989; Larsen, 1997), but without appropriate techniques, previous comparative studies have been limited exclusively to juvenile skeletal measures, almost always long bone lengths (Johnston, 1962; Y'Edynak, 1976; Merchant and Ubelaker, 1977; Hummert and Van Gerven, 1983; Jantz and Owsley, 1984; Lovejoy et al., 1990; Wall, 1991; Saunders et al., 1993; Ribot and Roberts, 1996; for a review, see Saunders, 2000), or to analysis of terminal (adult) statures only (for a review, see Larsen, 1997). Since juvenile height and weight data are available for a very large sample of living and recent populations (Eveleth and Tanner, 1990), estimation of such parameters in past populations would permit more direct comparisons of growth and development across a much wider genetic and environmental range.

In addition, estimation of juvenile body size is important for interpreting critical specimens in the hominin evolutionary lineage, including the juvenile *Homo erectus* (or *ergaster*) KNM-WT 15000 (Ruff and Walker, 1993) and the Lagar Velho specimen (Ruff et al., 2002). For example, the apparently large body size for age of KNM-WT 15000 has factored into assessments of his skeletal maturity, with implications for reconstructing evolutionary changes in life history variables (Clegg and Aiello, 1999; Smith, 2004). The stature and body mass of this individual are reconsidered later in this paper.

This study presents new stature and body mass estimation formulae for juvenile skeletal remains ranging in age from 1 to 17 years. The methods are for the most

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part based on techniques similar to those available for adults (Auerbach and Ruff, 2004), although a novel technique for estimating body mass based on femoral distal metaphyseal breadth is also presented. Preliminary versions of these techniques were presented previously, but for only a very limited age range (Ruff et al., 2002). Results are also interpreted with respect to more general implications regarding patterns of human skeletal growth and development.

MATERIALS AND METHODS

Sample and measurements

The sample used here is the same as that used in previous bone structural studies (Ruff, 2003a,c), selected from the Denver Growth Study sample (McCammon, 1970). This was a longitudinal growth study carried out between 1927 and 1967, although all individuals included in the present study were measured between 1941 and 1967. Subjects lived in the Denver area and were of European (mostly northern European) ancestry, and primarily of middle and upper middle class economic status. As part of the Denver study, standardized radiographs of the limb bones were taken at 6 month intervals from 6 months of age through late adolescence, although sometimes at yearly intervals in mid-late adolescence (earlier data from 2 and 4 months of age were also available, but are not used here). A sample of 20 individuals—10 males and 10 females—with the most complete radiographic records was identified. Data were collected from a total of 690 examinations or an average of 34.5 examinations per individual. Original radiographs of the femur and humerus were measured at the Lifespan Health Research Center of the Wright State University School of Medicine (Dayton, Ohio). Anthropometric dimensions, including body mass (weight), stature (or supine length for infants), and bi-iliac (maximum pelvic) breadth, also measured at each examination, were obtained from study archives. Supine length was converted to stature using a formula derived from young children where both had been measured (see Ruff, 2003a).

Diaphyseal (inter-metaphyseal) lengths of the femur and humerus were measured as maximum lengths, parallel to the long axis of the diaphysis, between proximal and distal ends, not including epiphyses. Total maximum lengths, including epiphyses, were measured as they are in standard osteometric studies of adults (Martin, 1928, measurement no. 1), i.e., from the most distal edge of the femoral medial condyle to the most proximal surface of the femoral head, and from the most distal edge of the humeral trochlea to the most proximal surface of the humeral head. While not necessarily exactly parallel to the long axes of the shafts, in effect they are very close to this orientation. All length measurements were taken to the nearest millimeter using a clear ruler. Diaphyseal and total lengths for the tibia and radius, measured in a similar way (Maresh, 1970), were obtained from study archives.

Because of the radiographic shadowing from partially overlying epiphyses, diaphyseal lengths could only be measured to about 11–12 years of age in most individuals. Missing diaphyseal lengths in this age range (mainly for 12-year-old) were estimated from total lengths of the same individuals using least squares regression formulae derived from subjects of similar age with both measurements (in all cases $r \geq 0.99$, %SEE [percent standard error of estimate] $< 1\%$).[1] Given the relative development of proximal and distal epiphyses, total femoral length, including epiphyses, could be measured beginning at about 7 years, and total humeral length beginning at about 11–12 years. Missing total humeral lengths in the 11–12 year age range were estimated from matched diaphyseal lengths in a way similar to that described above (and with similar precision). Tibial and radial data, obtained from study archives, were available to 12 years of age for diaphyseal lengths and beginning at 11 years of age for total lengths. Statures were estimated from diaphyseal lengths through 12 years of age, and from total lengths beginning at 11 years of age; thus, two sets of equations are available for ages 11 and 12 years.

Maximum superoinferior (S-I) femoral head breadth, used for body mass prediction, was measured using sharp-tipped digital calipers to the nearest 0.1 mm, after first placing a protective acetate sheet over the radiographs. The measurement is taken perpendicular to the femoral head-neck axis (Martin, 1928, measurement no. 18; also see Ruff et al., 1991: Fig. 1). The first age at which this dimension appeared to fairly accurately represent true femoral head size (i.e., including non-visible cartilage) varied, but in all individuals it could be measured by 7 years of age. Maximum mediolateral (M-L) breadth of the distal metaphyseal surface of the femoral diaphysis was also measured using the same technique. This measurement is taken between the most medially and laterally projecting points on the metaphyseal surface, close to but not necessarily exactly perpendicular to the long axis of the shaft. It was possible to measure this dimension from before 1 year of age through about 14 years of age in all individuals, and in progressively fewer individuals at older ages because of radiographic shadowing by the distal femoral epiphysis. In addition, an attempt was made to measure maximum M-L breadth of the distal femoral articular surface on the distal epiphysis, which was sufficiently developed to take the measurement beginning at about age 8–9 years in most individuals. However, it was later found that this dimension was not useful as a body mass predictor, possibly because of irregular bony contours that make it difficult to accurately measure true articular breadth from radiographs, and it was dropped from the study. Bi-iliac breadth, available from the study archives, was also used with long bone lengths to estimate body mass, as described below.

Measurement error was evaluated by remeasuring two individuals at 10 ages from infancy through adolescence, several weeks after their first measurement. Mean directional and random errors were less than 0.5% for all bone lengths, and less than 1% for femoral head and distal metaphyseal breadths. Maresh, who did most of the original length measurements of the tibiae and radii that were used here (Maresh, 1943, 1955, 1970), does not report specifically on reproducibility, but it is appa-

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[1] In previous studies (Ruff, 2003a,c), mean ratios rather than regression equations were used to derive femoral and humeral total maximum lengths from diaphyseal lengths. This was done because total lengths were estimated down to 6 months of age, for use in biomechanical and limb length proportional analyses, and regression equations sometimes give spurious results when extrapolated far beyond their original size ranges (here, that of 11–12 year-olds). The regression equations gave slightly more accurate results than the ratios for the limited age range considered here. However, as discussed later, ratios are again recommended when estimating total maximum lengths over a wider age (and size) range.

rent from his descriptions that lengths were measured very carefully and apparently consistently (e.g., see Maresh, 1970, p 161), so it is likely that measurement errors were no larger than those found here.

All radiographic measurements were corrected for magnification (parallax). Magnification factors were estimated from data presented by Green et al. (1946), and for the radius, Gindhart (1973), adjusted for differences in tube-film distance from that used in the Denver study, and accounting for body size variation, as described in detail elsewhere (Ruff et al., 2002). Briefly, for femoral, humeral, and tibial lengths 217 mm or greater, adjusted length = 0.949 × original length + 5.63. For smaller bones (except the radius), adjusted length = 0.975 × original length. For the radius, adjusted length = 0.98 × original length. Femoral distal metaphyseal and head breadth magnification factors were the same (2.5%) for bones with lengths under 217 mm, and the same slope (0.949) was used for larger specimens, with intercepts determined by average size differences between dimensions: for distal metaphyseal breadth, adjusted = 0.949 × original + 0.965; for head breadth: adjusted = 0.949 × original + 0.555. Resulting magnifications of 2% to about 4% are consistent with Maresh's (1955, 1970) general estimates. It is noteworthy that Maresh himself never attempted to correct magnification, and that all tabulations of long bone length data for the Denver sample, which have often been used for comparative purposes, are also uncorrected. Among older children and adolescents in the sample, magnification leads to overestimations of femoral lengths of 1–2 cm unless corrected.

Although the study sample was selected for its relative completeness, due to missed examinations and occasional problems with radiographs, such as improper orientation or missing films, some radiographic or anthropometric data were not available. Missing data were estimated through linear interpolation from temporally adjacent recorded values for the same individual. Examination of individual longitudinal data indicated that temporal trends were approximately linear over the relatively narrow time periods used for such interpolations, made possible because of the tight temporal spacing of the original examinations. The total percentage of missing data estimated through interpolation was 6–9% for anthropometric and femoral dimensions, and 12% for humeral length (somewhat higher because of slightly more frequent upper limb positioning problems). One girl in the sample had usable humeral radiographs only through 16.5 years of age. However, no significant change in humeral length had occurred in this individual over the previous year (15.5 year humeral length was within 1 mm of the 16.5 year value) and no change in any other of her long bone lengths occurred between 16.5 and 17 years. Therefore, her humeral length value for 16.5 years was used as her "17 year" data point. Aside from this, no missing data were estimated through extrapolation beyond the available data range, i.e., all individuals had available data from before 1 year of age through at least 17 years.

Tibial and radial lengths, obtained from the study archives, had in many cases been recorded only at annual rather than semi-annual intervals, with most of these being at the half-year interval (i.e., 0.5, 1.5 years of age, etc.). Maresh made no mention of this procedure in any of his publications, and it is not clear whether the alternate examination data are simply missing from the present database or were never obtained (in the latter case, the original investigators must have used extensive interpolation, since sample sizes in reported tabulations do not vary systematically between 6-month age periods, e.g., see Maresh, 1970). In any event, this necessitated many more interpolations for these lengths than for any of the other included dimensions—~40% of the values. However, because of the high density of available measurements (yearly) and the linearity of changes over short time intervals, this should have introduced very little if any systematic error.

Statistics

Stature prediction equations were generated from long bone lengths and body mass prediction equations from femoral head and distal metaphyseal breadths. Long bone lengths, have traditionally been used in "mathematical" (as opposed to "anatomical") stature estimation methods (Raxter et al., 2006), due to their high correlations with stature. Femoral head breadth has been shown to be a good predictor of body mass in adults (Auerbach and Ruff, 2004), and knee transverse dimensions are among the best predictors of body mass in mixed species analyses among primates (Ruff, 2003b). In addition, body mass was estimated from pelvic bi-iliac (maximum M-L) breadth and long bone lengths in older adolescents (>14 years), where the innominates and sacrum are sufficiently developed to reconstruct bi-iliac breadth. Body mass prediction from bi-iliac breadth and stature has been shown to work well in adults from various population samples (Ruff, 2000; Auerbach and Ruff, 2004; Ruff et al., 2005). Long bone lengths rather than stature were used here with bi-iliac breadth, since this eliminates one step in the process (estimation of stature from long bone lengths), which has its own associated error.

All prediction equations were generated using ordinary least squares regression of body size on skeletal dimensions. Although different regression models have been advocated in particular circumstances, such as examining allometric scaling patterns or when extrapolating well beyond the data range of the reference sample (Aiello, 1992; Hens et al., 1998, 2000; Konigsberg et al., 1998), least squares regression of this type is the most appropriate technique for prediction when the reference sample and target sample are similar (Smith, 1994; Hens et al., 1998). This implied assumption and alternative methods, when the assumption is not met, are further addressed at the end of this paper.

Because body proportions vary significantly throughout growth (Maresh, 1959; Hansman, 1970; Buschang, 1982; Jungers et al., 1988; Feldesman, 1992; Ruff and Walker, 1993, and see below), both stature and body mass prediction equations were generated within discrete age intervals. To somewhat limit the number of equations presented, and also in consideration of the degree of accuracy in age assignment normally possible from skeletal remains, these were generated for yearly intervals centered on the whole year, from 1 to 17 years of age. It should be noted that these equations are applicable to individuals ±0.5 years from the given age; for example, the 6-year-old equations apply to individuals 5.5–6.5 years of age. Initially, equations were also generated for the 6-month-old age group, but none of these produced significant regressions, so are not included here. The issue of age effects on results is discussed below together with the presentation of the equations.

Almost all analyses were carried out on the combined sex sample. This was done partly because of the relatively small sample size ($n = 20$ individuals at each age point); subdividing by sex leads to an even smaller sample of questionable statistical validity for generating prediction equations. Sex effects on some linear body proportions at a given age have been demonstrated, particularly during adolescence, due to the differential timing of growth spurts in males and females (Feldesman, 1992). In practice, sex effects on results are only of relevance for mid- to late-adolescence, since (except potentially using DNA analysis) sex cannot be determined with accuracy from skeletal remains prior to this age (Saunders, 2000), and most sex-related differences in body proportions would be expected to become more pronounced in adolescence. However, multiple analysis of variance over the age period 14–17 years failed to show any significant ($P \leq 0.05$) sex effects or sex–age interactions on stature or body mass predictions from long bone dimensions, although age was always a significant factor. Therefore, sexes were pooled for these analyses. The only exception to this were the equations for body mass prediction from bi-iliac breadth and long bone lengths, calculated only for the later adolescent years. Here sex was found to be a significant factor in predictions, as would be expected given the marked sex-related changes in shoulder to hip breadth proportions that occur during adolescence (Hansman, 1970) and the effects of such proportions on body mass prediction using this general technique (Ruff, 2000; Ruff et al., 2005). Although separating sexes here resulted in marginal sample sizes, body mass prediction errors are actually smaller than those from other combined-sex techniques in this age range, so the equations appear to be of use.

Because of dimensional and biomechanical effects, the allometric relationships between body mass and femoral head, and distal metaphyseal breadths would be expected to be non-linear (Ruff et al., 1993). However, as in a previous study of adults (Ruff et al., 1991), and perhaps because of the limited size range involved (within age groups), body mass predictions using raw and log-transformed data were found to give similar relative errors, although errors were usually slightly smaller using log-transformed data. Because log transformation introduces three extra steps (transformation of input data, de-transformation of output data, and correction for detransformation bias—see below), some researchers may prefer to use raw data; therefore, both the raw and (natural) log-transformed equations are given. When using the log-based equations, correction for detransformation bias must be carried out by multiplying the resulting detransformed (raw) body masses by a correction factor. Several techniques are available for this purpose (Smith, 1993b); the "quasimaximum likelihood estimator" (QMLE), calculated as $\exp(\mathrm{SEE}^2)/2)$, is given here, since it is the simplest, and when correction factors are very small, as is the case here, produces results very similar to those of other techniques (Smith, 1993a; Ruff, 2003b).

The main criterion used for evaluating the effectiveness of prediction equations is the percent standard error of estimate or %SEE. This is derived as the standard error of estimate (SEE) divided by the mean of the dependent (predicted) variable, that is, mean stature or body mass for that age group. Unlike the SEE, the %SEE can be compared across different size ranges and dimensional units, and is thus useful when these vary considerably, as is the case here.

Standard errors of estimate are also given for each equation. To calculate confidence intervals for an individual estimate, the following equation [modified from Zar (1984)] can be used:

$$CI = \pm t \cdot \sqrt{SEE^2 \cdot \left(1 + \frac{1}{n} + \frac{(X_i - \bar{X}^2)}{SD_x{}^2 \cdot (n-1)}\right)} \qquad (1)$$

where SD_x is the standard deviation of the x (predictor) variable, X_i is the value of the individual, X is the mean x, and t is the value from the t distribution corresponding to the confidence limit desired and degrees of freedom (e.g., for a 95% CI in most of the equations here (where $\mathrm{df} = 18$), t would be 2.10). Means and SD's for all individual skeletal variables are given in a table in the Results. (For stature CI calculations using femoral + tibial length, and humeral + radius length, SD's for the summed lengths are slightly larger than the sum of SD's for the individual bones, by a factor averaging 1.03.) Standard errors of estimate for log-transformed data (after detransformation) are non-symmetric. The %SEE's and SEE's for log-transformed equations given here are the average of the upper and lower estimates, corrected for detransformation bias.

In a few cases, regressions were not significant ($p > 0.05$). When they were near-significant ($.05 > p \leq 0.10$) the equations are listed but indicated as such. When $p > 0.10$ the equation is not given. All statistics were carried out using SYSTAT (1990).

RESULTS

General sample characteristics

Because as noted earlier, the appropriateness of least squares regression for prediction purposes is in part dependent on the closeness of correspondence between the reference and target samples, characteristics of the reference (Denver) sample are important considerations in application of these equations. Means, SD's, and ranges of the two skeletal breadths and four skeletal lengths used to estimate body mass and stature, respectively, are listed for each age group in the study sample in Table 1. Femoral distal metaphyseal M-L breadth is given through 13 years (the body mass prediction equation for this dimension at 14 years, the last year it was measurable in all individuals, was not significant). Femoral head S-I breadth is given beginning at 7 years, the first year it was measurable in all individuals. Diaphyseal lengths are given through age 12 years and total lengths from 11 through 17 years of age; thus, two sets of lengths are available for 11 and 12 years of age. Some slight fluctuations in minimum or maximum values in the last three age groups are due to measurement error.

To assess whether the present study sample of 20 individuals is broadly representative of the Denver Growth Study sample as a whole, femoral length data were compared with those reported earlier for the entire sample at corresponding ages (Maresh, 1970, p 180, Table F-7, average of male and female means). After correction of the previously reported mean data for magnification effects using the same factors employed here, the average difference between means at each age is less than 1%. It is harder to directly assess ranges of variation, since Maresh did not report full ranges and only gave sex-specific data, but data ranges here generally encompass previously reported 10th and 90th percentiles (minimum and maximum across both sexes, corrected for magnification). Thus, the sample selected for this study

TABLE 1. *Descriptive statistics for study sample* ($n = 20$)[a]

Age (years)	Femoral metaphyseal breadth[b]			Femoral head breadth[c]			Femoral length[d]			Tibial length[d]			Humeral length[d]			Radial length[d]		
	Mean	SD	Range	Mean	SD	Range	Mean	SD	Range	Mean	SD	Range	Mean	SD	Range	Mean	SD	Range
1	34.3	2.6	27.9–38.4	–	–	–	132.4^{d}	5.0	126–144	105.7^{d}	4.9	98–117	100.5^{d}	5.0	91–109	77.8^{d}	3.3	72–85
2	42.5	2.6	35.4–45.8	–	–	–	166.7^{d}	7.1	156–179	134.8^{d}	6.5	125–146	125.0^{d}	5.3	117–136	93.9^{d}	4.2	87–102
3	47.1	2.4	41.9–50.3	–	–	–	192.8^{d}	8.6	178–209	157.7^{d}	8.5	147–171	141.9^{d}	6.7	132–158	106.7^{d}	5.0	98–117
4	49.4	2.6	43.4–52.8	–	–	–	216.0^{d}	10.8	196–233	176.7^{d}	10.1	164–193	156.9^{d}	8.0	141–173	118.1^{d}	5.8	107–130
5	51.3	2.6	46.4–54.5	–	–	–	237.1^{d}	11.9	216–256	194.3^{d}	11.8	178–215	170.5^{d}	9.0	154–189	128.4^{d}	6.4	116–141
6	53.7	2.8	48.1–57.7	–	–	–	258.4^{d}	15.2	231–284	211.7^{d}	13.3	191–235	185.1^{d}	9.8	163–203	138.1^{d}	7.3	124–151
7	55.7	3.1	50.2–59.8	27.9	2.7	23.8–33.6	278.5^{d}	16.4	246–301	228.7^{d}	14.8	204–255	197.5^{d}	10.2	176–217	147.4^{d}	8.1	132–162
8	57.5	3.0	52.1–62.2	30.1	2.8	25.0–35.8	296.6^{d}	17.4	263–321	244.2^{d}	16.6	217–274	209.0^{d}	10.3	189–230	156.3^{d}	9.0	140–172
9	59.9	2.9	53.4–63.8	32.4	2.9	27.5–38.0	315.8^{d}	18.2	279–346	259.3^{d}	18.1	230–292	220.3^{d}	11.1	198–243	164.4^{d}	9.8	147–181
10	61.9	2.9	55.5–67.0	34.5	2.9	29.5–40.8	332.6^{d}	20.7	294–375	273.7^{d}	19.8	242–314	231.1^{d}	13.0	207–262	173.0^{d}	10.7	154–193
11	63.8	2.9	57.3–68.6	36.2	2.9	31.4–42.4	349.4^{d}	22.2	311–397	288.6^{d}	21.1	253–333	239.8^{d}	11.2	221–266	181.6^{d}	11.7	161–206
							383.7^{t}	24.5	342–439	324.2^{t}	23.6	282–377	261.0^{t}	14.7	239–298	194.8^{t}	13.1	172–224
12	66.0	2.6	59.2–69.4	38.3	3.1	32.9–44.2	366.9^{d}	19.9	333–407	304.1^{d}	20.4	272–343	248.8^{d}	12.5	230–283	191.0^{d}	11.9	172–214
							404.0^{t}	24.9	359–447	342.2^{t}	24.0	298–382	273.3^{t}	16.4	250–308	205.0^{t}	13.6	179–229
13	67.9	3.0	62.6–74.9	40.4	3.1	35.5–46.0	424.2^{t}	25.6	375–468	358.3^{t}	23.0	313–403	286.2^{t}	18.0	259–326	216.1^{t}	14.5	188–248
14	–	–	–	41.8	2.9	36.5–48.2	441.9^{t}	23.4	404–488	372.4^{t}	21.8	333–419	298.5^{t}	17.6	272–343	226.6^{t}	13.8	202–262
15	–	–	–	43.6	2.5	39.1–49.4	455.1^{t}	24.1	415–503	382.2^{t}	22.8	345–427	309.2^{t}	16.6	285–355	234.8^{t}	13.7	215–268
16	–	–	–	44.5	2.8	38.3–50.1	462.6^{t}	25.9	416–517	387.3^{t}	24.9	344–427	315.8^{t}	17.7	283–360	239.6^{t}	14.4	216–269
17	–	–	–	45.0	2.8	38.7–49.9	466.4^{t}	26.6	416–522	390.0^{t}	26.3	345–428	319.7^{t}	17.9	287–360	241.9^{t}	15.5	217–269

All dimensions in millimeters.

[a] $N = 19$ and 18 for femoral metaphyseal and head breadths in 4–5 year-olds and 6–8 year-olds, respectively (see text).

[b] Femoral distal metaphyseal mediolateral breadth.

[c] Femoral head superoinferior breadth.

[d] Superscript d: diaphyseal length; superscript t: total length, including epiphyses. To convert diaphyseal lengths to total lengths in the 13–17 year age groups, the following ratios of total/diaphyseal length may be used: Femur: 1.097; Tibia: 1.125; Humerus: 1.079; Radius: 1.072.

appears to be reasonably representative of the total Denver Growth Study sample.

In addition to descriptive statistics, methods for converting diaphyseal to total lengths, to be used for specimens in the 13–17 year age range with unfused epiphyses, are given at the bottom of Table 1. These are based on average ratios rather than regression formulae, derived from 12-year-old with both lengths available, since they would be used for individuals spanning a much larger size range, where least squares regression may give spurious results.[2] Variation in these ratios is small in the study sample: coefficients of variation range between 0.7 and 1.1%.

Body mass prediction

Body mass prediction equations from femoral head and distal metaphyseal breadths are given in Table 2. Initial examination of bivariate scatters of body mass against these dimensions indicated some extreme outliers in the age range of 4–8 years. One female had very large body mass values for all 5 years, and 1 male had very large body masses for ages 6 to 8 years. Body mass indices (weight/height^2) for these two individuals at ages 6–8 years, where comparative data are available (Must et al., 1991a,b), indicate that both fall at or above the 95th percentile for their age group among US white children of these ages.[3] Both are also well above all other individuals in the study sample in BMI at these ages. Neither is an outlier in BMI (relative to the rest of the sample, or to US standards) at other ages, where they fall within the sample bivariate scatter for body mass against skeletal breadths. Therefore, for body mass estimation, these outlier data points were deleted from the sample, for those ages only, resulting in sample sizes of 19 individuals for ages 4 and 5 years, and 18 individuals for ages 6–8 years.

Body mass estimation errors are smallest in years 2–7 (%SEE's 5–6%), are slightly larger in year 1 (%SEE 7%), and greatly increase from year 8 onwards. The decrease in error between year 1 and year 2 is part of a trend that begins earlier during the first year of life, and which is very likely related to the initiation of full weight-bearing on the lower limb (i.e., walking) at about 1 year of age. Figure 1 illustrates the strengthening relationship between body mass and femoral distal metaphyseal breadth between 0.5 and 2 years of age in the study sample. Prior to the initiation of walking there is no significant correlation between the two; the correlation is

TABLE 2. Equations for predicting body mass (kg) from femoral distal metaphyseal and head breadths (mm), raw and log-transformed

	Femoral metaphyseal breadth				Log$_e$(Femoral metaphyseal breadth)					Femoral head breadth				Log$_e$(Femoral head breadth)				
Age (years)	Slope	Int.	%SEE	SEE	Slope	Int.	CF[a]	%SEE	SEE	Slope	Int.	%SEE	SEE	Slope	Int.	CF[a]	%SEE	SEE
1	0.188	2.6	7.2	0.65	0.751	−0.45	1.003	7.1	0.64									
2	0.268	0.2	5.0	0.81	0.994	−1.28	1.001	4.8	0.56									
3	0.257	1.5	6.7	0.91	0.899	−0.86	1.002	4.8	0.65									
4	0.328	−0.7	6.9	1.08	1.048	−1.35	1.002	6.5	1.02									
5	0.367	−1.6	6.1	1.08	1.096	−1.47	1.002	6.2	1.09									
6	0.367	−0.4	6.6	1.32	1.034	−1.16	1.002	6.6	1.32									
7	0.419	−1.6	6.1	1.38	1.095	−1.33	1.002	6.3	1.43	0.495	8.0	5.9	1.35	0.650	0.92	1.002	6.2	1.41
8	0.414	0.5	9.0	2.28	1.010	−0.90	1.004	9.2	2.32	0.606	6.1	7.7	1.96	0.749	0.64	1.003	7.9	2.01
9	0.694[b]	−12.8	15.5	4.44	1.524	−2.89	1.010	14.4	4.13	1.155	−8.7	12.3	3.52	1.286	−1.12	1.006	11.3	3.24
10	0.992	−29.5	16.8	5.36	1.939	−4.55	1.012	15.8	5.02	1.279	−12.2	14.8	4.73	1.374	−1.41	1.009	13.9	4.42
11	0.938[b]	−23.9	19.1	6.84	1.690[b]	−3.46	1.016	18.0	6.45	1.626	−23.0	15.6	5.61	1.582	−2.11	1.011	14.7	5.28
12	1.351	−49.6	18.7	7.38	2.263	−5.82	1.015	17.6	6.97	1.850	−31.3	14.3	5.65	1.725	−2.62	1.009	13.5	5.31
13					1.766[b]	−3.67	1.019	19.7	8.74	1.830	−29.4	17.7	7.84	1.656	−2.35	1.014	16.7	7.41
14										1.438	−10.3	15.5	7.75	1.226	−0.68	1.011	14.9	7.44
15										–[c]	–	–	–	–	–	–	–	–
16										–	–	–	–	0.842[b]	0.88	1.009	13.6	6.03
17										1.750	−17.2	11.9	7.34	1.327	−0.94	1.006	11.4	7.01

[a] Correction factor by which to multiply detransformed (raw) estimate.
[b] Regression near-significant ($.05 < P \leq 0.10$).
[c] $P > 0.10$; no equation given.

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[2] As one example, ratios of maximum to diaphyseal length remain virtually constant (to within 0.2%) between 11 and 12-year-olds in the study sample, while regression equations change considerably. Thus, use of ratios derived from 11 and 12 year-olds in the size range typical for 17 year-olds results in almost identical maximum length estimates (difference < 1 mm), while use of 11 and 12 year-old regression equations leads to more variable estimates (difference > 3 mm). Percent standard errors of estimate for ratio estimates among 12 year-olds are very similar to those for regression estimates, and are all under 1%. Also see footnote 1.

[3] The Must et al. (1991a,b) BMI tables were derived from NHANES data collected in the early 1970's, about 20 years later, on average, than the comparable age period for the Denver Growth Study sample measured here. However, prevalence of obesity among US white children appears to have been fairly stable in the 1960s–1970s, at least (Troiano and Flegal, 1998), so these percentiles are likely to be appropriate (if not conservative, i.e., high) for the period under consideration.

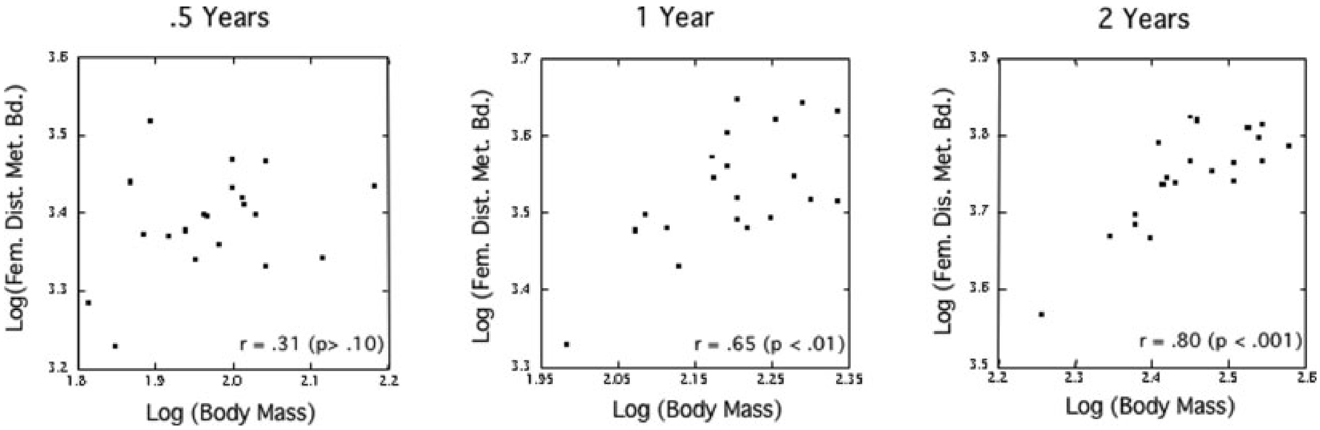

Fig. 1. Correlation between body mass and femoral distal metaphyseal M-L breadth at three different ages in the Denver sample. Each point represents an individual, measured longitudinally.

moderate at a year of age and stronger at 2 years of age. This is concordant with previously demonstrated longitudinal changes in diaphyseal strength in this sample (Ruff, 2003a) and may indicate some direct adaptation of the growing metaphysis to weight-bearing early in development. Interestingly, however, this relationship appears to considerably weaken in later childhood and early adolescence (Table 2), even though the metaphysis is still actively growing in this age range (Table 1).

Where they overlap in age, femoral head breadth has smaller associated errors in estimating body mass than distal metaphyseal breadth. This may be because femoral head S-I breadth better represents true articular size, since the femoral head is almost perfectly spherical, while femoral distal metaphyseal M-L breadth captures only part of distal femoral articular size. There is obviously an anteroposterior (A-P) component of the distal femoral metaphysis and epiphysis that is not reflected in the measured dimension, and the relative shape of the articulation (A-P/M-L breadth) may change significantly during growth (e.g., see Tardieu et al., 2006). Thus, if a well preserved femoral head epiphysis is available, it will provide a better body mass estimate. Log-transformed equations of either dimension have slightly smaller estimation errors than raw dimension equations in most age groups.

By adolescence, however, neither of the femoral breadth measurements provides very precise estimates of body mass. Percent standard errors of estimate are all above 13% from age 10 on. At 15 years of age, no equation reaches statistical significance. Some of this may be due to combining sexes here, given sex-related differences in timing of the adolescent growth spurt, which may affect skeletal and soft tissue parameters differently (see below). However, as noted earlier, sex does not enter as a significant covariate in statistical analyses; also, sex-specific regression equations at age 15 years are not significant, either. These particularly poor estimates are more likely due to volatile fluctuations in body mass that were observed in several individuals in this general age range, i.e., rapid gains in body mass followed by losses, probably due to dieting. These short-term temporary changes are very unlikely to have been paralleled by similar changes in skeletal dimensions, thus adding to data scatter. By age 17, %SEE's are considerably lower, probably reflecting smaller and more stable patterns of weight change.

Body mass prediction equations from bi-iliac breadth and total long bone lengths are given in Table 3 for ages 15–17 years. As described above, equations are presented separately for females and males because of significant sex-specific differences in body proportions in this age range. Note that skeletal bi-iliac breadth must be converted to living bi-iliac breadth, using the formula given at the bottom of Table 3, before application of the formulae. Closer examination of the multiple regressions indicates that variation in bi-iliac breadth is the primary determinant of variation in body mass, especially in females. This is also implied by the low slope values for long bone lengths in many of the female equations (although some of this is also due to the larger absolute magnitude of most bone lengths relative to bi-iliac breadth). However, for consistency, the complete multiple regression equations are given for all sex/age groupings.

Estimation errors using this technique are considerably smaller than those for comparable ages using femoral head breadth (Table 2). Therefore, this method should be preferred if appropriate material is available. Estimation errors (%SEE's) are about 4–8%, comparable to those for body mass estimates from femoral breadths in younger children (Table 2).

Stature prediction

Equations for predicting stature from femoral and tibial lengths are given in Table 4, and from humeral and radial lengths, in Table 5. Note that for convenience (and following the lead of most previous investigators, although not Trotter and Gleser, 1952, 1958), bone lengths are to be entered in mm, while predicted statures are in cm. Equations using diaphyseal lengths are given through age 12 years, and using maximum lengths from age 11 years on. For ages 13–17 years, diaphyseal lengths can be converted to maximum lengths if necessary using the ratios given at the bottom of Table 1. In addition to formulae based on individual bone lengths, equations are given for femoral+tibial length, and humeral+radial length. These were found to provide comparable or lower %SEE's than multiple regression equations in which the two bones were entered separately. Considering upper and lower limb bones in various combinations did not improve predictions over those given in Tables 4 and 5.

TABLE 3. *Equations for predicting body mass (kg) from bi-iliac breadth and long bone lengths (mm)*

Age (years)	Coefficient					Coefficient					Coefficient					Coefficient				
	Bil.[a]	Fem.[b]	Int.	%SEE	SEE	Bil.	Tib.[c]	Int.	%SEE	SEE	Bil.	Hum.[d]	Int.	%SEE	SEE	Bil.	Rad.[e]	Int.	%SEE	SEE
Females																				
15	0.342	0.063	−69.3	7.3	4.1	0.355	0.024	−53.8	7.6	4.3	0.350	0.133	−84.1	6.9	3.9	0.343	0.143	−74.4	6.9	4.1
16	0.374	0.055	−75.8	7.5	4.3	0.374	0.042	−66.6	7.7	4.4	0.390	0.104	−88.0	7.3	4.2	0.375	0.135	−82.7	7.4	4.3
17	0.338	0.051	−64.6	7.2	4.2	0.370	−0.005	−48.7	7.4	4.3	0.308	0.209	−91.3	7.4	4.3	0.246	0.270	−73.1	7.4	4.3
Males																				
15	0.286	0.102	−70.2	5.0	2.8	0.282	0.137	−75.4	4.2	2.3	0.289	0.137	−66.5	5.0	2.7	0.265	0.174	−59.1	5.0	2.7
16	0.404	0.168	−132.2	6.7	4.1	0.374	0.186	−118.6	6.6	4.0	0.394	0.216	−119.4	6.8	4.2	0.353	0.292	−110.4	6.6	4.0
17	0.296	0.153	−92.8	8.2	5.4	0.234	0.164	−68.0	7.7	5.0	0.308	0.209	−91.3	8.4	5.5	0.246	0.270	−73.1	7.8	5.1

[a] Pelvic bi-iliac breadth (mm). Coefficients are for living bi-iliac breadth = 1.17 · skeletal bi-iliac breadth − 30.
[b] Total maximum femoral length (including epiphyses) (mm).
[c] Total maximum tibial length (including epiphyses) (mm).
[d] Total maximum humeral length (including epiphyses) (mm).
[e] Total maximum radial length (including epiphyses) (mm).

As noted by many past investigators of adult stature estimation (e.g., Trotter and Gleser, 1952, 1958), because lower limb bones make a direct contribution to stature, equations based on the femur and tibia produce smaller estimation errors than those based on the upper limb bones. Telkka et al. (1962b), in their study of children, did not find this pattern, but they combined age ranges in their analysis, which may have affected their results. Within the lower limb, the sum of femoral and tibial lengths produces lower errors than either bone alone in about half the age groups. The tibia provides better estimates than the femur in the youngest age groups (1–6 years), while the femur is better among adolescents (except 17-year-olds). Within the upper limb, the sum of humeral and radial lengths is better than either bone alone in 7 of 19 comparisons. The radius is generally a better stature predictor than the humerus, except in some younger age groups, although differences are very slight in mid-late adolescence.

Unlike body mass prediction, there is no increase in error of stature estimation among adolescents. All lower limb %SEE's fall between 1.5% and 2.4%, and all upper limb %SEE's fall between 1.9% and 2.9%.

Body size of KNM-WT 15000

The juvenile early *Homo erectus* (or *ergaster*) KNM-WT 15000 skeleton (Brown et al., 1985; Walker and Leakey, 1993a) is used here as an example of how these techniques can be applied, as well as some their limitations (see Discussion). Relevant dimensions of this specimen are given in Table 6, along with resulting body mass and stature estimates based on the Denver sample equations. Confidence intervals (95%) were calculated using Eq. (1) above. For reasons discussed later, body size estimates for an age range of 11–13 years are given. Stature is estimated based on femoral and tibial lengths. Because femoral and tibial epiphyses were found *in situ*, total maximum lengths of these bones, including epiphyses, can be estimated with only minor reconstruction (Ruff and Walker, 1993; Walker and Leakey, 1993b). I measured femoral head S-I breadth of the original left femur as 44.9 mm, which is intermediate between previously published values for femoral head breadth of 44.0 mm (Brown et al., 1985) and 46.0 mm (Walker and Leakey, 1993b). Part of this variation is probably attributable to the slightly nonspherical shape of the femoral head in this specimen. Because the reference sample breadths were measured in the S-I plane, the same dimension was considered most appropriate to use for KNM-WT 15000.

Body mass estimates for KNM-WT 15000 based on femoral head breadth range between 50.0 and 52.8 kg, with estimates rising slightly with increasing age (Table 6). For ages 11–12 years, the age range used in the previous analysis of his body size (Ruff and Walker, 1993), the average of the four raw and log-transformed estimates is 51 kg, a bit above but still close to the previous estimate of 48 kg (Ruff and Walker, 1993). CI's (95%) are large (±13–18 kg), as expected given the increase in estimation errors in this age range noted above. They are also increased because KNM-WT 15000 falls relatively far from the mean of the reference sample distributions [see Eq. (1)].

Stature estimates for KNM-WT 15000 average about 157 cm using the femur, 161 cm using the tibia, and 160 cm using both bones. Confidence intervals (95%) are about ±5–7 cm. The previous stature estimate for KNM-WT 15000 was 160 cm (Ruff and Walker, 1993), quite

TABLE 4. Equations for predicting stature (cm) from lower limb bones lengths (mm)

	Femoral length (mm)				Tibial length (mm)				Femoral + tibial length			
Age (years)[a]	Slope	Int.	%SEE	SEE	Slope	Int.	%SEE	SEE	Slope	Int.	%SEE	SEE
1[d]	0.303	32.6	2.4	1.7	0.353	35.4	2.1	1.5	0.175	31.1	2.2	1.6
2[d]	0.294	35.7	2.4	2.1	0.380	33.5	1.8	1.6	0.185	29.0	2.0	1.7
3[d]	0.310	34.1	2.1	1.9	0.342	39.9	1.7	1.6	0.174	33.0	1.7	1.6
4[d]	0.295	37.7	2.0	2.0	0.327	43.7	1.8	1.9	0.163	37.7	1.8	1.8
5[d]	0.311	34.1	2.0	2.2	0.322	45.3	1.8	2.0	0.168	35.5	1.7	1.8
6[d]	0.287	40.5	1.9	2.1	0.330	44.9	1.8	2.1	0.160	39.5	1.6	1.9
7[d]	0.294	39.1	1.8	2.2	0.325	46.8	1.9	2.2	0.162	38.6	1.6	1.9
8[d]	0.284	42.8	1.8	2.3	0.304	52.9	1.6	2.0	0.153	44.3	1.5	1.9
9[d]	0.308	35.6	2.1	2.8	0.324	48.9	1.6	2.1	0.165	38.0	1.6	2.2
10[d]	0.292	40.6	2.1	2.9	0.321	50.1	1.5	2.1	0.160	40.8	1.6	2.2
11[d]	0.306	36.3	2.1	3.0	0.331	47.7	1.6	2.2	0.165	38.2	1.6	2.3
12[d]	0.320	31.4	2.1	3.2	0.333	47.9	1.6	2.6	0.148	38.7	1.5	2.5
11[t]	0.279	36.4	1.9	2.7	0.296	47.3	1.6	2.3	0.155	33.6	1.6	2.2
12[t]	0.290	31.8	2.0	3.0	0.309	43.3	2.1	2.4	0.158	31.3	1.8	2.4
13[t]	0.288	33.0	2.1	3.2	0.321	40.1	2.2	3.2	0.159	32.1	1.7	2.8
14[t]	0.294	31.5	1.9	3.1	0.307	46.8	2.2	3.5	0.145	44.8	1.8	2.8
15[t]	0.269	43.8	1.9	3.1	0.273	61.6	2.2	3.6	0.143	47.0	1.9	2.9
16[t]	0.270	43.9	2.0	3.4	0.274	62.7	2.3	3.7	0.149	43.4	1.8	3.2
17[t]	0.286	37.4	1.9	3.3	0.281	61.5	1.6	3.8	0.148	38.7	1.5	3.1

[a] d = using diaphyseal length; t = using total length, including epiphyses.

TABLE 5. Equations for predicting stature (cm) from upper limb bones lengths (mm)

	Humeral Length (mm)				Radial Length (mm)				Humeral+Radial Length			
Age (years)[a]	Slope	Int.	%SEE	SEE	Slope	Int.	%SEE	SEE	Slope	Int.	%SEE	SEE
1[d]	–[b]	–	–	–	0.386	42.7	2.7	1.9	0.131	49.4	2.9	2.1
2[d]	0.437	30.0	2.1	1.8	0.509	36.9	2.4	2.0	0.264	26.9	2.0	1.7
3[d]	0.393	38.1	2.1	2.0	0.514	39.0	2.2	2.1	0.235	35.5	2.0	1.9
4[d]	0.407	37.7	1.9	2.0	0.526	39.3	2.2	2.2	0.236	36.6	2.0	2.0
5[d]	0.394	40.6	2.3	2.4	0.548	37.6	2.3	2.4	0.236	37.4	2.2	2.4
6[d]	0.422	36.8	2.2	2.6	0.570	36.0	2.2	2.5	0.254	32.6	2.0	2.3
7[d]	0.445	33.2	2.3	2.8	0.574	36.4	2.1	2.6	0.261	31.1	2.1	2.5
8[d]	0.439	35.3	2.4	3.1	0.546	41.7	1.9	2.4	0.255	33.8	2.0	2.6
9[d]	0.448	34.3	2.9	3.8	0.565	39.9	2.2	2.9	0.260	32.8	2.5	3.3
10[d]	0.442	35.6	2.5	3.5	0.575	38.3	1.9	2.7	0.259	33.0	2.1	2.9
11[d]	0.475	28.6	2.6	3.8	0.570	39.7	2.2	3.1	0.252	36.7	2.3	3.3
12[d]	0.433	39.3	2.6	3.9	0.547	44.6	2.0	3.0	0.213	54.5	2.5	3.8
11[t]	0.465	21.6	2.6	3.7	0.513	43.4	2.1	3.0	0.131	49.4	2.9	3.1
12[t]	0.420	34.3	2.7	4.0	0.532	40.2	2.0	3.0	0.254	27.4	2.2	3.4
13[t]	0.397	41.6	2.4	3.7	0.507	45.8	2.1	3.3	0.243	32.8	2.3	3.3
14[t]	0.381	47.7	2.1	3.4	0.483	51.8	2.2	3.5	0.230	39.9	2.1	3.2
15[t]	0.368	52.1	2.3	3.8	0.455	59.3	2.2	3.7	0.222	44.5	2.0	3.4
16[t]	0.371	51.6	2.5	4.2	0.463	57.9	2.4	4.0	0.218	47.5	2.0	3.8
17[t]	0.396	44.3	2.6	4.4	0.465	58.6	2.5	4.2	0.219	47.2	2.2	3.9

[a] d = using diaphyseal length; t = using total length, including epiphyses.
[b] $P > 0.10$; no equation given.

close to the average of the values in Table 6. For reasons discussed previously (Ruff and Walker, 1993) and also in the Discussion, however, it is very likely that this is an overestimate of his true stature.

Except for tibia length at age 11 years, long bone lengths in each of the Denver 11–13 year age groups overlap with those of KNM-WT 15000 (compare with Table 1). However, because femoral head breadth in KNM-WT 15000 falls just beyond or near the limits for 11–13-year-olds in the Denver sample (Table 1), it is also of interest to compare his skeletal dimensions specifically with those of Denver individuals of similar age and size. The individual who comes closest to matching KNM-WT 15000 in age and skeletal dimensions is a 12.5-year-old female with a femoral head breadth of 45.1 mm, a maximum femoral length of 438.3 mm, and a maximum tibial length of 379.5 mm. Her body mass is 48.9 kg, close to present and previous estimates of body mass in KNM-WT 15000.

DISCUSSION

Body mass

Both femoral head S-I breadth and M-L breadth of the femoral distal metaphysis provide reasonable estimates of body mass in juvenile skeletons. Femoral head breadth provides better estimates, but is usable only from mid-childhood on, and in many situations, particularly prior to adolescence, may not be applicable due to non-recovery or poor preservation of the femoral head epiphysis. Determining S-I orientation for taking this measurement is relatively easy through articulation of

TABLE 6. Estimation of body size in KNM-WT 15000

	Femoral S-I breadth (mm)		Long bone lengths (mm)		
	Raw	Log	Femur	Tibia	Femur + Tibia
KNM-WT 15000	44.9	3.804	432	380	812
	Estimated body size (mean ± 95% CI)				
	Body mass (kg)[b]		Stature (cm)[c]		
Age	Raw	Log	Femur	Tibia	Femur + Tibia
11[a]	50.0 ± 14.5	50.3 ± 13.7	156.9 ± 6.4	159.8 ± 5.6	159.5 ± 5.3
12	51.8 ± 14.0	52.0 ± 13.2	157.1 ± 6.7	160.7 ± 5.5	159.6 ± 5.4
13	52.8 ± 17.8	52.6 ± 16.8	157.4 ± 6.9	162.1 ± 7.0	161.2 ± 6.1

[a] Estimated age in KNM-WT 15000 (age of reference sample).
[b] Using equations in Table 2.
[c] Using equations in Table 4.

the head with the neck metaphyseal surface, or by noting the position of the fovea capitis (closer to the inferior surface of the head). A possible alternative dimension to femoral head breadth—proximal femoral metaphyseal breadth—is not a practical or informative measure, due to the complexity of this surface (and the adjacent surface for the greater trochanter) during development and its rounded margins. In contrast, the medial and lateral borders of the femoral distal metaphyseal surface are relatively "sharp" and clearly defined from close to birth onwards (e.g., see Tardieu et al., 2006). Relatively good preservation of osteological material is necessary to determine this dimension accurately, although such preservation is not too uncommon, even in Paleolithic material (Trinkaus et al., 2002). While the dimension could theoretically be measured in osteological specimens until fusion of the distal femoral epiphysis to the shaft in late adolescence (Krogman and Iscan, 1986), it is radiographically measurable only through early adolescence, and so equations for older ages could not be generated here. In any event, femoral distal metaphyseal breadth appears to be less useful as a body mass predictor even in early adolescence, possibly because of variation in shape of the distal femur that is not reflected in M-L breadth alone (Tardieu et al., 2006).

Using either technique, relative errors in estimation of body mass increase from early childhood through adolescence. Percent standard errors of estimate in adolescence are similar to, but slightly smaller on average than those obtained from femoral head breadth in a US adult sample, also measured radiographically (Ruff et al., 1991). It is of interest to see how well the adult femoral head equations predict body mass in the Denver juvenile sample. Figure 2 shows the percentage deviation of body mass estimates using the adult white formula (Ruff et al., 1991: raw data, combined sex) compared to true body masses in the Denver sample, from ages 7 through 17 years. The adult formula greatly overestimates body mass during childhood, but percent prediction errors progressively decline during adolescence, until at age 17 differences between estimated and true body masses are nonsignificant ($P > 0.20$, paired t test). The reason for this pattern is that femoral head size (and probably long bone articulations in general, together with long bone lengths), "grow ahead" of body mass during childhood and adolescence, that is, they achieve a greater percentage of adult size earlier than body mass (Ruff et al., 1994). This is clearly illustrated in the growth curves for one individual shown in Figure 3. This girl had the earliest measurable femoral head breadth in the sample (3 years of age), allowing comparisons back to early childhood. Growth in femoral head breadth, and femoral length, clearly outpaces that in body mass during childhood and early adolescence. Thus, adult femoral head formulae will overestimate body mass in juveniles.

The increase in correlation between body mass and femoral distal metaphyseal breadth from the pre-walking to post-walking period (.5–2 years), shown earlier, indicates that metaphyseal growth, at least in width, may be directly affected by mechanical loading early in development. However, the decline in strength of this relationship after early to mid-childhood (2–7 years) suggests that articular size becomes progressively less responsive to changes in mechanical load (body weight) during development, even though epiphyseal and metaphyseal growth continues at a rapid rate until mid-adolescence (Fig. 3). This is concordant with experimental evidence showing a lack of correlation between changes in mechanical load and articular size in older juveniles (Lieberman et al., 2001). These observations also argue for the use of age-specific body mass estimation formulae throughout development.

Although statistically nonsignificant, there is still a slight (average 4.5%) overestimation of body mass in the present 17-year-olds using the previously generated adult-based formula (Ruff et al., 1991). Four individuals in the present sample (3 females, 1 male) had femoral head breadth and body mass data available at ages 20–22 years. Here the previous adult-based formula worked extremely well, with an average bias of only 0.1%, while the present 17-year-old formula (raw data) underestimated body mass by an average of 3%. These observations are consistent with continued (average) body mass increases in late adolescence and early adulthood (Ruff et al., 1991) after the femoral head has ceased or largely ceased growing (Fig. 3). Thus, the present formulae are applicable through age 17 years, and the adult formulae are appropriate thereafter. As discussed in the previous paper, 10% should be subtracted from body mass estimates using the adult formulae to account for increased adiposity of the sample due to its older age (average 52 years) and later time period (late 20th century) (Ruff et al., 1991). This correction factor, which was applied here, is apparently reasonable for estimating body weight in young, presumably healthy adults from the Denver sample. The fact that a body mass prediction equation previously developed for one sample works well for a different sample also implies some generality in the allometric scaling of this dimension after skeletal growth is complete.

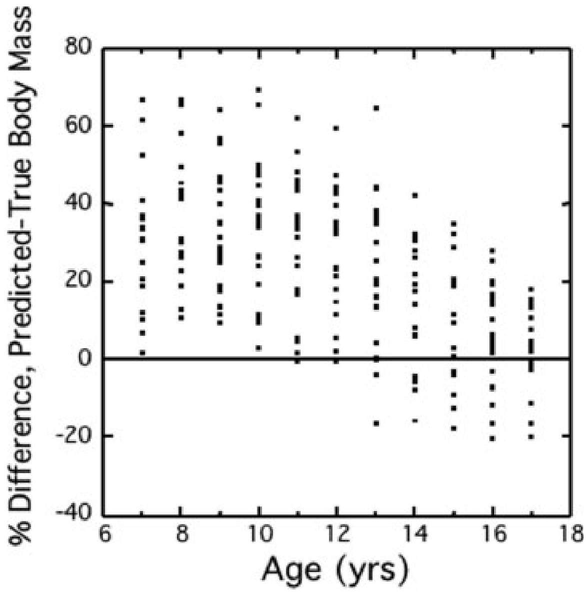

Fig. 2. Percent differences between body mass predicted from an equation based on femoral head breadth in adult US whites (Ruff et al., 1991) and true body mass in the Denver sample at different ages: [(predicted − true)/true] × 100. Each point represents an individual, measured longitudinally 17 times.

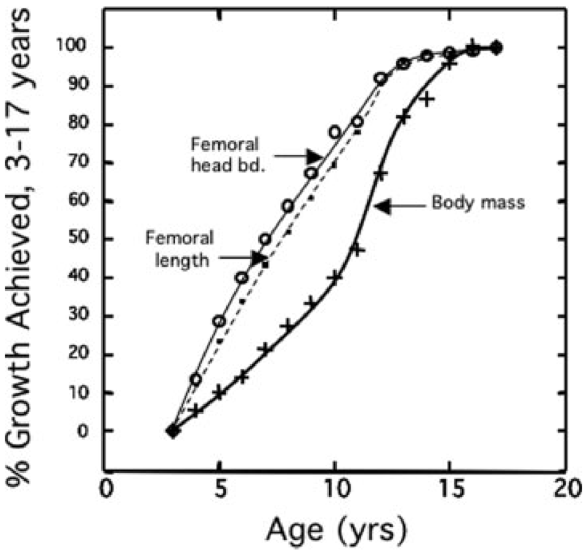

Fig. 3. Percent distance traveled between 3 and 17 years in one individual in the Denver sample, for femoral length, femoral head breadth, and body mass. Each point is one longitudinal measurement. Curves fit by eye.

Although much less commonly applicable, use of pelvic bi-iliac breadth together with long bone lengths provides better estimates of body mass than femoral head breadth in later adolescence. Percent standard errors of estimate are comparable to those obtained for adults using bi-iliac breadth and stature (Ruff, 2000). These formulae may be particularly valuable at ages 15–16 years, when regressions based on articular breadth are non-significant or only near-significant.

Stature

Relative errors in estimation of stature from long bone lengths found here are similar to those reported in studies of adults, with %SEE's of about 1.5–3% (Trotter and Gleser, 1952, my calculations from data presented in their Tables 5 and 13). As with body masses, it is of interest to compare stature estimates that would be derived using adult formulae with true statures in these juveniles. This is done in Figure 4, using Trotter and Gleser's (1952) formulae (male and female) for US white adults, based on maximum femur length. Diaphyseal lengths for ages under 11 years were converted to maximum lengths using the average ratio between the two in individuals where both dimensions could be measured (see Table 1). As was found for body masses, adult stature equations greatly overestimate stature in juveniles, with errors progressively decreasing with age. Feldesman (1992) reported similar results for a small sample of 12-year-old males. This is somewhat surprising given the relatively short limbs of pre-adolescent juveniles relative to overall stature (Hansman, 1970; Maresh, 1970), but may be due to extrapolation of adult least squares regression equations far below their reference ranges. By age 16 the adult formulae overestimate stature by only 0.7%, statistically nonsignificant ($P > 0.10$, paired t test), although still greater than that using the 16-year-old formula (<0.1%). By age 17 average error using the adult formula is less than 0.1% ($P = 0.80$). Thus, the juvenile equations should be used through at least 16 years of age, but the adult equations can be used starting at 17 years or older. Again, as with the body mass comparisons, the fact that a formula developed for one sample works well on another argues for some generality in the allometric scaling of long bone lengths to stature, at least within US whites (see below for more discussion of this issue). It also suggests that the Denver sample used here, although small, is fairly representative in terms of body proportions to the general population, i.e., Trotter and Gleser's larger sample.

Previous studies

There are no previous studies, to my knowledge, of body mass prediction from skeletal remains in juveniles, except for the preliminary analysis included in the Lagar Velho study (Ruff et al., 2002). A few studies of stature estimation in juveniles from long bone lengths have been carried out. The largest of these was that by Telkka et al. (1962a,b), based on radiographs of Finnish children in a cross-sectional sample ranging from near birth through 15 years of age. The authors grouped their data into three age ranges: before 1 year, 1–9 years, and 10–15 years, and derived prediction equations, by sex, for each age range (linear regressions except for those based on the femur in 1–9-year-olds and all equations for the under-1-year group). It is not possible to calculate %SEE's from their data, but their SEE's average almost twice as large as those obtained in the present study for comparable ages. Part of this may be attributable to grouping of data over relatively large age ranges, given the continuous change in body proportions during growth (see Fig. 4). Another problem with this study is the separation of males and females in all prediction equations. While there may be some biological justification for this, at least in adolescence (Feldesman, 1992), in practice it is not possible to sex the great majority of skeletal specimens prior to mid-adolescence, the age range covered in this study.

Other problems with the Telkka et al. (1962b) study include the non-standard (diagonal) measurement of tib-

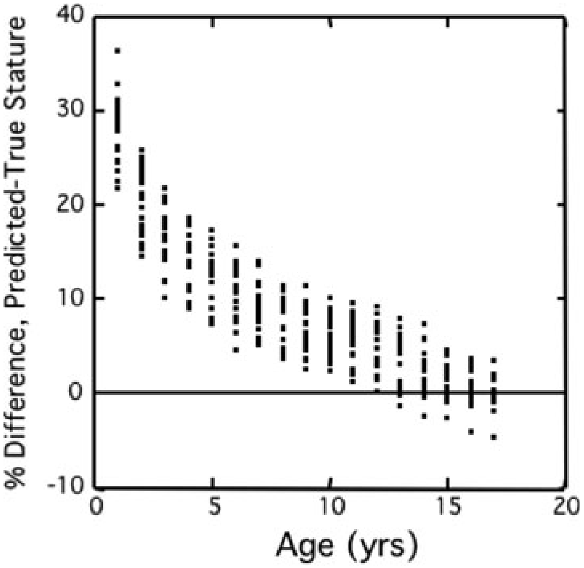

Fig. 4. Percent differences between stature predicted from an equation based on femoral length in adult US whites (Trotter and Gleser, 1952) and true stature in the Denver sample at different ages: [(predicted − true)/true] × 100. Femoral total maximum lengths, including epiphyses, derived in younger individuals from diaphyseal lengths as described in the text. Each point represents an individual, measured longitudinally 17 times.

ial diaphyseal length and the lack of correction for magnification. The authors cite another study with regard to typical "positioning" errors in radiography, but it is clear from their initial report that they did not attempt to correct for magnification *per se* (Telkka et al., 1962a). Since their tube-film distance was relatively short [110 cm, compared with 229 cm in the Denver study (Maresh, 1943)], magnification effects would be exacerbated, almost certainly reaching more than 5%. Furthermore, these errors would vary non-systematically with age, being larger in older individuals (see Methods above). Application of Telkka et al.'s. femoral formulae to 10–15-year-olds in the present study sample yields stature estimates averaging 2 cm too short, consistent with original overestimation of true bone lengths due to radiographic magnification. This difference is unlikely to be due to a difference in body proportions between the Telkka et al. and Denver samples, since relative sitting heights are quite similar in Finnish children measured at about the same time period as those of the Telkka et al. study (Takkunen, 1962) and in the Denver sample (Hansman, 1970). Thus, any application of the Telkka et al. formulae using actual anatomical bone lengths will yield stature estimates that are downwardly biased to a varying extent.

Olivier (1969, p 283–284) presented a table of statures corresponding to given femoral diaphyseal lengths for children, reprinted in Krogman and Iscan (1986, p 339). This was ostensibly based on an "extrapolated curve of Stewart's, established for femoral growth". No specific reference is given, but the only such curve published by Stewart is one for femoral length against age in an skeletal sample of "Eskimo" children, extrapolated upwards for "Caucasians" based on an average size difference between adult bones of the two groups (Stewart, 1954). In fact, the ages determined for the "Eskimo" children were only very approximate (Merchant and Ubelaker, 1977). Furthermore, Stewart's extrapolation between curves seems questionable based on more recent evidence (Y'Edynak, 1976). More seriously, it is not at all clear how Olivier associated femoral lengths with statures, since Stewart does not give statures for either of his juvenile samples. It can only be assumed that Olivier simply matched statures to age, and thus to Stewart's femoral lengths, using some (unspecified) reference source for "Caucasian" children. Since statures at any age vary considerably among "Caucasian" children (Eveleth and Tanner, 1990), this approach is obviously also very approximate. Given these various uncertainties, it is perhaps not surprising that Krogman and Iscan (1986, p 338) reported errors as high as 15 cm between predicted and actual statures using this technique. It cannot, therefore, be recommended.

Himes et al. (1977) derived stature prediction equations from second metacarpal length in a mixed cross-sectional/longitudinal sample of 1–7-year-old rural Guatemalan children, pooled over all ages and separated by sex. Estimation errors were reasonable (%SEE's of about 4.3%) although larger than in the present study. There are several limitations to use of these equations for typical skeletal remains, however. First, metacarpals are not nearly as often recovered in well preserved condition as the major long bones. Second, as in the Telkka et al. (1962b) study, the presentation of results by sex for such young juveniles is detrimental for application to the great majority of recovered skeletal material, which will be unsexed in this age range. The ages covered by the study are limited to younger children; this also combines data over an age range where limb length proportions are changing rapidly (Fig. 4). Stature was measured as supine length, which is larger by a variable amount than true standing stature (Tanner et al., 1966; Ruff, 2003a). It is not clear if radiographic magnification in measurement of the second metacarpal was corrected. Perhaps the most serious limitation of the study, however, as recognized by the original authors, is the nature of the reference sample—undernourished children who were "significantly shorter, lighter, and leaner than children from better circumstances" (Himes et al., 1977, p 452–453). Undernutrition can significantly affect not only overall body size, but also limb length proportions (Bogin et al., 2002), and thus stature formulae based on limb lengths. Of course, as discussed further below, the appropriateness of particular reference samples, including the Denver sample, is a general issue that must be addressed in any such analysis. However, this potential problem would seem to be particularly acute in this case.

Feldesman (1992) carried out a study of femur/stature ratios in 8–18-year-old US and British white children, derived from data collected in four previous growth studies. Changes with age were found in the ratio (mainly between younger children and adolescents, and between all ages and adults), as well as evidence for a gender effect in adolescents. The technique was recommended for 12–18-year-olds, using gender-specific ratios. There are some limitations to the method. First, it is only applicable to adolescents. Sex-specific ratios are given, but sexing of younger adolescents from skeletal remains is difficult. Only the femur and no other long bones can be used. Ratios were derived from mean data (in one case pooled from reported individual data), so that estimation error ranges for individuals are not possible to determine. Also, the use of ratios in general to estimate stature has been criticized on statistical grounds (Hens et al.,

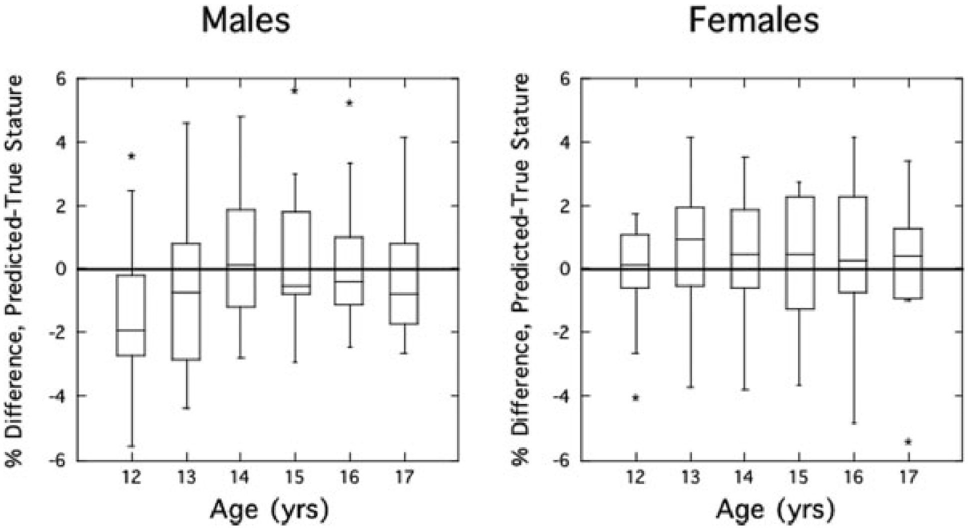

Fig. 5. Box plots of percent differences between statures predicted using Feldesman's (1992) femur/stature ratios and true statures in the Denver sample at different ages: [(predicted - true)/true] × 100. Horizontal lines are medians, boxes encompass the interquartile range and whiskers all other data values except for outliers (asterisks) more than 1.5 times the interquartile range from the median.

1998; Konigsberg et al., 1998). When applied to the present study sample data, the ratio technique generally works well: differences between predicted and actual statures are nonsignificant, across pooled 12–17-year-olds and within sex and age-specific groups ($P > 0.10$, all paired t tests). There is some evidence for subtle age and sex effects, however. Figure 5 shows the percent differences between stature estimates using Feldesman's ratios and true stature by sex for each year in the present study sample. Males show a curvilinear pattern of residuals, increasing from 12 to 14 years and decreasing thereafter. This parallels the age pattern in the femur/stature ratio among males demonstrated by Feldesman (1992: Fig. 1). Females show less of an age trend, but generally have more positive deviations. All individuals fall within ±6% of true statures, however. The overall good performance of the ratio technique in the Denver sample is perhaps not too surprising, as it was one of those used to generate the original ratios (Feldesman, 1992). The present age (but not sex) specific regression equations still perform somewhat better, with maximum estimation errors (based on femoral length) among individuals in this age range of less than ±4%.

A final comment regarding previous studies of juvenile skeletal remains concerns use of the Denver Study long bone lengths for comparative purposes. The Denver sample has often been used for comparisons with juvenile archaeological samples (Johnston, 1962; Y'Edynak, 1976; Merchant and Ubelaker, 1977; Lovejoy et al., 1990; Wall, 1991), using Maresh's (1955, 1970) tabulated means for each age. In no case were these dimensions corrected for magnification, which as noted earlier can be significant, particularly in older (larger) age groups. As Maresh himself noted, "they are not truly anatomical lengths" (1955, p 730), and thus should not be used in comparisons with anatomical lengths, unless corrected first. This factor will exaggerate the apparent size difference between the Denver and most (smaller) archaeological samples (Y'Edynak, 1976; Merchant and Ubelaker, 1977). Even comparisons of percent adult length achieved during growth (Lovejoy et al., 1990) will be affected somewhat, since magnification is systematically biased towards greater effects in older individuals. The summary data given here (Table 1) are corrected, and as pointed out, are very close to those determined for the Denver sample as a whole (Maresh, 1970), once corrected itself.

KNM-WT 15000

Stature and body mass of KNM-WT 15000 were previously estimated using a number of methods (Ruff and Walker, 1993). At that time it was noted that there were no appropriate formulae for estimating body mass from skeletal structural parameters, such as femoral head size in juveniles, and that use of adult formulae was very problematic due to changes in proportions during growth. Therefore, body mass was estimated based on reconstructed stature and pelvic bi-iliac breadth, using appropriately matched modern reference samples. However, dimensions of the pelvis in KNM-WT 15000 are difficult to determine with precision due to the unfused innominates and sacrum, and almost completely missing pubic elements (Walker and Ruff, 1993). In addition, there were questions regarding the (time of death) stature estimation, again in part based on lack of appropriate modern reference samples, specifically "tropically" proportioned children (Ruff and Walker, 1993). The new equations generated here provide an opportunity to readdress these issues.

The age of KNM-WT 15000 is another issue that must be considered when deciding which body size estimation equations to use. In the original analysis of his body size (Ruff and Walker, 1993), a chronological age of 11–12 years was considered appropriate, based on a combination of postcranial and dental indicators. Tooth development and eruption indicators give a best estimate of about 11 years of age (Smith, 1993). Postcranial indicators are less precise, but one observed postcranial event in KNM-WT 15000—union of the humeral trochlea and capitulum - has been reported to occur at a modal age of about 13 years in modern boys, although with a range of 11–15 years (Krogman, 1962), thus overlapping the dental estimate. More recently a younger age at death for KNM-WT 15000, closer to 8 than to 12 years, was implied by an analysis of dental enamel microanatomy (Dean et al., 2001), although the authors also caution that "Our data do not allow us to reconstruct a direct age for the emergence of molars M1 or M2, or an age at death for the Nariokotome or Sangiran specimens."

Large discrepancies between different maturity indices, and between developmental and chronological age, have been demonstrated among modern children (Lampl and Johnston, 1996; Clegg and Aiello, 1999; Smith, 2004). In addition, the apparently large body size (stature) of KNM-WT 15000 relative to most modern 11–12-year-old children has been viewed as a discrepancy (Clegg and Aiello, 1999; Smith, 2004), although this observation should be placed into the context of overall larger body size among Pleistocene *Homo* than in modern humans (Ruff et al., 1997). On balance, for the purposes of matching with an appropriately aged modern reference sample for body size estimation, a chronological age of about 12 ± 1 year still seems appropriate for KNM-WT 15000.

New stature estimates for KNM-WT 15000 using the tibia average 161 cm and using the femur 157 cm. (Interestingly, Feldesman (1992) obtained exactly the same estimate from KNM-WT 15000's femoral length using his femur/stature ratio method.) The tibial estimate is higher because KNM-WT 15000 has a long tibia relative to his femur, part of the evidence for his "tropically proportioned" body (Ruff and Walker, 1993). The average crural index (tibia/femur length × 100) among 11–13-year-olds in the Denver sample is 84.5, while KNM-WT 15000's crural index is 88.0. While the crural index is not a perfect indicator of relative limb length to stature, the two are significantly correlated (Ruff et al., 2002), and there are also other indications that KNM-WT fits a modern "tropical" body build (i.e., linear, with relatively long extremities) better than a higher latitude body build (Ruff and Walker, 1993). We have previously argued strongly for use of an appropriately matched reference sample in terms of relative limb proportions when estimating stature (Ruff and Walker, 1993; Holliday and Ruff, 1997; Auerbach and Ruff, 2004). Ecogeographic differences in body proportions are expressed in juveniles as well as adults (Ruff and Walker, 1993; Ruff et al., 2002). The Denver sample consistently falls between tropical and very high latitude (e.g., Inupiat) juvenile samples in relative limb length and other proportions (Ruff et al., 2002), consistent with its mid-higher latitude current location and ethnic origin. Thus, because they are based on a sample very likely characterized by relatively shorter limbs, the present stature equations will overestimate stature in KNM-WT 15000. This is especially true for values derived from the tibia, which shows more ecogeographic variability than the femur (Holliday, 1999; Holliday and Ruff, 2001).

As noted previously (Ruff and Walker, 1993), there are several reasons to suspect that KNM-WT 15000's original stature estimate of 160 cm, derived using ecogeographically but not age-matched stature estimation formulae, is a maximum possible stature, and that his true stature at death was several centimeters less than this. This would actually be consistent with the present results, and indicate a stature somewhat less than 157 cm. Unfortunately, there are still no comparable data from tropically proportioned juveniles with which to generate the most appropriate stature prediction equations for specimens such as KNM-WT 15000.

Variation in body proportions should not be as significant a problem in estimating body mass from femoral head size, since this technique is based on a mechanical relationship between body weight and articular size. In fact, equations based on femoral head size developed from one reference sample appear to perform very well across other samples encompassing a variety of body shapes (Auerbach and Ruff, 2004). Thus, the body mass estimates for KNM-WT 15000 given here should be valid, assuming no major change in hip joint reaction force relative to body mass between early *Homo* and modern humans (Ruff, 1995). [However, this may not apply to very early hominids, i.e., australopithecines (Ruff, 1998; Ruff et al., 1999)]. Estimates average about 50–53 kg, slightly above the original estimate of 48 kg, which was based on an entirely different approach (Ruff and Walker, 1993). The best individual match to KNM-WT 15000 in terms of age and skeletal dimensions within the Denver sample had a body mass of about 49 kg. Although body mass estimation errors from femoral head breadth are quite large in this age range, the general correspondence between present and previous results is reassuring, and suggests that a body mass of about 50 kg, at his time of death, is a reasonable estimate.

Limitations and other considerations

All of the Denver sample limb bone radiographs are of the left side (Maresh, 1943, 1970). Thus, left sides should be measured if possible when using the present formulae. However, the side factor is probably not significant. Bilateral asymmetry in lower limb bone lengths and articular or periarticular breadths is very small, averaging less than 0.4% in lengths and less than 0.2% in breadths (Auerbach and Ruff, 2006). Asymmetry in upper limb bones lengths is larger, averaging 1.3% for humeri and 0.8% for radii (Auerbach and Ruff, 2006). However, these figures are for adults, and ontogenetic data indicate that juveniles have less asymmetry. Steele and Mays (1995) examined humeral length asymmetry in juveniles and adults from the same archaeological population sample. Asymmetry among adults (1.2%) was similar to the average found among modern human adults (Auerbach and Ruff, 2006). Asymmetry in humeral length among juveniles averaged only 0.5% (weighted average of age group means), and given adult values, asymmetry in radial length among juveniles was probably smaller than this. Thus, even in the upper limb, adjustment for side is of dubious value, although if only right upper limb bones are available for stature estimation their lengths could be adjusted downwards by 0.5%, if desired, before application of the present formulae.

The present method requires determination of age to the nearest year before a prediction equation can be applied. When skeletal and dental materials for an individual are fairly complete, this is not an unreasonable expectation. Idiosyncratic and systematic biases due to genetic or environmental factors may, of course, significantly affect matching of developmental with chronological age (Lampl and Johnston, 1996). In these cases, however, it is likely that the developmental age estimate may actually provide a better basis for choosing a body mass or stature prediction equation, since changes in body proportions (for example, due to the adolescent growth spurt) would be expected to parallel developmental more than chronological age. Only chronological ages were available for the Denver sample, but aging techniques based on matching of developmental and chronological age were, for the most part, also developed for early-mid-20th century US white children (Krogman, 1962; Smith, 1991; Saunders, 2000), so the two ages are likely to have been (on average) similar in this sample. If there is a disjunction between skeletal and dental (de-

TABLE 7. Crural indices in the Denver sample

Age (years)[b]	Crural Index[a]		
	Mean	SD	SE
1[d]	79.8	1.9	0.4
2[d]	80.9	2.3	0.5
3[d]	81.8	2.2	0.5
4[d]	81.8	2.0	0.4
5[d]	81.9	2.3	0.5
6[d]	81.9	2.0	0.5
7[d]	82.1	2.3	0.5
8[d]	82.3	2.3	0.5
9[d]	82.1	2.4	0.5
10[d]	82.3	2.5	0.6
11[d]	82.4	2.3	0.5
12[d]	82.6	2.4	0.5
11[t]	84.5	2.1	0.5
12[t]	84.7	2.2	0.5
13[t]	84.5	2.2	0.5
14[t]	84.3	2.3	0.5
15[t]	84.0	2.5	0.6
16[t]	83.7	2.4	0.5
17[t]	83.6	2.4	0.5

[a] (Tibia length/Femur length) × 100.
[b] d = using diaphyseal length; t = using total length, including epiphyses.

velopmental) ages in a target individual, the skeletal age would be preferred. This was one reason for examining results for KNM-WT 15000 using a 11–13-year-old age range, as discussed above. If skeletal/dental material is less complete and only a multi-year age range can be determined for an individual, either the equation corresponding to the middle of that age range or an average of body size estimates over the entire age range can be used. Generally the two approaches will yield similar results, as demonstrated in Table 6. Since most of the prediction formulae given here are for combined sex, differences in maturation rate between males and females are averaged in the equations. This no doubt increases estimation error somewhat, but does allow application to children prior to mid-adolescence. Sex was not found to be a significant factor in prediction error among older adolescents, except for the bi-iliac/long bone equations.

The greatest limitation of the present study results is that they are based on only a small sample of modern juveniles—20 individuals (18–19 for some early childhood body mass estimation equations). Relative estimation errors are similar to (or smaller than) those derived from larger adult samples, however, and the success of more broadly based adult formulae in predicting body mass and stature in Denver 17-year-olds indicates that they are representative of the general US white population, at least in terms of body proportions. As argued above with reference to KNM-WT 15000, the new stature estimation equations must be applied with caution to other samples with possibly different limb length to stature proportions. The most feasible approach for evaluating such proportions in most cases is to calculate the crural index (tibia/femur length) and compare this with the value for the Denver sample at a corresponding age (see Auerbach and Ruff, 2004 for an application in adults). Summary statistics for the crural index at each age in the Denver sample are given in Table 7. Standard deviations may be used to evaluate individual specimens, and standard errors sample means. For example, KNM-WT 15000's crural index of 88.0 is 1.5–1.7 SD's above the means for 11–13-year-olds in the Denver sample, strongly suggesting a different body proportion. Of course, sample means are more effective for evaluating overall population affinities in proportions, and thus appropriateness of the Denver equations (i.e., some individuals within any population may have relatively extreme values, but if the sample as a whole is similar to Denver, the Denver equations should be appropriate).

As noted earlier, differences in body proportions should not be as strong a factor in determining whether the Denver sample is an appropriate reference sample for estimating body mass.[4] However, for both stature and body mass estimations, use of ordinary least squares regression of body size on skeletal dimensions (also referred to as "inverse calibration" regression; Konigsberg et al., 1998) is problematic when the target sample differs significantly in size from the reference sample, especially when this involves extrapolations well beyond the reference sample size range (Aiello, 1992; Hens et al., 1998; Konigsberg et al., 1998). In these situations alternative methods, such as model II (reduced major axis, RMA, or major axis, MA) or "classical calibration" (regression of skeletal dimension on body size, followed by solving for body size) have been advocated (Olivier, 1976; Jungers, 1988; Aiello, 1992; Hens et al., 1998, 2000; Konigsberg et al., 1998). Hens, Konigsberg, and colleagues have been particularly strong advocates of "classical calibration" as the generally most preferred technique when target and reference samples are different in size distribution, or when such information can not be determined *a priori* (Hens et al., 1998, 2000; Konigsberg et al., 1998). Reduced major axis regression has had equally strong supporters (Sjovold, 1990; Aiello, 1992). This issue is considered further in the Appendix, which includes alternative formulae and recommendations for their use. It is argued there that when extrapolating beyond the Denver size range, prediction equations derived from least squares regression of body size on skeletal dimensions still produce reasonable results for stature estimation, while RMA equations may be preferred for body mass estimation in some circumstances.

CONCLUSIONS

Using a subset of the Denver Growth Study sample, body mass and stature can be estimated from juvenile skeletal remains with errors that are equal to or smaller than those associated with similar adult formulae. Femoral distal metaphyseal breadth is an effective predictor of body mass in children, and femoral head breadth can be used in older children and adolescents. Estimation error increases with age, with the largest errors in mid-adolescence. In later adolescents, multiple regressions based on pelvic bi-iliac breadth and long bone lengths provide an alternative body mass estimation method, with lower estimation errors. Stature can be estimated from long bone diaphyseal lengths through age 12, and from total maximum lengths, including epiphyses, from age 11 on. As in adults, the lower limb bones provide better estimates.

Long bone length and articular breadth proportions relative to stature and body mass, respectively, change continuously throughout growth; thus, age-specific pre-

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[4] Linear body proportions could have some effect on the bi-iliac/long bone length equations; however, since these are largely driven by variation in bi-iliac breadth, this would probably not be as significant a factor as in stature estimation.

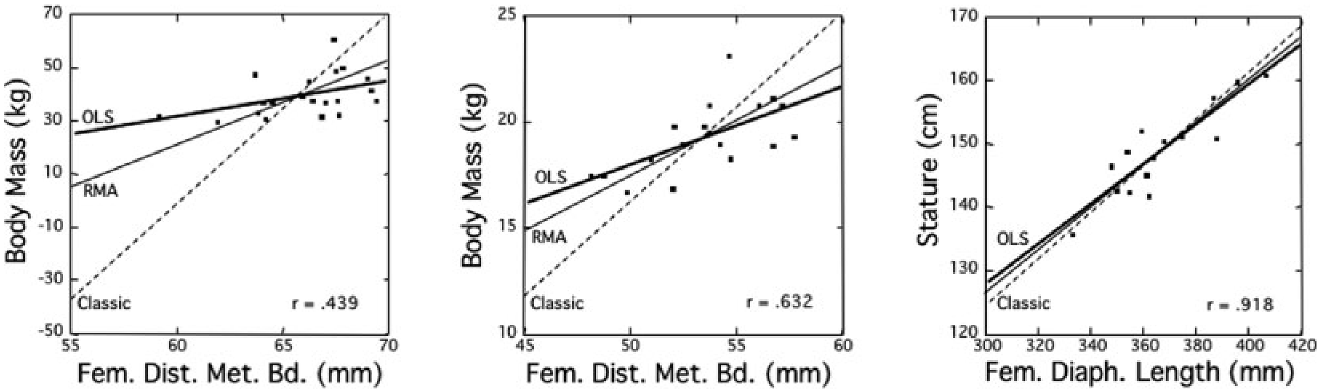

Fig. 6. Prediction of body mass and stature in the Denver sample using three different regression models. OLS and heavy line: ordinary least squares; RMA and thin line: reduced major axis; Classic and dashed line: "classical calibration". Left plot: body mass estimation from femoral distal metaphyseal breadth in 12-year-olds; middle plot: body mass estimation from femoral distal metaphyseal breadth in 6-year-olds; right plot: stature estimation from femoral diaphyseal length in 12-year-olds. RMA line not labeled in right plot. Points represent individuals.

diction formulae are necessary. For the same reason, equations based on adult reference samples give grossly biased body size estimates in juveniles. By age 17, adult equations work reasonably well, indicating that beyond this age methods based on adult reference samples are appropriate. There is some indication that the distal femoral articulation responds in early childhood to the increased loading that accompanies weight-bearing (walking), but that this mechanical responsiveness declines during growth.

New body size estimates for the KNM-WT 15000 juvenile (at his time of death) are similar to those determined in a previous study using different methods. Body mass is estimated at about 50–53 kg (previous estimate, 48 kg), and stature at slightly under 157 cm (previous maximum estimate, 160 cm). Stature estimates are more affected by differences in body proportions than are body mass estimates. There are still no entirely suitable stature estimation techniques for juveniles with "tropically" proportioned bodies.

APPENDIX

Alternative regression methods

Both "classical calibration" and RMA methods were compared with ordinary least squares regression of body size on skeletal parameter (or "inverse calibration" regression, see Konigsberg et al., 1998) for predicting body mass or stature in several representative situations using the Denver sample data. (For simplicity these will be referred to here as classical calibration, RMA, and OLS, even though OLS technically also applies to classical calibration.) Body size estimation near or below the lower extreme of the Denver size range was emphasized in these tests, given the larger body size of the Denver sample compared to many archaeological samples (e.g., see Johnston, 1962; Y'Edynak, 1976; Merchant and Ubelaker, 1977), but the same conclusions apply to extrapolations above the sample size range.

Figure 6 shows bivariate plots of body mass against femoral distal metaphyseal breadth in Denver 12-year-olds and 6-year-olds, and stature against femoral diaphyseal length in 12-year-olds, with lines generated using the three regression models. Body mass estimation in the 12-year-olds is representative of prediction equations with relatively low correlations and large estimation errors, with an r of 0.439 and a %SEE of almost 19%. In this situation classical calibration performs poorly: even at x values not far from the mean, predicted y (body mass) is outside the observed range of y values, and at or beyond the lower edge of the x distribution, predicted body masses are negative. Reduced major axis performs somewhat better, but still produces unrealistically low body mass estimates near or beyond the lower end of the range of predictor (x) values. In this situation OLS performs best, with realistic estimates throughout, although estimation error remains high, as noted. When correlations are moderate, as in the 6-year-old body mass estimation shown in Figure 6 ($r = 0.632$), classical calibration still performs relatively poorly, predicting unrealistically low estimates at or slightly beyond the lower x range. Here, however, RMA appears to work better than OLS for estimating values through extrapolation beyond the reference sample range. When correlations are high, as in stature prediction among 12-year-olds ($r = 0.918$), choice of regression model makes relatively little difference, as would be expected (Figure 6), with all stature estimates within 3% even at an extrapolation well below the lower x range (e.g., a femoral diaphyseal length of 300 mm, >5 SD from the Denver mean).

Based on these and similar results, the OLS equations presented in the main text are recommended for prediction purposes, even somewhat outside the size range of the Denver sample, except when correlations are moderate ($0.60 > r < 0.85$), when RMA equations are appropriate and may be used if desired. Reduced major axis equation parameters for prediction equations of this kind are given in Table A1. These include body mass prediction equations based on femoral distal metaphyseal breadth from age 1 through 7 years and those based on femoral head breadth from age 7 through 13 years (both raw and logged data), and the femoral head breadth equation at age 17 years (logged data only). Other body mass prediction equations based on femoral head or distal metaphyseal breadth have correlations lower than 0.60. Correlations using bi-iliac breadth and long bone lengths are all higher than 0.85 (except 17-year-old males, $r = 0.823$). Almost all stature equations

TABLE A1. RMA equations for predicting body mass (kg) from femoral distal metaphyseal and head breadths (mm), raw and log-transformed (see text)

	Femoral metaphyseal breadth		Log$_e$(Femoral metaphyseal breadth)		Femoral head breadth		Log$_e$(Femoral head breadth)	
Age (years)	Slope	Int.	Slope	Int.	Slope	Int.	Slope	Int.
1	0.304	−1.4	1.157	−1.9				
2	0.343	−3.0	1.235	−2.2				
3	0.445	−7.4	1.503	−3.2				
4	0.518	−9.9	1.595	−3.5				
5	0.543	−10.4	1.600	−3.5				
6	0.581	−11.2	1.581	−3.3				
7	0.606	−11.1	1.544	−3.1	0.695	3.3	0.908	0.1
8					0.918	−2.2	1.123	−0.6
9					1.662	−25.1	1.781	−2.8
10					2.024	−37.9	2.107	−4.0
11					2.502	−54.7	2.397	−5.0
12					2.548	−58.1	2.344	−4.9
13					3.086	−80.2	2.684	−6.1
17							2.186	−4.2

also have correlations of greater than 0.85, except for some very young (<4 years) age groups and a few additional equations based on upper limb bone lengths, and even these latter equations have correlations greater than 0.80. Extrapolation would be expected to be less of a problem in very young age groups where sample-specific long bone lengths have not diverged as far (Johnston, 1962), and among older juveniles moderate extrapolation in stature estimation is likely to be a less serious issue than matching of body proportions between target and reference samples.

The choice of which equation—OLS or RMA—to use in a particular application is to some extent the decision of the individual investigator, depending on the degree of size overlap between the target sample and the Denver reference sample (for further discussion, see Konigsberg et al., 1998). Perhaps the best recommendation when the two samples appear to differ systematically in size is to try both sets of equations and compare results. Estimation errors for RMA equations are not given in Table A1, but empirical tests within the data range of the Denver sample, for equations with correlations between 0.60 and 0.85, indicate slight increases in %SEE's over those for OLS (about 1.1–1.2 times greater), as would be expected (Konigsberg et al., 1998). However, because OLS produces greater directional bias outside the reference sample range when correlations are well below 1.0 (Konigsberg et al., 1998), true %SEE's in this situation will probably be broadly comparable between the two methods, and those for RMA equations may actually be lower. Correction factors for detransformation bias in using log-transformed equations should also be very similar to those given for OLS equations in Table 2, and in any event are quite small for these equations (<1.5%).

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LITERATURE CITED

Aiello LC. 1992. Allometry and the analysis of size and shape in human evolution. J Hum Evol 22:127–148.

Auerbach BM, Ruff CB. 2004. Human body mass estimation: a comparison of "morphometric" and "mechanical" methods. Am J Phys Anthropol 125:331–342.

Auerbach BM, Ruff CB. 2006. Limb bone bilateral asymmetry: variability and commonality among modern humans. J Hum Evol 50:203–218.

Bogin B, Smith P, Orden AB, Varela Silva MI, Loucky J. 2002. Rapid change in height and body proportions of Maya American children. Am J Hum Biol 14:753–761.

Brown F, Harris J, Leakey R, Walker A. 1985. Early *Homo erectus* skeleton from West Lake Turkana, Kenya. Nature 316:788–792.

Buschang PH. 1982. Differential long bone growth of children between two months and eleven years of age. Am J Phys Anthropol 58:291–295.

Clegg M, Aiello LC. 1999. A comparison of the Nariokotome *Homo erectus* with juveniles from a modern human population. Am J Phys Anthropol 110:81–93.

Dean C, Leakey MG, Reid D, Schrenk F, Schwartz GT, Stringer C, Walker A. 2001. Growth processes in teeth distinguish modern humans from *Homo erectus* and earlier hominins. Nature 414:628–631.

Eveleth PB, Tanner JM. 1990. Worldwide variation in human growth, 2nd ed. Cambridge: Cambridge University Press.

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

Gindhart PS. 1973. Growth standards for the tibia and radius in children aged one month through eighteen years. Am J Phys Anthropol 39:41–48.

Green WT, Wyatt GM, Anderson M. 1946. Orthoroentgenography as a method of measuring the bones of the lower extremities. J Bone Joint Surg 28:60–65.

Hansman C. 1970. Anthropometry and related data, anthropometry skinfold thickness measurements. In: McCammon RW, editor. Human growth and development. Springfield: Charles C. Thomas. p 103–154.

Hens SM, Konigsberg LW, Jungers WL. 1998. Estimation of African ape body length from femur length. J Hum Evol 34:401–411.

Hens SM, Konigsberg LW, Jungers WL. 2000. Estimating stature in fossil hominids: which regression model and reference sample to use? J Hum Evol 38:767–784.

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

Holliday TW. 1999. Brachial and crural indices of European late upper paleolithic and mesolithic humans. J Hum Evol 36:549–566.

Holliday TW, Ruff CB. 1997. Ecogeographic patterning and stature prediction in fossil hominids: comment on Feldesman and Fountain. Am J Phys Anthropol 103:137–140.

Holliday TW, Ruff CB. 2001. Relative variation in human proximal and distal limb segment lengths. Am J Phys Anthropol 116:26–33.

Hummert JR, Van Gerven DP. 1983. Skeletal growth in a Medieval population from Sudanese Nubia. Am J Phys Anthropol 60:471–478.

Jantz RL, Owsley DW. 1984. Long bone growth among Arikara skeletal populations. Am J Phys Anthropol 63:13–20.

Johnston FE. 1962. Growth of the long bones of infants and young children at Indian Knoll. Am J Phys Anthropol 20:249–254.

Johnston FE, Zimmer LO. 1989. Assessment of growth and age in the immature skeleton. In: Iscan MY, Kennedy KAR, editors. Reconstruction of Life from the skeleton. New York: Wiley-Liss. p 11–21.

Jungers WL. 1988. Lucy's length: stature reconstruction in Australopithecus afarensis (A.L. 288–1) with implications for other small-bodied hominids. Am J Phys Anthropol 76:227–231.

Jungers WL, Cole TM, Owsley DW. 1988. Multivariate-analysis of relative growth in the limb bones of Arikara Indians. Growth Dev Aging 52:103–107.

Konigsberg LW, Hens SM, Jantz LM, Jungers WL. 1998. Stature estimation and calibration: bayesian and maximum likelihood perspectives in physical anthropology. Yrbk Phys Anthropol 41:65–92.

Krogman WM. 1962. The human skeleton in forensic medicine. Springfield, IL: Charles C. Thomas.

Krogman WM, Iscan MY. 1986. The human skeleton in forensic medicine, 2nd ed. Springfield, IL: Charles C. Thomas.

Lampl M, Johnston FE. 1996. Problems in the aging of skeletal juveniles: perspectives from maturation assessments of living children. Am J Phys Anthropol 101:345–355.

Larsen CS. 1997. Bioarchaeology: interpreting behavior from the human skeleton. Cambridge: Cambridge University Press.

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.

Lovejoy CO, Russell KF, Harrison ML. 1990. Long bone growth velocity in the Libben population. Am J Hum Biol 2:533–541.

Maresh MM. 1943. Growth of the major long bones in healthy children. Am J Dis Child 66:227–257.

Maresh MM. 1955. Linear growth of long bones of extremities from infancy through adolescence. Am J Dis Child 89:725–742.

Maresh MM. 1959. Linear body proportions. Am J Dis Child 98:27–49.

Maresh MM. 1970. Measurements from roentgenograms, heart size, long bone lengths, bone, muscles and fat widths, skeletal maturation. In: McCammon RW, editor. Human growth and development. Springfield: Charles C. Thomas. p 155–200.

Martin R. 1928. Lehrbuch der anthropologie. Jena: Fischer.

McCammon RW. 1970. Human growth and development. Springfield, IL: Charles C. Thomas.

Merchant VL, Ubelaker DH. 1977. Skeletal growth of the protohistoric Arikara. Am J Phys Anthropol 46:61–72.

Must A, Dallal GE, Dietz WH. 1991a. Reference data for obesity: 85th and 95th percentiles of body mass index (wt/ht^2)—a correction. Am J Clin Nutr 54:773.

Must A, Dallal GE, Dietz WH. 1991b. Reference data for obesity: 85th and 95th percentiles of body mass index (wt/ht^2) and triceps skinfold thickness. Am J Clin Nutr 53:839–846.

Olivier G. 1969. Practical anthropology. Springfield, IL: Charles C. Thomas.

Olivier G. 1976. The stature of Australopithecus. J Hum Evol 5:529–534.

Raxter MH, Auerbach BM, Ruff CB. 2006. A revision of the Fully technique for estimating statures. Am J Phys Anthropol 130:374–384.

Ribot I, Roberts C. 1996. A study of non-specific stress indicators and skeletal growth in two mediaeval subadult populations. J Arch Sci 23:67–79.

Rösing FW. 1988. Korperhohenrekonstruktion aus skelettmassen. In: Knussman R, editor. Anthopologie handbuch der vergleichenden anthropologie des menschen begründet von rodolf martin. Stuttgart: Fischer. p 586–600.

Ruff CB. 1995. Biomechanics of the hip and birth in early Homo. Am J Phys Anthropol 98:527–574.

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

Ruff CB. 2000. Body mass prediction from skeletal frame size in elite athletes. Am J Phys Anthropol 113:507–517.

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

Ruff CB. 2003b. Long bone articular and diaphyseal structure in Old World monkeys and apes. II. Estimation of body mass. Am J Phys Anthropol 120:16–37.

Ruff CB. 2003c. 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.

Ruff CB, McHenry HM, Thackeray JF. 1999. The "robust" australopithecine hip: cross-sectional morphology of the SK 82 and 97 proximal femora. Am J Phys Anthropol 109:509–521.

Ruff CB, Niskanen M, Junno JA, Jamison P. 2005. Body mass prediction from stature and bi-iliac breadth in two high latitude populations, with application to earlier higher latitude humans. J Hum Evol 48:381–92.

Ruff CB, Scott WW, Liu AY-C. 1991. Articular and diaphyseal remodeling of the proximal femur with changes in body mass in adults. Am J Phys Anthropol 86:397–413.

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

Ruff CB, Trinkaus E, Holliday TW. 2002. Body proportions and size. In: Zilhão J, Trinkaus E, editors. Portrait of the artist as a child: the Gravettian human skeleton from the Abrigo do Lagar Velho and its archaeological context. Lisbon: Instituto Português de Arqueologia. p 365–391.

Ruff CB, Trinkaus E, Walker A, Larsen CS. 1993. Postcranial robusticity in *Homo*. I. Temporal trends and mechanical interpretation. Am J Phys Anthropol 91:21–53.

Ruff CB, Walker A. 1993. Body size and body shape. In: Walker A, Leakey R, editors. The Nariokotome *Homo erectus* skeleton. Cambridge: Harvard University Press. p 234–265.

Ruff CB, Walker A, Trinkaus E. 1994. Postcranial robusticity in *Homo*. III. Ontogeny. Am J Phys Anthropol 93:35–54.

Saunders SR. 2000. Subadult skeletons and growth-related studies. In: Katzenburg MA, Saunders SR, editors. Biological anthropology of the human skeleton. New York: Alan R. Liss.

Saunders SR, Hoppa R, Southern R. 1993. Diaphyseal growth in a nineteenth century skeletal sample of subadults from St. Thomas' Church, Belleville, Ontario. Int J Osteoarch 3:265–281.

Sjovold T. 1990. Estimation of stature from long bones utilizing the line of organic correlation. Hum Evol 5:431–447.

Smith BH. 1991. Standards of human tooth formation and dental age assessment. In: Kelly MA, Larsen CS, editors. Advances in dental anthropology. New York: Wiley-Liss. p 143–168.

Smith BH. 1993. The physiological age of KNM-WT 15000. In: Walker A, Leakey R, editors. The Nariokotome *Homo erectus* skeleton. Cambridge: Harvard University Press. p 195–220.

Smith RJ. 1993a. Bias in equations used to estimate fossil primate body mass. J Hum Evol 25:31–41.

Smith RJ. 1993b. Logarithmic transformation bias in allometry. Am J Phys Anthropol 90:215–228.

Smith RJ. 1994. Regression models for prediction equations. J Hum Evol 26:239–244.

Smith SL. 2004. Skeletal age, dental age, and the maturation of KNM-WT 15000. Am J Phys Anthropol 125:105–120.

Steele J, Mays S. 1995. Handedness and directional asymmetry in the long bones of the human upper limb. Int J Osteoarch 5:39–49.

Stewart TD. 1954. Evaluation of evidence from the skeleton. In: Gradwohl RBH, editor. Legal medicine. St. Louis: Mosby p 407–450.

SYSTAT: Statistics VE. 1990. Evanston, IL: SYSTAT, Inc.

Takkunen RL. 1962. Anthropometric studies on Finnish children. Annales Paediatriae Fenniae 8 (Suppl 19):1–127.

Tanner JM, Whitehouse RH, Takaishi M. 1966. Standards from birth to maturity for height, weight, height velocity, and weight velocity: British children, 1965, Part 1. Arch Dis Child 41:454–471.

Tardieu C, Glard Y, Garron E, Boulay C, Jouve JL, Dutour O, Boetsch G, Bollini G. 2006. Relationship between formation of the femoral bicondylar angle and trochlear shape: independence of diaphyseal and epiphyseal growth. Am J Phys Anthropol 130:491–500.

Telkka A, Palkama A Virtama P. 1962a. Estimation of stature from radiographs of long bones in children I. Children aged from one to nine. Ann Med Exp Biol Fenniae 40:91–96.

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

Trinkaus E, Ruff CB, Esteves F, Coelho JMS, Silva M, Mendonça M. 2002. The lower limb remains. In: Zilhão J, Trinkaus E, editors. Portrait of the artist as a child: the Gravettian human skeleton from the Abrigo do Lagar Velho and its archaeological context. Lisbon: Instituto Português de Arqueologia. p 435–465.

Troiano RP, Flegal KM. 1998. Overweight children and adolescents: description, epidemiology, and demographics. Pediatrics 101:497–504.

Trotter M, Gleser GC. 1952. Estimation of stature from long bones of American whites and Negroes. Am J Phys Anthropol 10:463–514.

Trotter M, Gleser GC. 1958. A re-evaluation of estimation of stature based on measurements of stature taken during life and of long bones after death. Am J Phys Anthropol 16:79–123.

Walker A, Leakey R, editors. 1993a. The Nariokotome *Homo erectus* skeleton. Cambridge: Harvard University Press.

Walker A, Leakey R. 1993b. The postcranial bones. In: Leakey RE, Walker A, editors. The Nariokotome *Homo erectus* skeleton. Cambridge: Harvard University Press. p 95–160.

Walker A, Ruff CB. 1993. Reconstruction of the pelvis. In: Walker A, Leakey R, editors. The Nariokotome *Homo erectus* skeleton. Cambridge: Harvard University Press. p 221–233.

Wall CE. 1991. Evidence of weaning stress and catch-up growth in the long bones of a Central California Amerindian sample. Ann Hum Biol 18:9–22.

WHO. 1995. Physical status: the use and interpretation of anthropometry. Geneva: World Health Organization.

Y'Edynak G. 1976. Long bone growth in Western Eskimo and Aleut skeletons. Am J Phys Anthropol 45:569–574.

Zar JH. 1984. Biostatistical analysis. Englewood Cliffs: Prentice-Hall.