

Article

Novel Formulae for Estimating Weight in Children Using Epiphyseal and Metaphyseal Breadths and Torsional Rigidity (J) Values of the Femur and Tibia Derived from a Modern New Mexico Sample

Julia Meyers ^{1,2}, Lesley Harrington ³ , Deborah C. Merrett ⁴  and Hugo F. V. Cardoso ^{1,*} 

¹ Department of Archaeology, Simon Fraser University, Burnaby, BC V5A 1S6, Canada; julia.meyers22@gmail.com

² Department of Anthropology, University of British Columbia, Vancouver, BC V6T 1Z4, Canada

³ Department of Archaeology, University of Alberta, Edmonton, AB T6G 2H4, Canada; l.harrington@ualberta.ca

⁴ Department of Anthropology, Lakehead University, Thunder Bay, ON P7B 5E1, Canada; dcmerret@lakeheadu.ca

* Correspondence: hcardoso@sfu.ca

Abstract

Background/Objective: Most weight estimation formulae developed for children from skeletal measurements are based on 20 individuals from the Denver Growth Study. This limitation is mainly due to the availability of data. The formulae produced using these data are limited to a small range of variation in weight, which may result in reduced applicability. This study develops new weight estimation formulae relying on a larger and more diverse sample of deceased children ($n = 77$) of known age and weight from the New Mexico Decedent Image Database. **Methods:** A classical calibration regression approach was used to generate weight estimation equations from virtual metaphyseal breadths, epiphyseal breadths, and torsional rigidity (J) of the femur and tibia. Equations were developed separately for the two sexes, two BMI categories, and three age categories. **Results:** Midshaft femoral J values (45.5% of the total diaphyseal length) and proximal tibial J values (75% of the total diaphyseal length) correlate most highly with body weight and when used to develop weight estimation formulae produce the least amount of error. In general, the breadth measures were less correlated and had larger error than the J values, though the distal femoral metaphyseal breadth produced the highest coefficients of determination and lowest error of the breadth formulae. **Conclusions:** While these formulae are based on a sample of modern children, the variation that they encompass and the different equations provided allow users to apply them in a variety of circumstances. However, weight estimation may have limited value due to large prediction errors.

Keywords: body mass estimation; cross-sectional geometry; lower limb; breadth measurements



Academic Editor: Sara C. Zapico

Received: 11 May 2026

Revised: 13 July 2026

Accepted: 14 July 2026

Published: 22 July 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

Weight estimation formulae based on skeletal parameters serve as essential tools for biological anthropologists across several domains: reconstructing identity in forensic investigations, characterizing activity patterns and adaptive strategies in archaeological populations, and exploring body size and life history evolution among hominins. A handful of studies have been particularly influential in establishing weight estimation equations from skeletal measurements in children, with the Denver Growth Study [1]

providing the primary dataset for this work. The Denver Growth Study was a detailed longitudinal investigation of human growth conducted between 1927 and 1967 [1–4]. The sub-sample relevant to weight estimation comprised ten boys and ten girls, examined at two-month intervals from ages two to six months, and subsequently at six-month intervals until approximately 16 to 20 years of age depending on the participant. At each examination, radiographs were obtained alongside measurements of body mass, stature (or supine length for infants), and bi-iliac breadth. Participants were drawn from the Denver, Colorado area, were all identified as “white”, and came from middle- to upper-class socioeconomic backgrounds [5]. The central role of the Denver cohort in weight estimation formula development reflects both the exceptional comprehensiveness of its documented weight data and serial radiographs across the entire growth period, and the absence of other comparable pediatric samples combining known weights with measurable skeletal elements.

The most extensively applied equations for estimating body mass from long bone dimensions were established by Ruff [6] using Denver Growth Study radiographs, with formulae based on femoral distal metaphyseal breadth and femoral head breadth. Robbins and colleagues [7] subsequently developed a complementary set of equations from a sub-sample of the same study, utilizing measurements of torsional rigidity (J) at the femoral midshaft. Both Ruff [6] and Robbins and colleagues [7] constructed age-specific formulae, reflecting evidence that the relationship between skeletal dimensions and body mass shifts across the course of growth [8]. These formulae have since been applied across a broad range of contexts, including modern forensic casework involving juvenile remains [9], investigations of growth and childhood experience in archaeological assemblages [10–13], and studies of hominin children and small-bodied adult hominins [6,14]. Methodologically, the formulae depend either on metaphyseal or epiphyseal breadth measurements of the femur [6] or on torsional rigidity (J) values derived from the femoral diaphysis at midshaft [7].

Because all these formulae were generated from a limited number of individuals from the same population, the variation in the relationship between weight and measurable skeletal elements is low and restricted. As a consequence, the broader applicability of these formulae may be constrained, not only by the particular historical and socioeconomic circumstances of that sample, but by the range of variation sampled. Given the conditions under which the Denver Growth Study children were raised, caloric or nutritional stress was unlikely, and no individuals in the sample were underweight, overweight or obese [1]; most participants fell within what was considered a normal weight-for-age range in the 20th century (i.e., generally between the 5th and 95th percentiles). This characteristic of the reference sample limits the utility of derived formulae by effectively excluding both very low-weight and overweight individuals. One practical consequence is that applying Denver-derived equations in contemporary forensic settings fails to account for the positive secular trend in body weight documented across populations worldwide throughout the 20th century [15]. In the United States alone, the prevalence of overweight children rose markedly between 1980 and 2000, with the heaviest children continuing to increase in weight over this period [16–18]. Whether the Denver reference sample can produce formulae capable of accurately estimating weight in children above normal BMI percentiles remains an open question [19].

Yim and colleagues [20] and Spake and colleagues [21] evaluated the performance of several formulae from Ruff [6] and Robbins and colleagues [7] on a 21st-century pediatric sample and found systematic underestimation of weight across both formula sets. Underestimation was more pronounced for metaphyseal breadth-based formulae than for J -based formulae, and in both cases the degree of underestimation increased with age [21].

This pattern was attributed to a combination of back-transformation bias in the logged data and the well-documented positive secular trend in pediatric weight across the 20th and 21st centuries [21]. Compounding these concerns, research has demonstrated that both longitudinal and appositional bone growth in children from past populations differs from that observed in 20th-century children, with generally reduced overall growth and more frequent growth disruptions [22–24]. Beyond these limitations, existing formulae assess only specific regions of the femur—namely breadth and J at defined locations—with little investigation of alternative femoral sections or other weight-bearing long bones such as the tibia [19]. A further practical limitation is that age-specific formulae require either documented age or an age estimate, which introduces an additional source of error into weight reconstruction [13].

To advance understanding of the relationship between skeletal growth and body mass, this study examines a contemporary sample of children with documented age and weight at death to develop a novel set of weight prediction formulae that are independent of age [19]. These formulae are derived from a combination of femoral and tibial breadth measurements and torsional rigidity values from individuals spanning a broader range of body mass indices than those represented in the Denver Growth Study. Incorporating greater BMI diversity enables a more thorough characterization of the ontogenetic relationship between long bone dimensions and body weight and extends the potential applicability of the resulting formulae to more varied forensic and bioarchaeological contexts.

2. Materials and Methods

The study sample consisted of 77 individuals (34 female, 43 male) ranging in age from one month to 19 years, drawn from the greater Albuquerque, New Mexico region (hereafter referred to as “the New Mexico sample”) [19]. These data were obtained from virtual wet bone specimens derived from pre-autopsy CT scans held by the Office of the Medical Investigator (OMI) of New Mexico, USA. Scanning was performed using a Philips Brilliance Big Bore 16-slice CT scanner (Royal Philips LLC, Amsterdam, The Netherlands), with a slice thickness of 1 mm and 0.5 mm overlap; each individual is represented by approximately 10,000 slices. Each DICOM volume captures the full body of the deceased using a field of view ranging from 180 to 500 mm. De-identified demographic data, medical histories, and CT images are archived at the New Mexico Decedent Image Database (NMDID), jointly curated by the OMI of New Mexico and the University of New Mexico, Albuquerque New Mexico, USA. Birth years across the sample ranged from 1994 to 2015.

Individuals were selected from the NMDID to reflect diverse socioeconomic and racialized backgrounds represented in New Mexico’s contemporary population, thereby maximizing variation in both body weight and skeletal dimensions [19]. Manner of death varied across accidental, natural, suicide, and homicide categories. Demographic variables were recorded during the death investigation, with additional information for some individuals sourced from next-of-kin interviews conducted by the New Mexico OMI, including living height and weight. Height and weight were recorded by the medical examiner as cadaver measurements. Steps were taken to minimize the impact of decomposition on body weight, but a small amount of differential may exist between living weight and cadaver weight. An initial review of CT scans was performed to exclude any individuals whose height or weight data were compromised by peri- or post-mortem factors. The age of 19 years was selected as the cut off to correspond with the beginning of adulthood for males and females (as outlined by Bogin [25], see further details below). The age, sex, and BMI distribution of the sample are summarized in Table 1. To investigate the relationship between BMI and skeletal size parameters, individuals were assigned to one of three BMI categories: below -2 z-scores or the 5th percentile (underweight); between -2 and $+2$

z-scores or the 5th to 95th percentile (normal weight); and above +2 z-scores or the 95th percentile (overweight and obese). BMI distribution in the sample was limited by very few individuals falling under the 5th percentile in BMI in the NMDID. Therefore, individuals under the 5th percentile for BMI were grouped in with the 5th to 95th percentile individuals when developing formulae. The BMI distribution of the sample is illustrated in Figure 1, which broadly reflects demographic patterns of childhood obesity in New Mexico, where 41.1% of children are overweight or obese by the time they reach third grade [26]. Age categories were determined based on the developmental stages outlined by Bogin [25] and were staggered by sex to reflect the earlier development of girls in the juvenile stage. Children aged one month to 5.9 years old were put into a combined infant-child (hereafter referred to as child) sample, girls aged 6–10.9 and boys aged 6–12.9 were put in the juvenile sample, and boys aged 11 and above and girls aged 13 and above were put in the adolescent category.

Table 1. Size and composition of the sample by age, sex, and BMI percentile category. Total sample size, as well as minimum, maximum, mean, and standard deviation for age, sex, and BMI percentiles are also provided.

Age	Sex		BMI Percentile		Age Category		
	Male	Female	<95th	>95th	Child	Juvenile	Adolescent
0.0–0.9	2	2	3	1	4	-	-
1.0–1.9	2	4	5	1	6	-	-
2.0–2.9	5	2	6	2	7	-	-
3.0–3.9	4	1	-	4	5	-	-
4.0–4.9	2	-	-	2	2	-	-
5.0–5.9	3	1	1	3	4	-	-
6.0–6.9	3	1	3	3	3	1	-
7.0–7.9	1	3	-	2	-	4	-
8.0–8.9	-	-	-	-	-	0	-
9.0–9.9	7	3	8	2	-	10	-
10.0–10.9	2	1	2	1	-	2	1
11.0–11.9	2	3	4	1	-	2	3
12.0–12.9	-	3	2	1	-	2	1
13.0–13.9	1	3	1	3	-	-	4
14.0–14.9	1	-	1	-	-	-	1
15.0–15.9	1	2	2	1	-	-	3
16.0–16.9	1	1	-	2	-	-	2
17.0–17.9	2	2	1	3	-	-	4
18.0–18.9	2	2	2	2	-	-	4
19.0–19.9	2	-	-	2	-	-	2
Total <i>n</i>	43	34	41	36	31	21	25
Min Age	0.09	0.28	0.09	0.41	0.9	6.01	11.23
Max Age	18.51	18.51	18.51	18.51	5.96	10.94	18.51
Mean Age	7.98	8.98	8.12	9.3	2.67	8.86	15.18
SD of Age	5.68	5.76	5.55	5.97	1.83	1.42	2.55

Metaphyseal and epiphyseal breadth measurements and polar second moments of area (J) for the femur and tibia were obtained from the whole-body CT scans [19]. DICOM files were loaded into Dragonfly 3D View software version 2023 (Dragonfly Montreal, Quebec, Canada) and oriented following the protocols established by Spake and colleagues [27]. Long bones were aligned along sagittal and coronal planes to replicate positioning on an osteometric board, achieved by aligning the coronal plane with the posterior surface of the distal epiphysis and the sagittal plane with the lateral surface of the distal epiphysis.

Virtual breadth measurements were recorded at the maximum breadths of the proximal and distal metaphyses and at the maximum breadths of the proximal and distal epiphyses for each bone (Figure 2), using Dragonfly's Slab function. This function applies slab maximum intensity projection (slab MIP), in which multiple CT sections are overlaid to generate an opaque two-dimensional image from which maximum bone contours can be identified, with the ruler tool then used to record maximum breadth. Distal femoral breadth and proximal and distal tibial breadths were measured mediolaterally for both the epiphyses and metaphyses. The proximal femoral metaphyseal measurement was taken perpendicular to the neck-shaft angle along a superoinferior axis, while the femoral epiphyseal measurement captured both the superoinferior maximum breadth of the femoral head, consistent with the approach of Ruff [6], and a mediolateral maximum breadth. In the case of young individuals, epiphyses were measured as soon as they were visible and measurable. All epiphyses and metaphyses were measured using the same criteria, as detailed above and regardless of age, for consistency of bone dimensions over the growth period. Slab MIP projection facilitates simultaneous visualization of both bone ends even when they do not appear within the same CT slice, which is particularly advantageous for capturing the full medial and lateral curvature of the metaphysis or epiphysis [27]. A full description and visual reference for external bone measurements are provided in Table 2 and Figure 2.

Diaphyseal cross-sectional slices were extracted using the snapshot function in Dragonfly and exported as TIFF images. Torsional rigidity (J) was subsequently calculated using the Slice Geometry function of the BoneJ plugin version 7.1.9 (NIH, Bethesda, MD, USA) [28] within ImageJ2 version 1.53 software (NIH, Bethesda, MD, USA) [29], with image thresholding performed via the Otsu algorithm. Automated measurements were derived from multiple sequential cross-sectional images. Two-dimensional bone images were converted to 8-bit black-and-white images, oriented along anteroposterior and mediolateral planes, and J was computed as the sum of $I_{\max}$ and $I_{\min}$. J values were not standardized by weight, given that size-related variation in J was directly relevant to the weight estimation formulae being developed. For the femoral diaphysis, J was calculated at 25%, 45.5%, 75%, and 80% of total diaphyseal length (measured from distal to proximal). For the tibia, J was assessed at 25%, 50%, and 75% of diaphyseal length. The 45.5% location approximates the diaphyseal midpoint of an unfused femur, while the 80% section captures the subtrochanteric region [8]. Measuring J at multiple locations along the diaphysis—including midshaft and both proximal and distal regions—was intended to characterize variation in torsional rigidity across the full length of the bone rather than at a single site [19]. Measurement descriptions and illustrations are provided in Table 2 and Figure 2, respectively.

Prior to building formulae, two-way analysis of covariance (ANCOVA) tests were performed to evaluate differences in bone dimensions between sexes and BMI weight groups, with age included as a covariate. An interaction term was also tested to identify whether differences in bone dimensions occurred within specific combinations of sex and weight status. Levene's test for homogeneity of variance was applied to the data before ANCOVA calculations were carried out.

Weight prediction formulae were derived from metaphyseal and epiphyseal breadth measurements and J values using classical calibration rather than inverse calibration, as the former is more appropriate when estimated weights cannot be assumed to fall within the range of the reference sample [6,29]. In classical calibration, the skeletal measurement (dependent variable) is first regressed onto weight (independent variable) via least squares, after which the resulting equation is algebraically rearranged to express weight as the dependent variable. Raw breadth measurements were log-transformed using the

natural logarithm prior to analysis. This transformation addressed both the exponential nature of the breadth-weight relationship and a practical lower limit issue: below a certain threshold, untransformed regression equations would yield negative weight estimates, which the log transformation resolved. Estimated weights from log-transformed formulae were subsequently back-transformed to kilograms using the natural exponential function, with the understanding that a small amount of bias is introduced through this transformation-retransformation process. J values were not log-transformed, as the relationship between weight and J was sufficiently linear and the difference in error between logged and unlogged versions was negligible, meaning no back-transformation bias affects J-based weight estimates.

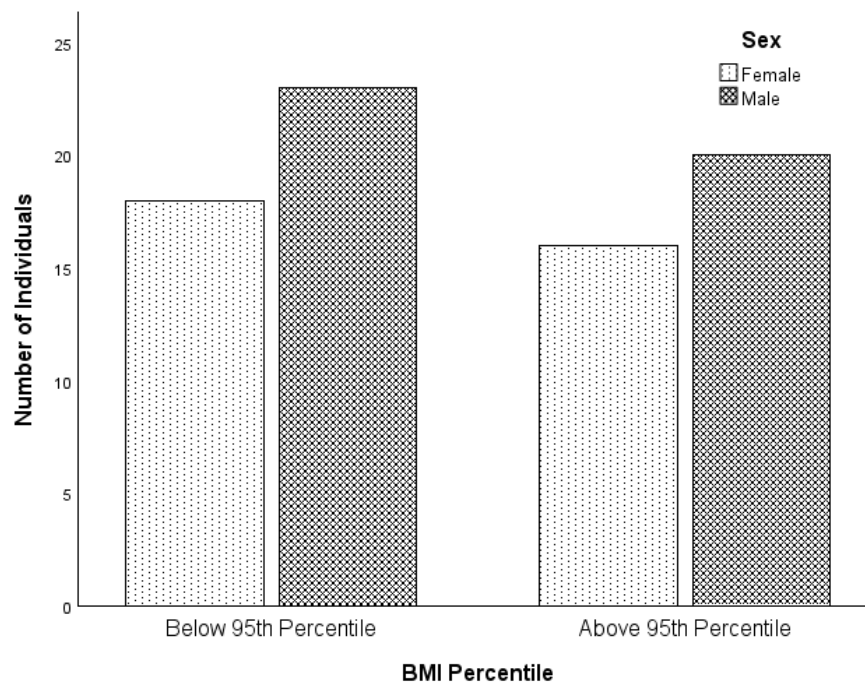


Figure 1. Distribution of BMI percentile (below 5th percentile, between 5th and 95th percentile, and above 95th percentile) in the sample divided by sex.

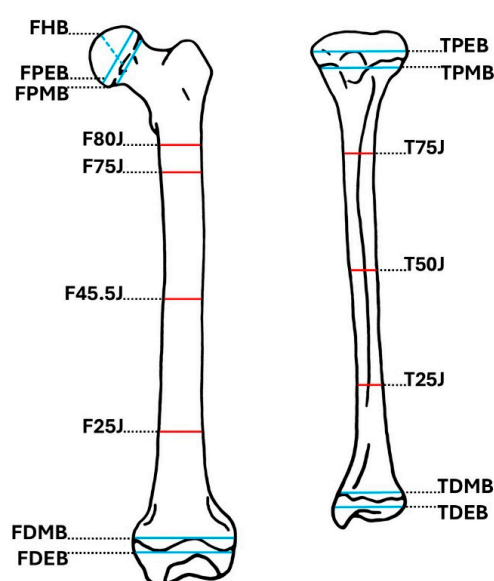


Figure 2. Illustration of external breadth (blue) and cross-sectional J (red) measurements (J) on the femur and tibia. Illustration by Hugo F.V. Cardoso.

Table 2. Description of the femoral and tibial dimensions collected.

Femur	Description	Tibia	Description
Breadth measurements			
FHB	Head breadth	TPEB	Proximal epiphysis breadth
FPEB	Proximal epiphysis breadth	TPMB	Proximal metaphysis breadth
FPMB	Proximal metaphysis breadth	TDMB	Distal metaphysis breadth
FDMB	Distal metaphysis breadth	TDEB	Distal epiphysis breadth
FDEB	Distal epiphysis breadth		
Cross-sectional J measurements			
F80J	Cross-section at 80% of diaphyseal length	T75J	Cross-section at 75% of diaphyseal length
F75J	Cross-section at 75% of diaphyseal length	T50J	Cross-section at 50% of diaphyseal length
F45.5J	Cross-section at 45.5% of diaphyseal length	T25J	Cross-section at 25% of diaphyseal length
F25J	Cross-section at 25% of diaphyseal length		

Separate formulae were developed for different subsets of the sample: the combined-sex group, males only, females only, individuals below (underweight/normal weight) and above (overweight/obese) the 95th BMI percentile, and individuals in the child, juvenile, and adolescent developmental categories [19]. By omitting age stratification, these formulae allow weight estimation to proceed independently of both age and sex. The BMI-and age-stratified formulae were designed to better represent the variation in the bone dimension–body mass relationship across differing body compositions and age categories. In practice, prior knowledge of whether an individual falls above or below the 95th BMI percentile is not required; rather, these formulae offer alternative options for scenarios where some information about an individual’s likely weight status is available. Ultimately, the skeletal measurement ranges represented within each BMI-specific set of formulae are the most important consideration, as they help determine which equation is likely to be most appropriate based on the skeletal measurements of the unknown weight individual. In the case of age, it is often easier to place children in a life history stage, than age them accurately. Even when that placement is uncertain, the range of skeletal measurements within each age category also provides options for determining which equation to apply. All statistical analyses were conducted in SPSS v.21 (IBM, Chicago, IL, USA).

For each formula, residuals were defined as estimated minus actual weight, such that negative values indicate underestimation and positive values indicate overestimation. Internal validation was performed by computing the mean residual (MR) and mean absolute residual (MAR) as respective measures of accuracy and precision, with the MR tested against zero using a one-sample *t*-test. Additional summary statistics reported for each formula include the mean, standard deviation, and range (minimum–maximum) of the predictor variable (in unlogged form for breadth measurements), as well as the coefficient of determination (R^2) for the classic calibration model. The range of the predictor variable indicates the bounds within which each model can be considered valid.

A mean standard error (MSE) was calculated for each formula from individual-level standard errors following Lucy [30], providing the basis for computing prediction intervals. Unlike confidence intervals, prediction intervals are derived from individual point values rather than the sample mean; consequently, their reliability depends on homoscedasticity—uniform variance of errors across the age range of the regression. MSE values from breadth-based formulae were back-transformed from their logged form to express prediction error in kilograms and to enable direct comparison with MSE values from J-based formulae. The bias introduced by the log transformation and back-transformation process was acknowledged throughout. Heteroscedasticity of residuals was evaluated visually by plotting standardized residuals against standardized predicted values. As a further assessment of

internal validity, the percentage of individuals whose actual weight fell within the 95% prediction interval for each model was calculated (% coverage).

3. Results

Before conducting the two-way ANCOVA, Levene's test (Tables 3 and 4) revealed unequal variances between the sexes for femoral proximal epiphyseal breadth (FPEB), femoral head breadth (FHB), tibial proximal epiphyseal breadth (TPEB), tibial distal epiphyseal breadth (TDEB), J at 25% of the femoral diaphysis, and J at 25%, 50%, and 75% of the tibial diaphysis. Variances across weight status groups were found to be homogeneous for all variables. The two-way ANCOVA revealed no statistically significant differences in femoral or tibial breadth measurements attributable to either sex or weight group when controlling for age (Table 3). Among J values, significant between-group differences were identified at 25% and 75% of the femoral diaphyseal length, and at 50% and 75% of the tibial diaphyseal length (Table 4). J at 45.5% of the femoral diaphysis exhibited a significant main effect of sex ($p = 0.000$) and a significant sex-by-weight-group interaction ($p = 0.014$), while the main effect of weight status alone did not reach significance ($p = 0.452$).

Table 3. F- and p -values for the two-way ANCOVA tests examining differences in femoral and tibial breadth measurements (variable) between the sexes and the BMI groups, with age as a co-variate. Asterisk indicates unequal variances at $\alpha < 0.05$.

Variable	Group	F	p
FPEB			
	Sex *	1.175	0.283
	BMI	0.210	0.889
	Interaction	0.156	0.926
FDEB			
	Sex	0.004	0.952
	BMI	0.761	0.520
	Interaction	0.608	0.612
FPMB			
	Sex	0.984	0.325
	BMI	2.711	0.052
	Interaction	0.162	0.921
FDMB			
	Sex	0.408	0.525
	BMI	1.745	0.167
	Interaction	2.232	0.093
FHB			
	Sex *	0.073	0.788
	Weight	0.490	0.691
	Interaction	1.108	0.352
TPEB			
	Sex *	0.223	0.638
	Weight	0.387	0.762
	Interaction	0.801	0.498
TDEB			
	Sex *	0.027	0.870
	Weight	0.218	0.884
	Interaction	0.431	0.731

Table 3. *Cont.*

Variable	Group	F	<i>p</i>
TPMB			
	Sex	0.263	0.610
	Weight	0.960	0.417
	Interaction	1.299	0.282
TDMB			
	Sex	0.120	0.730
	Weight	0.462	0.710
	Interaction	1.991	0.124

Table 4. F- and *p*-values for the two-way ANCOVA tests examining differences in femoral and tibial J measurements (variable) between the sexes and the weight groups, with age as a co-variate. Significant differences are indicated in bold ($\alpha < 0.05$). Asterisk indicates unequal variances at $\alpha < 0.05$.

Variable	Group	F	<i>p</i>
F25J			
	Sex *	0.814	0.370
	Weight	2.823	0.045
	Interaction	0.117	0.950
F45.5J			
	Sex	172.129	0.000
	Weight Status	0.572	0.452
	Interaction	3.785	0.014
F75J			
	Sex	1.285	0.261
	Weight Status	4.823	0.004
	Interaction	0.469	0.705
F80J			
	Sex	1.016	0.317
	Weight Status	2.729	0.051
	Interaction	0.280	0.840
T25J			
	Sex	1.563	0.216
	Weight Status	2.692	0.053
	Interaction	0.493	0.689
T50J			
	Sex	2.502	0.118
	Weight Status	4.001	0.011
	Interaction	0.440	0.725
T75J			
	Sex	1.718	0.194
	Weight Status	3.131	0.031
	Interaction	0.320	0.811

The classical calibration models for femoral and tibial breadth measurements are presented in Tables 5–7 organized by sex, BMI, and age group respectively, while Tables 8–10 summarize the corresponding models for femoral and tibial J measurements. For each

formula, Tables 5–10 report sample size (n), mean (M), standard deviation (SD), minimum (Min), maximum (Max), coefficient of determination (R^2), and mean standard error (MSE) for each unlogged breadth measurement and each J measurement. Across the combined-sex and sex-specific models (Table 5), the femoral and tibial distal metaphyses consistently produced the lowest MSE values, with the tibial proximal metaphysis yielding the next lowest errors.

For the underweight/normal weight formulae (below the 95th percentile; Table 7), the femoral distal and tibial proximal metaphyses again returned the lowest MSE values, with the tibial distal metaphysis ranking next. Among the overweight/obese formulae (above the 95th percentile), the femoral distal and tibial proximal metaphyses similarly produced the lowest MSE , this time comparable in magnitude to the femoral head breadth. Across all external bone dimension measurements, femoral head breadth achieved the highest R^2 value (0.94; Figure 3), while tibial distal epiphysis breadth yielded the lowest (0.84; Figure 4). Graphically, these variables demonstrate the homogeneity of variance across BMI weight groups observed for all breadth measurements within each BMI-specific formula. Notably, the MSE values associated with the underweight/normal weight formulae are approximately half the magnitude of those produced by the overweight/obese formulae.

Among the age groups there did not appear to be one breadth measurement that acted as a consistent predictor of weight (Table 8). The femoral proximal and distal epiphyses had the lowest MSE values among the child formulae, and tibial distal metaphysis had the highest MSE values. The distal femoral epiphysis also had the highest R^2 value (0.805). The juvenile group generated a large MSE across all breadth formulae, with the highest being produced by the distal femoral epiphysis. The R^2 values were all uniformly below 0.5 for the juvenile formulae as well. The adolescent formula produced smaller MSE s than the juvenile group, the lowest also being produced by the distal femoral epiphysis (32.10 kg), but the coefficient of determination was still only 0.66. Error variance appeared to increase with increased size and age, moving from low in the child group, to higher in the juvenile and adolescent groups.

Within the complete sample, the formula derived from J measured at 75% of the tibial diaphysis returned the lowest mean standard error (MSE) of 12.6 kg. The equation based on J at 45.5% of the femoral diaphysis produced a virtually equivalent MSE , while formulae using J at 25% and 75% of the femur and at 25% and 50% of the tibia yielded only marginally higher error values (Table 8). By contrast, formulae utilizing log-transformed breadth measurements consistently generated larger MSE s, surpassing those of the untransformed J variables by roughly 3–12 kg across the overall sample. Among females, the lowest MSE was similarly associated with J at 75% of the tibia (11.34 kg), while in males the minimum error was obtained from the formula using J at 45.5% of the femur (12.14 kg). For females, equations derived from distal femoral metaphyseal breadth produced comparably low MSE values; however, the remaining sex-specific breadth-based formulae generally returned higher errors. The highest R^2 among all J measurements (0.96) was observed for J at 75% of the tibia in the male sex-specific formulae (Figure 5), while the lowest R^2 (0.79) was associated with J at 75% of the tibia in the juvenile formulae (Figure 6). Visually homogeneity of variance was observed across weight categories in the BMI-specific formulae, though an increase in dispersion was observed as weight increased in the sex-specific formulae.

Table 5. Regression formulae for predicting weight using the natural logarithm of the femoral and tibial breadth measurements, for the sexes combined and separately for each sex. In the formulae, x is the natural logged weight value (kg), and y is the logged breadth measurement (mm). Mean (M), standard deviation (SD), minimum and maximum breadth values, coefficient of determination (R^2), and mean standard error (MSE) are given for unlogged measurements.

	FPEB	FDEB	FPMB	FDMB	FHB	TPEB	TDEB	TPMB	TDMB
Sexes combined									
<i>n</i>	70	73	76	74	75	75	72	76	75
Eqn	$x = y - 1.378/0.554$	$x = y - 2.032/0.540$	$x = y - 1.997/0.383$	$x = y - 2.878/0.332$	$x = y - 2.029/0.394$	$x = y - 1.868/0.564$	$x = y - 1.336/0.599$	$x = y - 2.593/0.369$	$x = y - 2.119/0.393$
M	31.61	57.29	29.28	58.07	31.71	51.61	34.15	50.25	34.07
Min	6.50	12.60	9.00	19.40	11.70	13.70	5.70	15.30	10.90
Max	51.30	91.10	45.20	87.50	51.20	85.30	56.30	79.20	52.60
SD	0.46	0.50	0.35	0.30	0.36	0.50	0.55	0.34	0.36
R²	0.88	0.89	0.92	0.93	0.92	0.91	0.88	0.92	0.91
MSE	20.32	20.45	18.62	14.53	17.44	19.46	20.64	15.82	16.12
Female									
<i>n</i>	32	33	34	33	32	33	32	34	33
Eqn	$x = y - 0.933/0.667$	$x = y - 1.877/0.583$	$x = y - 1.974/0.384$	$x = y - 2.801/0.346$	$x = y - 2.001/0.400$	$x = y - 1.703/0.611$	$x = y - 1.029/0.681$	$x = y - 2.528/0.380$	$x = y - 1.920/0.439$
M	31.55	58.51	29.37	57.45	32.54	53.66	35.30	50.27	33.91
Max	46.80	82.10	44.80	74.30	45.40	76.30	85.30	42.20	75.80
Min	6.50	14.20	13.80	28.40	15.70	13.90	5.70	21.20	13.70
SD	0.52	0.48	0.32	0.28	0.33	0.50	0.58	0.32	0.37
R²	0.89	0.92	0.92	0.92	0.92	0.92	0.89	0.90	0.90
MSE	17.56	15.84	18.42	13.47	17.23	15.79	17.92	14.15	14.97

Table 5. Cont.

	FPEB	FDEB	FPMB	FDMB	FHB	TPEB	TDEB	TPMB	TDMB
Male									
<i>n</i>	38	40	42	41	43	42	40	42	42
Eqn	$x = y - 1.676/0.479$	$x = y - 2.126/0.525$	$x = y - 2.005/0.385$	$x = y - 2.915/0.329$	$x = y - 2.030/0.393$	$x = y - 1.972/0.533$	$x = y - 1.524/0.547$	$x = y - 2.621/0.368$	$x = y - 2.219/0.372$
M	31.66	56.29	29.21	58.58	31.09	49.99	33.22	50.24	34.20
Max	51.30	91.10	45.20	87.50	51.20	85.30	56.30	79.20	52.60
Min	12.30	12.60	9.00	19.40	11.70	13.70	7.00	15.30	10.90
SD	0.41	0.51	0.37	0.31	0.37	0.50	0.52	0.35	0.35
R²	0.89	0.87	0.92	0.94	0.92	0.89	0.88	0.93	0.94
MSE	23.20	23.76	21.26	16.83	18.99	21.53	23.11	18.34	17.80

Table 6. Regression formulae for predicting weight using the natural logarithm of the femoral and tibial breadth measurements, for the two weight groups separately. In the formulae, x is the natural logged weight value (kg), and y is the logged breadth measurement (mm). Mean (M), standard deviation (SD), minimum and maximum breadth values, coefficient of determination (R²), and mean standard error (MSE) are given for unlogged measurements.

	FPEB	FDEB	FPMB	FDMB	FHB	TPEB	TDEB	TPMB	TDMB
<95th Percentile BMI									
<i>n</i>	36	40	41	41	41	40	40	41	41
Eqn	$x = y - 0.916/0.719$	$x = y - 1.504/0.732$	$x = y - 1.806/0.454$	$x = y - 2.732/0.390$	$x = y - 1.874/0.460$	$x = y - 1.418/0.728$	$x = y - 0.742/0.804$	$x = y - 2.380/0.451$	$x = y - 1.968/0.459$
M	30.33	53.16	27.12	54.84	29.83	48.14	32.07	47.46	32.32
Min	9.00	12.60	9.00	19.40	11.70	13.70	5.70	15.30	10.90
Max	49.30	88.60	45.20	77.40	48.90	80.30	53.10	73.00	49.30
SD	11.88	22.64	8.90	14.69	10.41	21.17	14.72	14.58	10.19
R²	0.86	0.89	0.88	0.91	0.88	0.92	0.86	0.92	0.92
MSE	9.31	8.53	10.23	7.11	9.18	8.10	8.89	7.07	7.42

Table 6. Cont.

	FPEB	FDEB	FPMB	FDMB	FHB	TPEB	TDEB	TPMB	TDMB
>95th Percentile BMI									
<i>n</i>	34	33	35	34	35	35	32	35	34
Eqn	$x = y - 1.418/0.519$	$x = y - 2.450/0.423$	$x = y - 2.104/0.344$	$x = y - 2.919/0.310$	$x = y - 1.994/0.387$	$x = y - 2.082/0.486$	$x = y - 1.807/0.454$	$x = y - 2.683/0.332$	$x = y - 2.074/0.387$
M	32.96	62.31	31.82	62.09	33.86	55.57	36.75	53.53	36.17
Max	51.30	91.10	45.10	87.50	51.20	85.30	56.30	79.20	52.60
Min	6.50	23.10	16.60	30.70	17.30	20.00	12.30	23.70	15.10
SD	11.79	19.78	8.76	15.51	10.19	19.95	12.99	14.38	11.07
R²	0.90	0.88	0.91	0.92	0.94	0.89	0.89	0.90	0.90
MSE	17.44	17.81	21.53	15.05	14.76	17.20	15.85	14.70	16.02

Table 7. Regression formulae for predicting weight using the natural logarithm of the femoral and tibial breadth measurements, for the child, juvenile, and adolescent groups. In the formulae, x is the natural logged weight value (kg), and y is the logged breadth measurement (mm). Mean (M), standard deviation (SD), minimum and maximum breadth values, coefficient of determination (R²), and mean standard error (MSE) are given for unlogged measurements.

	FPEB	FDEB	FPMB	FDMB	FHB	TPEB	TDEB	TPMB	TDMB
Child									
<i>n</i>	24	28	30	30	30	29	29	31	31
Eqn	$x = y - 0.559/0.811$	$x = y - 1.160/0.845$	$x = y - 1.753/0.464$	$x = y - 2.655/0.407$	$x = y - 2.138/0.334$	$x = y - 1.413/0.700$	$x = y - 0.617/0.834$	$x = y - 2.305/0.468$	$x = y - 2.005/0.419$
M	2.84	3.44	2.98	3.73	3.03	3.31	2.87	3.55	3.12
Max	3.44	4.06	3.42	4.11	3.43	3.94	3.46	3.93	3.59
Min	1.87	2.53	2.20	2.97	2.46	2.62	1.74	2.73	2.39
SD	0.39	0.45	0.28	0.25	0.22	0.39	0.49	0.29	0.28
R²	0.69	0.80	0.77	0.72	0.63	0.76	0.67	0.71	0.61
MSE	4.30	4.39	6.60	6.79	8.30	6.00	5.98	5.94	8.07

Table 7. Cont.

	FPEB	FDEB	FPMB	FDMB	FHB	TPEB	TDEB	TPMB	TDMB
Juvenile									
<i>n</i>	21	20	21	20	20	21	20	20	20
Eqn	$x = y - 2.959/0.146$	$x = y - 3.641/0.147$	$x = y - 2.923/0.138$	$x = y - 3.485/0.180$	$x = y - 3.082/0.117$	$x = y - 3.708/0.091$	$x = y - 2.816/0.238$	$x = y - 3.332/0.181$	$x = y - 2.966/0.179$
M	3.48	4.16	3.42	4.12	3.50	4.03	3.66	3.97	3.60
Max	3.71	4.33	3.61	4.29	3.68	4.29	3.84	4.15	3.79
Min	3.23	4.05	3.26	4.00	3.25	3.67	3.39	3.80	3.42
SD	0.14	0.08	0.10	0.08	0.12	0.13	0.13	0.08	0.09
R²	0.08	0.251	0.16	0.43	0.06	0.04	0.24	0.38	0.30
MSE	43.70	22.36	32.54	18.10	50.73	137.30	21.20	18.60	21.52
Adolescent									
<i>n</i>	25	24	25	24	25	25	23	25	24
Eqn	$x = y - 3.239/0.122$	$x = y - 3.758/0.139$	$x = y - 2.897/0.173$	$x = y - 3.473/0.190$	$x = y - 3.149/0.140$	$x = y - 3.717/0.132$	$x = y - 3.166/0.163$	$x = y - 3.334/0.193$	$x = y - 3.069/0.172$
M	3.77	4.36	3.65	4.12	3.76	4.29	3.87	3.97	3.81
Max	3.94	4.51	3.81	4.29	3.94	4.45	4.03	4.15	3.96
Min	3.48	4.20	3.29	4.00	3.58	4.12	3.68	3.80	3.59
SD	0.10	0.09	0.14	0.08	0.10	0.09	0.10	0.08	0.10
R²	0.22	0.41	0.26	0.66	0.31	0.36	0.49	0.44	0.53
MSE	67.13	43.89	54.10	32.10	61.66	49.83	41.80	36.42	33.10

Table 8. Regression formulae for predicting weight using the femoral and tibial J measurements, for the sexes combined and separately for each sex. In the formulae, x is the weight value (kg), and y is the J value (mm⁴). Mean (M), standard deviation (SD), minimum and maximum breadth values, coefficient of determination (R²), and mean standard error (MSE) are given for J values.

	F25J	F45.5J	F75J	F80J	T25J	T50J	T75J
Sexes combined							
<i>n</i>	75	76	74	76	73	76	76
Eqn	$x = y + 8317.4/958.8$	$x = y + 6670.6/717.1$	$x = y + 3902.1/751.3$	$x = y + 5796.5/1001.4$	$x = y + 1209.5/337.7$	$x = y + 4525.4/540.9$	$x = y + 9368.2/941.6$
M	33,911	24,769	29,468	37,729	13,884	19,169	31,761
Max	151,789	113,613	118,993	236,322	59,330	103,468	181,041
Min	1314	343	1461	2346	646	372	1077
SD	36,287	26,882	28,527	39,467	12,889	20,405	35,358
R²	0.9	0.10	0.9	0.9	0.9	0.9	0.9
MSE	13.2	12.6	13.4	17.5	13.6	13.3	12.6
Female							
<i>n</i>	34	34	34	33	34	34	34
Eqn	$x = y + 4746.8/850.2$	$x = y + 4476.6/667.9$	$x = y + 3776.4/731.6$	$x = y + 2418.4/895.7$	$x = y + 109.2/298.9$	$x = y + 2360.7/454.3$	$x = y + 4986.0/790.9$
M	32,596	24,860	29,008	37,606	13,021	17,595	29,751
Max	95,541	80,279	80,132	124,323	30,903	49,305	77,982
Min	1913	710	1461	2346	646	898	1151
SD	25,683	20,453	22,342	29,003	9069	13,592	23,399
R²	0.9	0.9	0.9	0.9	0.9	0.9	0.9
MSE	13.0	14.0	13.8	17.1	13.3	12.2	11.3

Table 8. Cont.

	F25J	F45.5J	F75J	F80J	T25J	T50J	T75J
Male							
<i>n</i>	40	42	43	43	42	42	42
Eqn	$x = y + 8962.6/997.9$	$x = y + 7493.2/735.4$	$x = y + 3650.1/758.5$	$x = y + 7265.0/1077.7$	$x = y + 1381.7/352.4$	$x = y + 4604.6/573.1$	$x = y + 9786.9/996.6$
M	43,452	24,695	29,156	40,366	14,021	20,443	33,314
Max	151,789	113,613	118,993	236,322	59,330	103,468	181,041
Min	1314	343	2037	2976	648	372	1077
SD	43,452	31,128	32,071	46,264	15,068	24,500	39,909
R²	0.9	0.9	0.9	0.9	0.9	0.9	0.9
MSE	13.8	12.1	13.0	21.5	13.5	13.5	13.0

Table 9. Regression formulae for predicting weight using the femoral and tibial J measurements, for the two weight groups separately. In the formulae, x is the weight value (kg), and y is the J value (mm⁴). Mean (M), standard deviation (SD), minimum and maximum breadth values, coefficient of determination (R²), and mean standard error (MSE) are given for J values.

	F25J	F45.5J	F75J	F80J	T25J	T50J	T75J
<95th Percentile BMI							
<i>n</i>	41	41	41	40	41	41	41
Eqn	$x = y + 7022.0/1018.9$	$x = y + 6140.4/754.7$	$x = y + 2086.2/746.6$	$x = y + 1088.4/949.0$	$x = y + 1476.5/392.9$	$x = y + 2485.2/518.4$	$x = y + 6260.3/942.1$
M	23,600	16,541	20,351	26,958	10,330	13,094	22,051
Min	1314	343	1461	2346	646	372	1077
Max	103,907	70,614	70,558	87,770	35,692	45,048	85,263
SD	21,958	16,216	15,994	19,874	8148	10,660	19,126
R²	0.79	0.79	0.80	0.83	0.85	0.86	0.89
MSE	10.14	10.00	9.86	8.79	8.21	7.74	6.98

Table 9. Cont.

	F25J	F45.5J	F75J	F80J	T25J	T50J	T75J
>95th Percentile BMI							
<i>n</i>	34	35	36	36	35	35	36
Eqn	$x = y + 15,024.0/1007.5$	$x = y + 11,581.0/755.6$	$x = y + 7689.2/782.8$	$x = y + 13,339.0/1069.9$	$x = y + 3735.1/352.3$	$x = y + 8000.4/572.2$	$x = y + 15,853.0/995.1$
M	46,345	33,749	38,429	49,697	17,372	26,285	42,776
Max	151,789	113,613	118,993	236,322	59,330	103,468	181,041
Min	2082	831	2888	2976	718	898	1853
SD	46,009	33,945	35,743	51,597	16,051	26,465	45,403
R ²	0.95	0.96	0.94	0.89	0.95	0.94	0.95
MSE	14.01	12.41	15.35	22.04	14.41	16.53	15.24

Table 10. Regression formulae for predicting weight using the femoral and tibial J measurements for the child, juvenile, and adolescent groups. In the formulae, x is the weight value (kg), and y is the J value (mm⁴). Mean (M), standard deviation (SD), minimum and maximum breadth values, coefficient of determination (R²), and mean standard error (MSE) are given for J values.

	F25J	F45.5J	F75J	F80J	T25	T50	T75
Child							
<i>n</i>	30	30	31	31	30	30	31
Eqn	$x = y + 317.5/500.5$	$x = y + 1438.5/379.9$	$x = y - 880.4/441.0$	$x = y - 3558.4/451.6$	$x = y + 54.9/209.1$	$x = y - 177.4/238.2$	$x = y + 165.9/389.8$
M	7669	4644	8017	10,866	3274	3970	6142
Max	23,092	16,502	22,190	26,412	8163	10,889	16,021
Min	1314	343	1461	2346	646	372	1077
SD	5039	3604	5241	5954	1966	2391	3553
R ²	0.6	0.6	0.4	0.3	0.6	0.6	0.7
MSE	6.8	5.8	9.4	11.1	5.8	6.8	5.2

Table 10. Cont.

	F25J	F45.5J	F75J	F80J	T25	T50	T75
Juvenile							
<i>n</i>	20	21	21	20	21	21	21
Eqn	$x = y - 11,310.0/319.4$	$x = y - 6600.7/272.75$	$x = y - 9774.0/335.6$	$x = y - 8914.9/560.5$	$x = y - 5605.3/160.0$	$x = y - 6733.8/246.4$	$x = y - 12,548.0/318.1$
M	23,022	16,476	21,926	28,822	11,399	15,655	24,067
Max	42,917	28,176	35,125	50,396	17,947	27,038	39,951
Min	6063	8126	10,768	15,375	3667	3882	6352
SD	8550	5326	6743	9397	3732	5679	8738
R²	0.1	0.2	0.2	0.3	0.2	0.2	0.1
MSE	25.9	17.7	18.3	14.6	22.0	21.7	26.6
Adolescent							
<i>n</i>	25	25	25	25	25	25	25
Eqn	$x = y + 4978.8/945.6$	$x = y + 4110.6/706.24$	$x = y + 693.2/729.8$	$x = y + 10,635.0/1061.6$	$x = y - 2221.4/306.5$	$x = y + 9027.6/590.5$	$x = y + 13,501.0/997.4$
M	74,111	54,963	60,354	78,164	27,759	40,360	69,929
Max	151,789	113,613	118,993	236,322	59,330	103,468	181,041
Min	23,710	15,424	25,803	33,201	9496	6933	22,156
SD	37,193	27,359	29,015	46,011	12,328	22,746	38,243
R²	0.7	0.8	0.7	0.6	0.7	0.8	0.8
MSE	20.2	18.2	20.7	20.8	21.9	18.3	18.2

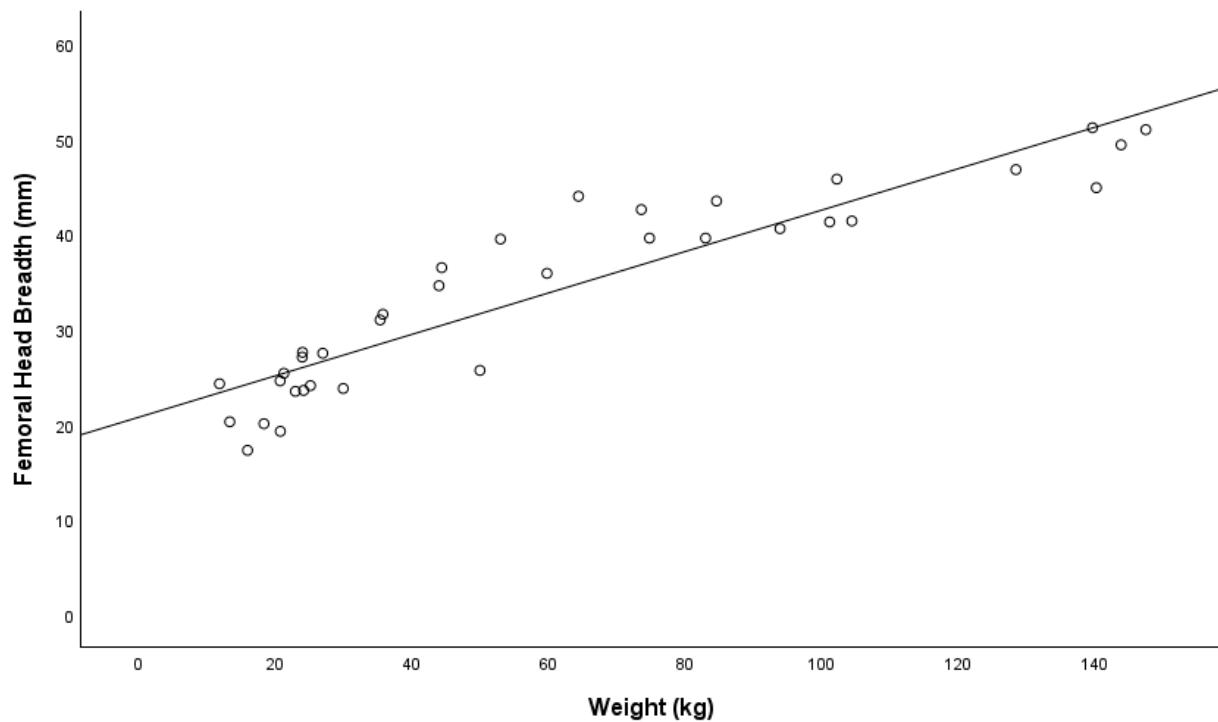


Figure 3. Unlogged femoral head breadth (mm) regressed on weight (kg), for the >95th percentile of BMI formulae ($R^2 = 0.94$).

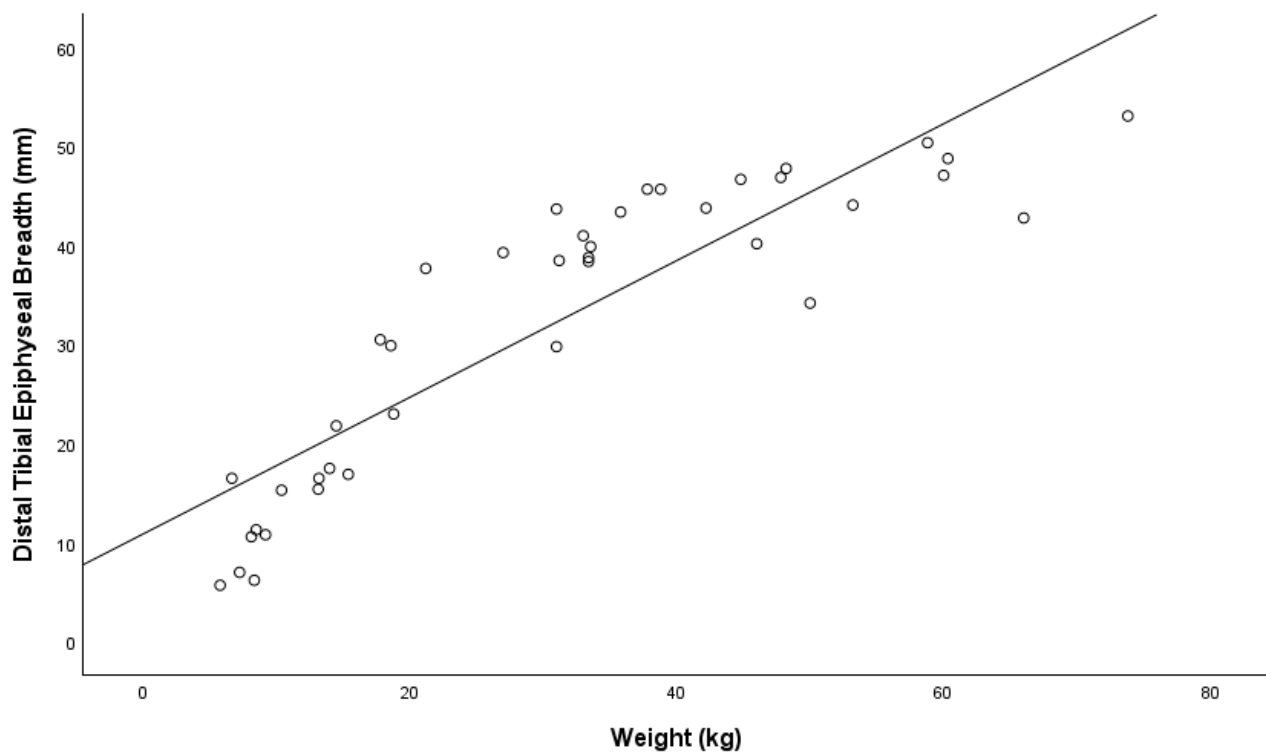


Figure 4. Unlogged tibial distal epiphyses breadth (mm) regressed on weight (kg) for the <95th percentile of BMI formulae ($R^2 = 0.84$).

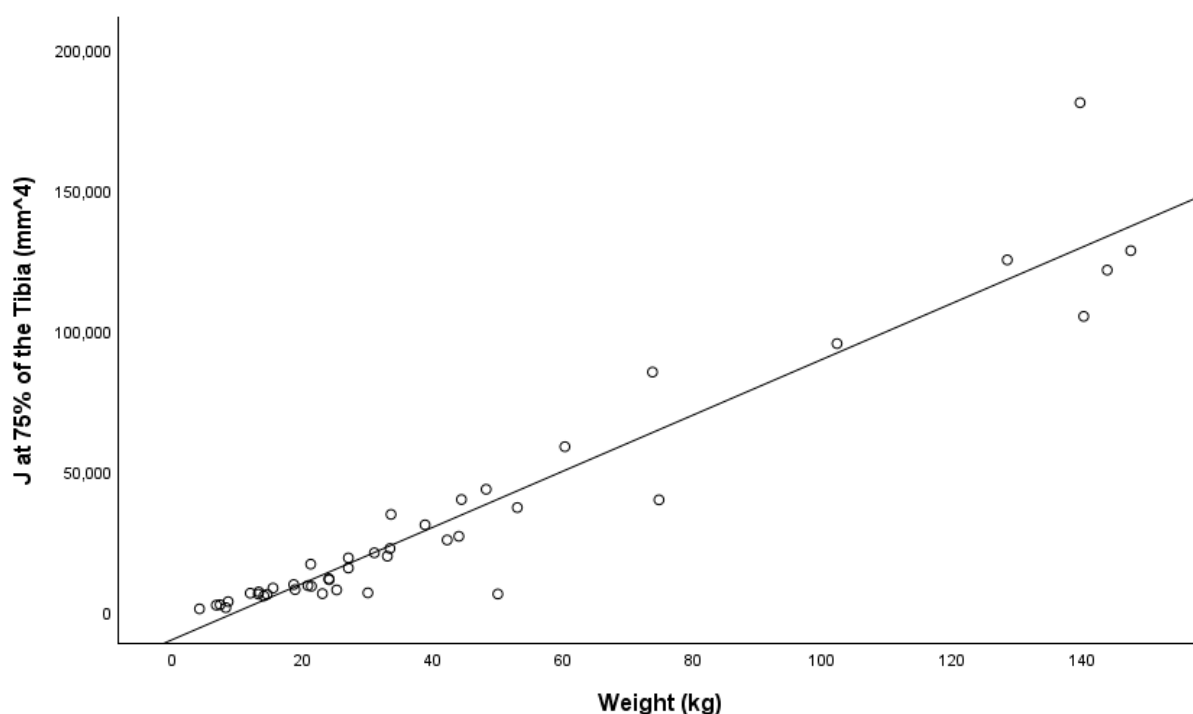


Figure 5. J at 75% of the tibial length (mm^4) regressed on weight (kg) for the male formulae ($R^2 = 0.94$).

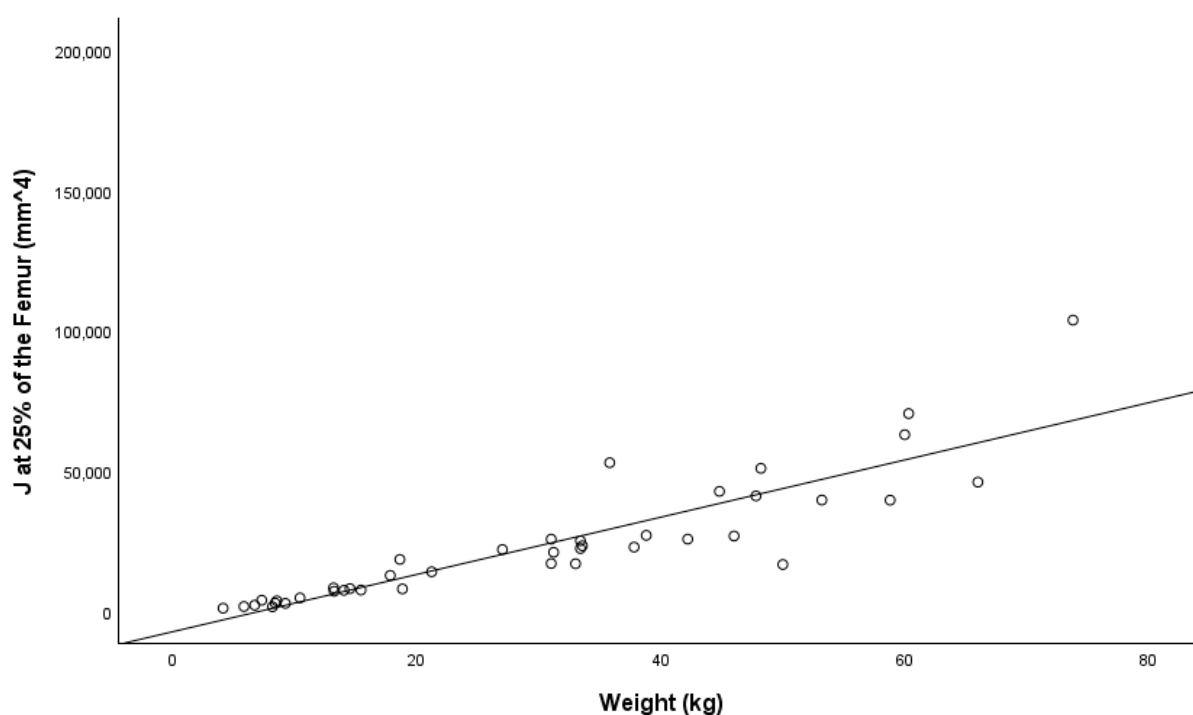


Figure 6. J at 25% of the femoral length (mm^4) regressed on weight (kg) for the <95% percentile of BMI formulae ($R^2 = 0.79$).

Within the BMI-specific formulae, the equation using J at 75% of the tibia returned the lowest MSE for individuals below the 95th BMI percentile (6.98 kg), while the formula based on J at 45.5% of the femur produced the smallest MSE for those above the 95th percentile (12.41 kg).

The age-specific formulae based on J produced slightly higher MSE values in the child group than formulae based on breadth measurements, but much lower MSE values than

the breadth formulae for the juvenile and adolescent formulae (Table 10). The lowest MSE among the child formulae (5.2 kg) was produced by the J at 75% of the tibia, while the highest was produced by J at 80% of the femur (11.1 kg). Like the breadth-based formulae, the juvenile J-based formulae also had the lowest R^2 values overall and highest MSE among the age-specific formulae, and the formulae for J at 75% of the tibia produced an MSE of 26.6 kg. The MSEs were around the same for the adolescent formulae, ranging from 18.2 kg to 21.9 kg, but the R^2 values were higher (the lowest was 0.6 for the J at 80% of the femur formulae).

Mean residuals for the log-transformed breadth equations ranged from -2.37 to 20.34 kg (Tables 11–13). The presence of numerous large residuals—the majority of which were positive and concentrated in the juvenile and adolescent subsample—indicates a tendency toward overestimation of body mass in the logged models. Although the breadth-based equations with the lowest MSE values, both for the overall sample and the various subsamples, generally returned mean residuals near zero, most still exhibited a directional bias toward overestimation. The primary exception was the below-95th-percentile subsamples, where body mass was more frequently underestimated.

For the J-based formulae, mean residuals (MRs) ranged from -0.04 to -3.4 kg (Tables 14–16). The majority of the formulae produced MRs at or very close to zero, and thus any deviation from zero in these MR values reflected minor discrepancies attributable solely to rounding of regression coefficients. However, the adolescent group of formulae produced MRs ranging from 0.2 to -3.4 kg. Given that the MR values for the majority of the J-based equations were effectively equivalent to zero, the untransformed formulae demonstrate no meaningful systematic bias in body weight estimation in these formulae. Therefore, it is likely that the adolescent formulae do have some systematic bias present and tend to underestimate weight in lighter individuals and overestimate weight in heavier individuals (Figure 7).

Table 11. Mean residuals (MR), mean absolute residuals (MAR), and percentage of individuals whose known weights fall within the 95% prediction interval for formula using the natural logarithm of the femoral and tibial breadth measurements for the sexes combined and separately for each sex.

	FPEB	FDEB	FPMB	FDMB	FHB	TPEB	TDEB	TPMB	TDMB
Sexes combined									
<i>n</i>	70	73	76	74	75	75	72	76	75
MR	-0.12	-0.91	0.16	-0.73	0.95	-0.36	-0.77	-0.47	-0.19
MAR	13.79	14.12	12.67	10.18	11.71	13.39	13.83	11.06	11.23
% Range	91.43	93.15	90.79	93.24	93.33	93.33	94.44	92.11	93.33
Female									
<i>n</i>	32	33	34	33	32	33	32	34	33
MR	0.17	-0.37	1.45	0.27	1.09	0.13	-0.51	0.55	1.16
MAR	10.66	11.41	12.31	9.44	10.41	11.31	12.55	10.56	10.62
% Range	93.75	90.91	94.12	87.88	96.85	93.94	93.75	97.06	96.97
Male									
<i>n</i>	38	40	42	41	43	42	40	42	42
MR	-0.02	-1.12	-0.96	-2.37	0.85	-0.50	-0.66	-1.82	-1.40
MAR	15.34	16.21	13.13	10.28	12.43	14.74	14.62	11.10	11.00
% Range	97.37	90.00	90.48	90.24	90.70	90.48	90.00	90.48	92.86

Table 12. Mean residuals (MR), mean absolute residual (MAR), and percentage of individuals whose known weights fall within the 95% prediction interval for formula using the natural logarithm of the femoral and tibial breadth measurements for the two weight groups separately.

	FPEB	FDEB	FPMB	FDMB	FHB	TPEB	TDEB	TPMB	TDMB
<95th Percentile BMI									
<i>n</i>	36	40	41	41	41	40	40	41	41
MR	0.28	−0.16	0.47	−0.39	0.98	−0.05	−0.01	−0.24	−0.14
MAR	6.32	5.93	6.12	5.00	6.04	5.48	6.22	4.68	5.22
% Range	91.67	92.50	90.24	92.68	95.12	90.00	92.50	90.24	95.12
>95th Percentile BMI									
<i>n</i>	34	33	35	34	35	35	32	35	34
MR	−0.37	0.74	1.64	0.87	1.05	0.90	0.79	1.48	0.74
MAR	12.11	13.74	13.95	10.15	10.22	13.23	11.60	10.65	11.59
% Range	94.12	93.94	97.14	94.12	94.29	94.29	93.75	94.29	94.12

Table 13. Mean residuals (MR), mean absolute residuals (MAR), and percentage of individuals whose known weights fall within the 95% prediction interval for formula using the natural logarithm of the femoral and tibial breadth measurements for the child, juvenile, and adolescent groups.

	FPEB	FDEB	FPMB	FDMB	FHB	TPEB	TDEB	TPMB	TDMB
Child									
<i>n</i>	24	28	30	30	30	29	29	31	31
MR	1.162	0.744	−0.049	0.345	0.751	−0.240	0.223	0.584	2.088
MAR	2.887	3.356	4.681	4.491	5.976	4.357	4.231	3.825	5.360
% Range	96%	93%	97%	97%	97%	94%	94%	97%	97%
Juvenile									
<i>n</i>	21	20	21	20	20	21	20	20	20
MR	14.271	4.394	7.994	−0.452	16.730	41.634	1.318	−0.324	0.802
MAR	29.913	14.801	20.124	11.505	34.008	57.215	15.437	11.433	13.856
% Range	95%	95%	95%	90%	86%	95%	95%	90%	90%
Adolescent									
<i>n</i>	25	24	25	24	25	25	23	25	24
MR	12.519	8.996	14.545	−0.537	9.384	11.545	0.997	7.081	2.823
MAR	46.729	32.951	40.122	23.113	42.683	35.896	32.805	27.597	25.314
% Range	100%	100%	100%	100%	100%	100%	100%	100%	100%

Across the overall sample, breadth-based equations returned mean absolute residual (MAR) values spanning 2.89 to 81.49 kg (Table 11), while J-based formulae yielded consistently lower MAR values of 3.3 to 19.2 kg (Table 16). Between 89.33% and 100% of individuals across these equations fell within the 95% prediction interval. In the female subsample, MAR values ranged from 9.44 to 12.90 kg for breadth-based equations (Table 11) and from 8.11 to 10.06 kg for J-based equations (Table 14). Among males, breadth formula MAR values fell between 9.44 and 12.55 kg (Table 11), with J-based formula MAR values ranging from 7.81 to 11.45 kg (Table 14). The proportion of individuals whose actual weight

fell within the 95% prediction interval spanned 88.24% to 96.96% in females and 87.5% to 97.37% in males.

Table 14. Mean residuals (MRs), mean absolute residuals (MARs), and percentage of individuals whose known weights fall within the 95% prediction interval for formula using femoral and tibial J measurements for the sexes combined and separately for each sex.

	F25J	F45.5J	F75J	F80J	T25J	T50J	T75J
Sexes combined							
<i>n</i>	75	76	74	76	73	76	76
MR	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MAR	8.76	8.55	8.52	9.79	8.85	8.77	7.69
% Range	89.33	90.79	90.54	94.74	90.41	93.42	93.42
Female							
<i>n</i>	34	34	34	33	34	34	34
MR	−0.04	0.00	0.12	0.00	0.00	0.00	0.00
MAR	8.83	9.73	8.75	10.60	9.88	9.02	8.11
% Range	88.24	94.12	88.24	93.94	94.12	94.12	94.12
Male							
<i>n</i>	40	42	43	43	42	42	42
MR	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MAR	9.17	7.83	8.06	11.45	8.61	8.53	7.81
% Range	87.50	88.10	93.02	95.35	90.48	92.86	95.24

Table 15. Mean residuals (MRs), mean absolute residuals (MARs), and percentage of individuals whose known weights fall within the 95% prediction interval for formula using the femoral and tibial J measurements for the two weight groups separately.

	F25J	F45.5J	F75J	F80J	T25J	T50J	T75J
<95th Percentile BMI							
<i>n</i>	38	38	36	37	38	38	39
MR	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MAR	6.40	6.03	6.02	6.21	5.13	5.07	4.25
% Range	92.68	90.24	90.24	90.00	90.24	90.24	95.12
>95th Percentile BMI							
<i>n</i>	34	35	36	36	35	35	36
MR	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MAR	10.02	9.39	9.99	12.01	9.70	10.71	9.45
% Range	94.12	100.00	91.67	94.44	91.43	97.14	97.22

For the subsample below the 95th BMI percentile, breadth-based equations produced MAR values of 4.68 to 6.32 kg (Table 12), with 90% to 95.12% of individuals captured within the prediction interval. J-based formulae for this same subsample returned MAR values between 4.25 and 6.40 kg (Table 15), with 90% to 95.15% of cases falling within the prediction interval. In the subsample above the 95th BMI percentile, breadth-based formula MAR values ranged from 10.15 to 13.95 kg, with 93.15% to 97.14% of individuals

contained within the prediction interval. The corresponding J-based formulae produced MAR values of 9.39 to 12.01 kg, with between 91.43% and 100% of individuals falling within the prediction interval.

Table 16. Mean residuals (MRs), mean absolute residuals (MARs), and percentage of individuals whose known weights fall within the 95% prediction interval for formula using femoral and tibial J measurements for the child, juvenile, and adolescent groups.

	F25J	F45.5J	F75J	F80J	T25J	T50J	T75J
Child							
<i>n</i>	30	30	31	31	30	30	31
MR	0.28	−0.03	0.84	0.90	−0.77	−0.91	−0.08
MAR	3.75	3.33	6.06	6.85	3.88	4.16	3.96
% Range	93.33	93.33	93.55	93.55	93.33	93.33	93.55
Juvenile							
<i>n</i>	20	21	21	20	21	21	21
MR	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MAR	17.42	11.77	13.30	9.54	15.61	14.73	19.21
% Range	90.00	95.24	90.48	90.00	95.24	95.24	95.24
Adolescent							
<i>n</i>	25	25	25	25	25	25	25
MR	0.72	0.17	−1.09	−3.40	1.05	1.23	0.65
MAR	16.85	15.45	16.98	15.65	17.64	14.64	13.30
% Range	100.00	100.00	100.00	100.00	100.00	100.00	100.00

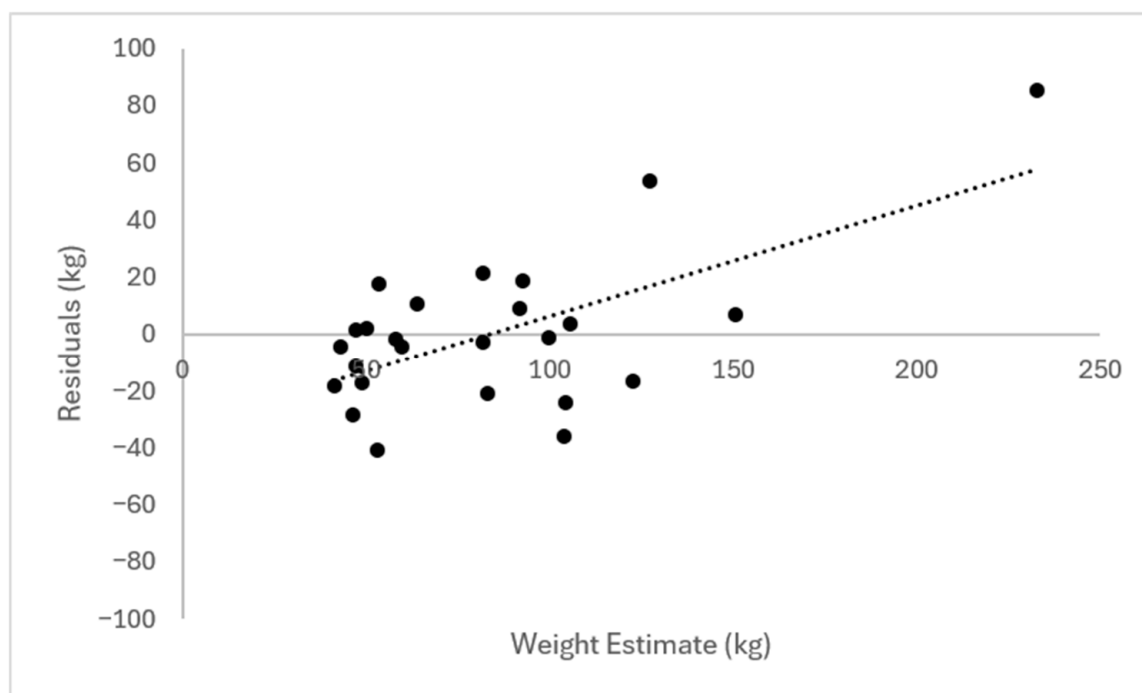


Figure 7. Residuals (kg) plotted against weight estimates (kg) produced from the adolescent formulae using J at 80% of the diaphysis.

The age-specific formulae produced a similar trend between the J and the breadth formulae, the difference being the magnitude of the absolute residuals. The child formulae generated the lowest MAR among both sets of measurements; ranging from 3.3 to 6.9 kg in the breadth formulae (Table 13) and 2.9 to 6.0 kgs among the J formulae (Table 16). MAR values became significantly larger among the juvenile and adolescent subsamples, particularly for the breadth formulae (Tables 14 and 15), ranging from 11.4–34 kg in the juvenile subsample to 23.1–46.7 kg in the adolescent subsample.

4. Discussion

The results of the current study, in conjunction with those of Yim and colleagues [21] and Spake and colleagues [22], lend further support to the conclusion that unstandardized J values reflect body mass more accurately than long bone breadth measurements, particularly among older children. Both Spake et al. [22] and Yim et al. [21] previously demonstrated that torsional rigidity-based weight estimation formulae produced less underestimation of body mass in modern pediatric populations relative to breadth-based approaches. However, some breadth-based equations performed nearly as well as the average J-based formulae.

The ANCOVA results indicated that sex differences in weight estimation parameters were largely non-significant, with the notable exception of J at 80% of the femoral diaphysis. A significant interaction between sex and weight status was additionally detected for J at 45.5% of the femoral diaphysis. These results suggest that sex-specific equations may be preferable when applying J at 80% of the femoral shaft, though these formulae also tended to yield the highest MSE and MR values. Furthermore, given that male and female growth trajectories diverge following puberty, applying generalized adolescent equations across sexes may introduce additional error. Relative to breadth-based formulae, J-based equations are likely to remain more sensitive to weight-related mechanical loading in both sexes. Future research should therefore investigate whether sex-related differences influence the accuracy of J-derived equations specifically in post-pubertal individuals.

Weight status exerted significant effects on several J measurements, including J at 25% and 75% of the femoral diaphysis and at 50% and 75% of the tibial diaphysis. Considered together, the ANCOVA findings and the MSE, MR, and MAR values suggest that formulae based on J at 45.5% of the femur and 75% of the tibia may perform particularly well in individuals above the 95th BMI percentile. More broadly, most J-derived measurements appear more responsive to body weight variation than metaphyseal or epiphyseal breadth measurements. Among individuals below the 95th BMI percentile, the equation using J at 75% of the tibia generated the lowest error among J-based formulae and, unlike the breadth-based equations, exhibited no detectable systematic bias in mean residuals.

J values also differed in their predictive power across the different age categories. While MSE and MR values were similar for the breadth and J formulae among the child subsample, the ability of J to more accurately predict weight became more apparent in the juvenile and adolescent subsamples. The MSE and, in particular, the MR and MAR values were much lower among the J formulae than among the breadth formulae, though both demonstrated some tendency to underestimate weight.

Certain skeletal parameters produced more accurate weight estimates across the overall sample and within subsamples. The MSE provides the basis for computing 95% prediction intervals for future breadth and J measurements, while the MAR offers an indication of formula precision. Together, these metrics reveal that specific bone parameters perform better within the overall sample and within particular subsamples.

J-based formulae produced lower MSE values across the majority of subsamples, which is likely attributable to the fact that cross-sectional parameters such as J are more

directly influenced by mechanical loading throughout an individual's life, and loading is closely tied to body weight [22,31,32]. Joint breadth parameters are comparatively less responsive to loading changes once the epiphyses have fused, being more constrained by biomechanical requirements of joint function, whereas torsional rigidity continues to respond to loading and can undergo remodeling into adulthood [33]. The presence of heteroscedasticity between breadth measurements and body weight further suggests that breadth variables may be less reliable weight predictors than J-derived measurements. In contrast, J-based equations generally produced more consistent MSE values across formulae, with the primary exception of those derived from J at 80% of femoral diaphyseal length. Formulae using the 80% femoral cross-section typically generated higher MSE values than those from other diaphyseal locations, except within the juvenile and above-95th-percentile BMI subsamples. A similar pattern was evident in MAR values, where equations incorporating J at 80% of the femur generally yielded the largest mean absolute residuals. This may reflect the anatomical position of that cross-section near the proximal femur, where J values could be influenced by factors beyond torsional loading, including variation in the subtrochanteric region—an area in adults that is strongly shaped by body proportions [34,35].

Notably, comparison of MSE and MAR values between the below- and above-95th-percentile BMI subsamples revealed that error values were frequently lower, or at least comparable, within the BMI-stratified groups relative to the broader sample. This finding implies that torsional rigidity equations may perform better when developed for specific BMI or weight categories. Consequently, the reported minimum and maximum J value ranges for each equation should be carefully considered when selecting the most appropriate formula for a given individual.

Among breadth-based equations, femoral metaphyseal breadth generally yielded the lowest MSE and MAR values across subsamples. Unexpectedly, distal metaphyseal breadth—and in some cases proximal metaphyseal breadth—of the femur produced comparably low error values. In the tibia, metaphyseal breadth-derived formulae consistently outperformed those based on epiphyseal breadths, likely reflecting differences in the developmental timing of these skeletal regions. Measurement error may have also contributed to this pattern, given that epiphyseal dimensions were obtained from CT scans of bones *in situ*, where identifying the true maximum epiphyseal breadth can be more challenging. Femoral breadth equations were generally less consistent overall, with the exception of distal femoral breadth, which repeatedly generated among the lowest MSE and MAR values.

Error patterns in the breadth-based equations across sex, age, and weight subsamples broadly mirrored those observed for the J-derived equations: values were relatively stable across the overall, male, and female samples; increased progressively across age-category subsamples; and were lower in the below-95th-percentile BMI group while higher in the above-95th-percentile group. However, divergence between the two approaches became more apparent when comparing age-category error values with those from BMI-specific subsamples. The superior performance of J values as body mass predictors across the sample is consistent with the findings of Spake and colleagues [22], who evaluated both J- and breadth-based equations [36] and found that while both approaches tended to underestimate body weight, J-based equations exhibited less bias, particularly among older children.

Mean residual (MR) values offer additional insight into systematic tendencies toward overestimation or underestimation within specific formulae and samples. The bias observed in the logged breadth equations suggests these formulae may be less suitable for individuals whose breadth measurements fall outside the normal distribution represented in the sample. When an individual's breadth values do fall within the normal range, how-

ever, the logged breadth equations offer certain advantages, including stronger coefficients of determination between breadth and weight and lower MAR values relative to unlogged breadth equations. Formulae yielding residuals significantly different from zero should generally be avoided for the relevant sample groups (Tables 11–16). The tendency of logged equations to underestimate lighter individuals and overestimate heavier ones should be taken into account during application (Figure 8).

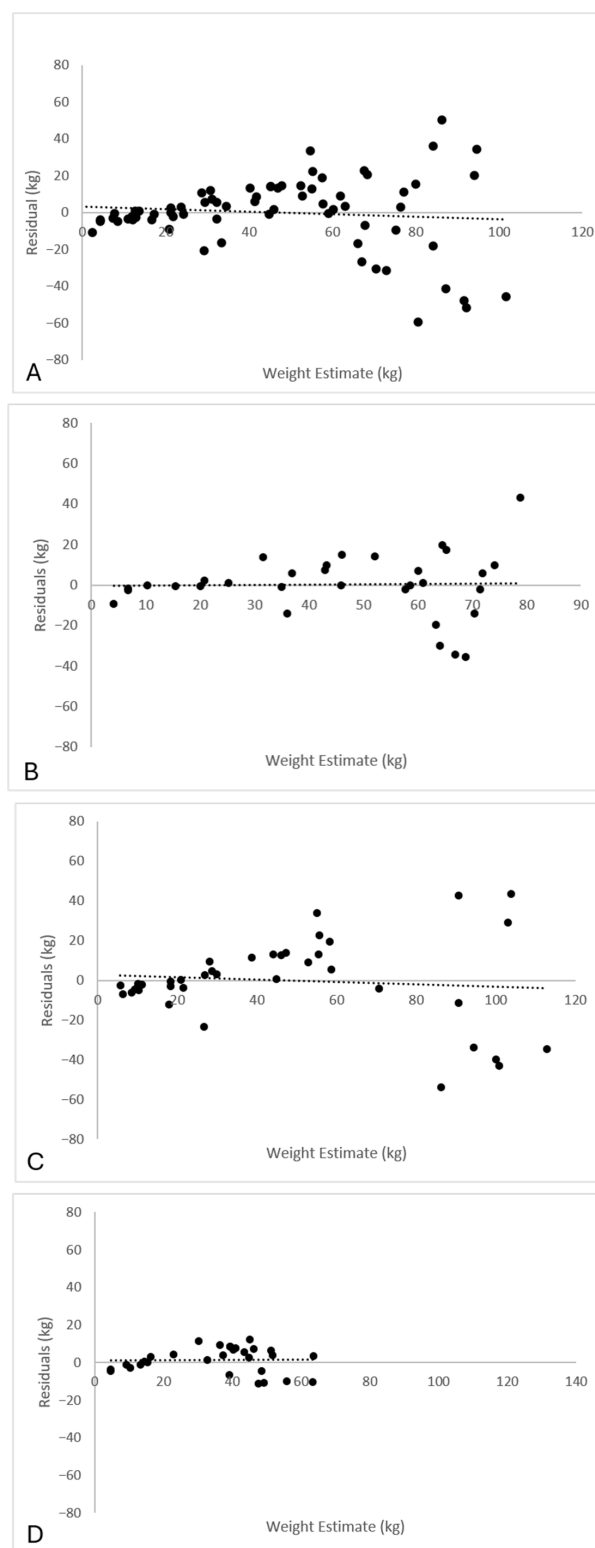


Figure 8. Cont.

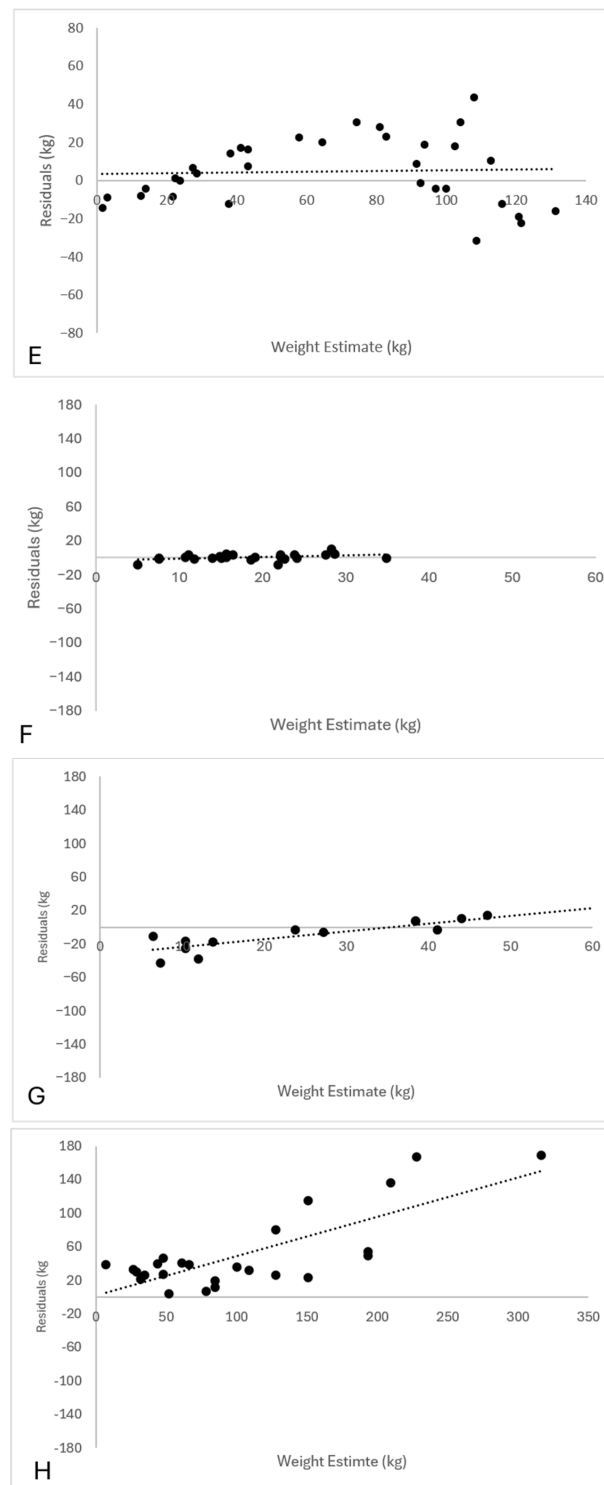


Figure 8. De-transformed residuals (kg) plotted against weight estimates (kg) produced from formulae using proximal femoral epiphyseal breadth. Residuals plots show the overall formulae (A), the female (B) and male (C) formulae, the <95th percentile (D) and >95th percentile (E) formulae, and the child (F), juvenile (G), and adolescent (H) formulae.

Examination of raw residuals from the logged breadth formulae reveals a more complex pattern. Equations developed for the overall sample, both sex-specific samples, and the BMI-stratified groups all show alternating underestimation of younger individuals and overestimation of older individuals (or vice versa), though these deviations are small and non-significant. The age category formulae, however, display a markedly different pattern:

all age groups significantly underestimate weight at the younger end of the subsample and overestimate at the older end, calling into question the practical utility of age-stratified breadth-based formulae.

Examining raw residuals from the J-based formulae reveals that these equations tend to underestimate weight in younger individuals and overestimate in older individuals, generally from age 7–10 onwards depending on the formula. In the overall sample tibial formulae, overestimation may begin when J exceeds 15,000–30,000 mm⁴, and in femoral formulae when J exceeds 30,000–40,000 mm⁴; J values above these thresholds may therefore carry an elevated risk of overestimation. The ranges reflect the fact that the proximal and distal ends of the femur and the proximal tibia tend to have higher average J values. Female formulae begin overestimating weight slightly later than male formulae. Female formulae may begin to overestimate above 20,000–35,000 mm⁴ in the femur and 12,500–30,000 mm⁴ in the tibia, while male formulae may begin to overestimate above 30,000–45,000 mm⁴ in the femur and 17,000–30,000 mm⁴ in the tibia. Age-based formulae begin overestimating weight at approximately the midpoint of each age group's range: the child group overestimates above 3000–9000 mm⁴ (femoral) and 3000–5000 mm⁴ (tibial); the juvenile group above 15,000–25,000 mm⁴ (femoral) and 12,000–27,000 mm⁴ (tibial); and the adolescent group above 61,000–85,000 mm⁴ (femoral) and 43,000–79,000 mm⁴ (tibial). Above-95th-percentile formulae consistently showed higher J thresholds for overestimation than below-95th-percentile formulae: the below-95th-percentile group overestimates above 18,000–30,000 mm⁴ (femoral) and 12,000–25,000 mm⁴ (tibial), while the above-95th-percentile group overestimates above 38,000–50,000 mm⁴ (femoral) and 15,000–40,000 mm⁴ (tibial). None of the residuals from the J-based formulae differed significantly from zero.

Direct comparison between the equations developed here and those of Ruff [6] and Robbins and colleagues [7] from the Denver Growth Sample is somewhat constrained by methodological differences. The earlier studies produced age-specific equations and examined only three femoral cross-sections. The characteristics of the New Mexico sample did not permit age-by-age formula development due to insufficient subsample sizes; however, CT imaging enabled formula derivation from a substantially larger number of skeletal locations—nine femoral regions (four J-based, five breadth-based) and seven tibial regions (three J-based, four breadth-based). The modern CT-based sample also encompassed a considerably broader range of body weights for age, whereas individuals in the Denver Growth Sample generally fell between the 5th and 95th weight-for-age percentiles. A further complication in direct comparison is that Ruff [6] and Robbins and colleagues [7] employed inverse calibration regression, necessitating comparison of MSE values from the present study with standard error of estimate (SEE) values from the earlier work. The SEE values from those studies were generally lower than the error values obtained here. Ruff's [6] distal femoral metaphyseal breadth equations produced SEE values of 0.64–8.74 kg for ages 1–13 years, and femoral head breadth equations yielded SEE values of 1.41–7.01 kg for ages 7–17 years. The J-based equations of Robbins and colleagues [7] produced SEE values of 0.27–7.84 kg for individuals aged 1–17 years. By contrast, the lowest MSE value from the present study was 11.34 kg for J at 75% of the tibia in females. These larger errors most likely reflect the broader weight ranges within each subsample, stemming from both wider age ranges and the greater BMI variation present in the modern sample [19].

Comparison of the two reference samples reveals meaningful differences in body size composition. As noted by Ruff [6], individuals in the Denver Growth subsample fell within the 95th BMI percentile for white children of their era [37]. The New Mexico sample, by contrast, was deliberately selected to include individuals above, below, and within the 5th–95th BMI percentile range, in order to reflect contemporary patterns of obesity in

North American populations [16–18]. The higher MSE values produced by the present formulae most likely result from the use of age-aggregate rather than age-specific equations, which introduces greater weight variation within each subsample. For instance, the child subsample may include individuals weighing between 3 and 20 kg, whereas Ruff's [6] age-specific approach produces a separate formula for each year from ages 1–5, capturing only one year's weight variation at a time. When predicting the weight of a 5-year-old using distal metaphyseal breadth, Ruff's [6] age-specific equations yield a SEE of 1.08 kg, whereas the generalized formulae from this study produce an MSE of 14.53 kg. Given that 42% of the 24 children in the child subsample fall above the 95th BMI percentile, this difference likely also reflects the greater BMI heterogeneity in the New Mexico sample relative to the Denver Growth cohort [19].

The longitudinal design of the Denver Growth Study used by Ruff [6] and Robbins and colleagues [7] is generally advantageous when compared with cross-sectional studies like the present one, but there are some limitations that can be addressed by cross-sectional data. Continuous measurement of the same individuals across the full growth period is methodologically valuable and captures individual growth trajectories, but reliance on only 20 individuals severely restricts the range of growth trajectories captured. All error in those analyses reflects variability within the same 20 individuals, rather than across a larger and more diverse sample of 77 as in the present study. Consequently, the higher MSE values associated with the New Mexico formulae likely provide a more realistic estimate of prediction error when applied to a random individual drawn from a population with growth variation more representative of that present in the modern sample. Both longitudinal and cross-sectional studies can be useful in examining growth trajectories in terms of temporal change and large-scale range, respectively.

A novel contribution of this study is the demonstration that the tibia can serve as a viable skeletal element for developing body weight estimation equations in children. The formulae generated here also enable direct comparison of the predictive utility of different lower limb regions and different growth-related variables (breadth measurements versus J values). Although femoral midshaft-derived formulae produced the most precise estimates overall, tibial torsional rigidity measurements yielded comparably accurate results—a finding of particular significance given that tibial J values have not previously been examined for body weight estimation in children. The relative consistency of estimates across different lower limb regions is somewhat unexpected, since more distal limb segments are generally assumed to exhibit greater developmental plasticity. However, some evidence suggests that proximal portions of individual long bones may in fact be more developmentally plastic than distal regions [38]. Equations based on proximal tibial metaphyseal breadth also generated MSE values comparable to those from distal femoral metaphyseal breadth across the overall, female and male subsamples. Collectively, these findings point to a developmental relationship between the distal femur and proximal tibia, potentially reflecting adaptive responses to limb loading or the biomechanical demands of bipedal locomotion. As Ruff [6] observed, the association between femoral metaphyseal breadth and body weight strengthens when locomotion begins but weakens during later childhood and adolescence—a pattern also reflected in the progressively larger standard error values observed across the child, juvenile, and adolescent subsamples in the present study. If analogous biomechanical processes govern both the distal femur and proximal tibia, this could account for the comparable coefficients of determination and MSE values observed between these two skeletal regions.

Throughout ontogeny, the diaphyses of both the femur and tibia develop under the combined influence of biological and mechanical constraints: periosteal development and endosteal resorption shape cortical bone biologically, while mechanical loading progres-

sively drives cortical patterning [39]. Periosteal surfaces are more sensitive to loading than endosteal surfaces, and torsional rigidity (J) is therefore likely to reflect an individual's cumulative loading history, which includes body weight [40], particularly during childhood [41]. While Robbins and colleagues [7] established a method for estimating body mass from femoral midshaft cross-sectional properties, no prior formulae for children have incorporated tibial cross-sectional geometry. The present findings suggest that the tibia can function as an equivalent predictor of body weight to the femur, most likely because both bones are subject to similar mechanical and biological constraints related to body mass and physical activity.

Although the formulae derived from the New Mexico sample carry larger MSE values than those of Ruff [6] and Robbins and colleagues [7], and may be of limited value, they offer several practical advantages. First, both earlier methods require age estimation from dentition before the formulae can be applied. Second, these formulae can be applied to multiple cross-sectional regions of the femur and tibia, so that if the midshaft or distal metaphysis of the femur is absent or damaged, weight can still be estimated from an alternative parameter. It is recommended that the MSE associated with each formula and any directional bias in residuals be carefully considered when selecting among formulae. However, many of the overall sample, sex-specific, and BMI percentile formulae carry MSE values within more acceptable ranges. Formulae with lower overall MSE values are therefore preferable in use.

There are several ways practitioners can determine which formulae is most appropriate for use in their specific case. Most importantly, formula-specific maximum and minimum J and breadth measurements from the femur and the tibia act as a range for practitioners looking to find a suitable formula. The age-specific formulae require for an individual to be placed in a life history stage, rather than for their age to be estimated accurately. When looking to use the BMI-specific formulae in forensic contexts, independent information (e.g., clothing and personal effects) could also help to suggest if an individual was overweight or obese. In the case of paleoanthropology, individuals can be generally be assumed to not be overweight or obese.

The fact that males are slightly over-represented in the samples used to develop the New Mexico formulae could potentially skew the formulae to underestimate the weight of girls in the sex-independent formulae. Additionally, the inclusion of individuals under the 5th percentile for BMI in the >95th formulae could also result in the underestimate of weight in children with the 5th to 95th percentile, though these individuals made up a very small percentage of the sub-sample. These formulae have potential applications in both forensic and bioarchaeological contexts, where skeletal preservation is frequently incomplete and the survival of entire elements cannot be assumed. They may be especially useful in contemporary North American forensic casework, as they were derived from a modern forensic sample that more accurately reflects current patterns of height, weight, and BMI than the decades-old Denver Growth Study cohort.

5. Conclusions

The primary objective of this study was to develop a series of weight estimation formulae derived from a modern, 21st-century pediatric population, utilizing multiple breadth and J measurements obtained from the femur and tibia, for application in contemporary forensic contexts. Given the nature of the reference sample, these formulae are most appropriately applied to the estimation of body weight in modern pediatric populations. Femoral midshaft J values (at 45.5% of total diaphyseal length) and proximal tibial J values (at 75% of total diaphyseal length) exhibited the strongest relationship with body weight and, when incorporated into weight estimation formulae, produced the lowest prediction errors. These

results suggest that across the diaphysis, body size is well reflected by torsional rigidity along the entire shaft rather than at the midshaft alone. Formulae derived from J values consistently yielded the lowest MSE and MAR values overall and demonstrated greater utility than breadth-based formulae for individuals with BMI above the 95th percentile. These J-based formulae generally tended to underestimate weight in younger and lighter individuals while overestimating in older and heavier individuals.

Breadth measurements were, in general, less strongly determined by body weight and produced larger prediction errors than J values, though distal femoral metaphyseal breadth was the exception, yielding the highest coefficient of determination and lowest error among all breadth-based parameters. Breadth-based formulae were less precise overall and exhibited systematic bias in mean residuals, likely attributable to heteroscedasticity across sex and age categories as well as to bias introduced during the back-transformation of log-transformed data. On the basis of these findings, J-based formulae are recommended as the more reliable option for accurate pediatric weight estimation. However, due to large prediction errors, weight estimation may often be of limited value. Cross-validation testing of the formulae on individuals from outside or unrelated to the sample is still needed to further determine their applicability on a general forensic population or generalizability. A practical advantage of the formulae developed in this study is their applicability in cases where the femur is absent or where specific femoral regions—such as the complete femoral head or distal metaphysis—are missing or damaged, given that tibial measurements offer a comparable alternative.

Author Contributions: Conceptualization, J.M., L.H. and H.F.V.C.; methodology, J.M. and H.F.V.C.; formal analysis, J.M.; visualization, J.M. and H.F.V.C.; resources, H.F.V.C.; data curation, J.M. and H.F.V.C.; writing—original draft preparation, J.M.; writing—review and editing, J.M., H.F.V.C., L.H. and D.C.M.; supervision, H.F.V.C. and L.H.; funding acquisition, J.M. and H.F.V.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by a Doctoral Scholarship from the Social Science and Humanities Research Council of the Government of Canada and a Discovery Grant from the Natural Sciences and Engineering Research Council (NSERC RGPIN-2016-05863).

Institutional Review Board Statement: Ethical review and approval were waived for this study due to the research being conducted on images available through the publicly-accessible New Mexico Decedent Image Database and protocol #20190154, of 30 March 2019.

Informed Consent Statement: Not applicable. This study used de-identified CT scans and next-of-kin interview data from the University of New Mexico's New Mexico Decedent Image Database (NMDID). Access to the de-identified database is governed by the NMDID Data Access, Sharing, and Use Agreement, which permits use for scientific research and prohibits re-identification of individuals. The authors did not collect the primary data themselves; their use of the data was subject to the NMDID's terms and conditions.

Data Availability Statement: CT images and demographic of all individuals can be found through the NMDID website: <https://nmdid.unm.edu/> (accessed on 13 July 2026).

Acknowledgments: The authors wish to acknowledge the New Mexico Decedent Image Database (NMDID), the Office of the Medical Examiner of New Mexico, and the University of New Mexico. The authors also wish to thank the three anonymous reviewers for their helpful comments and suggestions.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Maresh, M.M. Measurements from roentgenograms. In *Human Growth and Development*; McCannon, R.W., Ed.; Charles C Thomas: Springfield, IL, USA, 1970; pp. 157–188.
2. Maresh, M.M. Growth of major long bones in healthy children: A preliminary report on successive roentgenograms of the extremities from early infancy to twelve years of age. *Am. J. Dis. Child.* **1943**, *66*, 227–257. [\[CrossRef\]](#)
3. Maresh, M.M. Linear growth of long bones of extremities from infancy through adolescence; continuing studies. *Am. J. Dis. Child.* **1955**, *89*, 725–742. [\[CrossRef\]](#)
4. Ruff, C.B. Bone structural data for the Denver longitudinal growth study. *Am. J. Biol. Anthropol.* **2022**, *178*, 544–547. [\[CrossRef\]](#)
5. McCammon, R.W. *Human Growth and Development*; Charles C Thomas: Springfield, IL, USA, 1970.
6. Ruff, C.B. Body size prediction from juvenile skeletal remains. *Am. J. Phys. Anthropol.* **2007**, *133*, 698–716. [\[CrossRef\]](#) [\[PubMed\]](#)
7. Robbins, G.; Sciulli, P.W.; Blatt, S.H. Estimating body mass in subadult human skeletons. *Am. J. Phys. Anthropol.* **2010**, *143*, 146–150. [\[CrossRef\]](#) [\[PubMed\]](#)
8. Ruff, C.B. Growth in bone strength, body size, and muscle size in a juvenile longitudinal sample. *Bone* **2003**, *33*, 317–329. [\[CrossRef\]](#) [\[PubMed\]](#)
9. Sciulli, P.W.; Blatt, S.H. Evaluation of juvenile stature and body mass prediction. *Am. J. Phys. Anthropol.* **2008**, *136*, 387–393. [\[CrossRef\]](#) [\[PubMed\]](#)
10. Trinkaus, E.; Ruff, C.B.; Esteves, F.; Coelho, J.M.S.; Silva, M.; Mendova, M. The lower limb remains. In *Portrait of the Artist as a Child*; Zilhão, J., Trinkaus, E., Eds.; Instituto Portugues de Arqueologia: Lisbon, Portugal, 2002; pp. 435–465.
11. Cowgill, L.W.; Trinkaus, E.; Zeder, M.A. Shanidar 10: A Middle Paleolithic immature distal lower limb from Shanidar Cave, Iraqi Kurdistan. *J. Hum. Evol.* **2007**, *53*, 213–223. [\[CrossRef\]](#) [\[PubMed\]](#)
12. Harrington, L. Ontogeny of Postcranial Robusticity Among Holocene Hunter-Gatherers of Southernmost Africa. Ph.D. Thesis, University of Toronto, Toronto, ON, Canada, 2010.
13. Cowgill, L.W. Juvenile body mass estimation: A methodological evaluation. *J. Hum. Evol.* **2018**, *115*, 78–84. [\[CrossRef\]](#) [\[PubMed\]](#)
14. Walker, C.S.; Yapuncich, G.S.; Sridhar, S.; Cameron, N.; Churchill, S.E. Evaluating morphometric body mass prediction equations with a juvenile human test sample: Accuracy and applicability to small-bodied hominins. *J. Hum. Evol.* **2018**, *115*, 65–77. [\[CrossRef\]](#) [\[PubMed\]](#)
15. Sun, S.S.; Deng, X.; Sabo, R.; Carrico, R.; Schubert, C.M.; Wan, W.; Sabo, C. Secular trends in body composition for children and young adults: The Fels Longitudinal Study. *Am. J. Hum. Biol.* **2012**, *24*, 506–514. [\[CrossRef\]](#) [\[PubMed\]](#)
16. Troiano, R.P.; Flegal, K.M.; Kuczmarski, R.J.; Campbell, S.M.; Johnson, C.L. Overweight prevalence and trends for children and adolescents: The National Health and Nutrition Examination Surveys, 1963 to 1991. *Arch. Pediatr. Adolesc. Med.* **1995**, *149*, 1085–1091. [\[CrossRef\]](#) [\[PubMed\]](#)
17. Ogden, C.L.; Carroll, M.D.; Flegal, K.M. High body mass index for age among US children and adolescents, 2003–2006. *JAMA—J. Am. Med. Assoc.* **2008**, *299*, 2401–2405. [\[CrossRef\]](#)
18. Komlos, J.; Breitfelder, A.; Sunder, M. The transition to post-industrial BMI values among US children. *Am. J. Hum. Biol.* **2009**, *21*, 151–160. [\[PubMed\]](#)
19. Meyers, J. Impacts of the Growth Environment on Cortical Bone Plasticity During Childhood. Ph.D. Thesis, Simon Fraser University, Burnaby, BC, Canada, 2023. Available online: <https://summit.sfu.ca/item/36770> (accessed on 13 July 2026).
20. Yim, A.D.; Konigsberg, L.W.; Hwa, H.L.; Chen, J.Y.; Liu, H.M. Subadult body mass estimation from skeletal remains: Validation for femoral cross-section methods in a contemporary Taiwanese population. In *Proceedings of the Program of the Annual Meeting of the American Academy of Forensic Sciences, Anaheim, CA, USA, 17–22 February 2020*; AAFS: Colorado Springs, CO, USA, 2020; p. 116.
21. Spake, L.; Meyers, J.; Cardoso, H.F. Juvenile Body Mass Estimation from the Femur Using Postmortem Computed Tomography Data. *Hum. Biol.* **2021**, *93*, 125–137. [\[CrossRef\]](#) [\[PubMed\]](#)
22. Watts, R. The long-term impact of developmental stress. Evidence from Later Medieval and Post-Medieval London (AD1117–1853). *Am. J. Phys. Anthropol.* **2015**, *158*, 569–580. [\[CrossRef\]](#) [\[PubMed\]](#)
23. Newman, S.L.; Gowland, R.L. Dedicated followers of fashion? Bioarchaeological perspectives on socio-economic status, inequality, and health in urban children from the industrial revolution (18th–19th C), England. *Int. J. Osteoarchaeol.* **2017**, *27*, 217–229. [\[PubMed\]](#)
24. Cowgill, L.W.; Harrington, L.; MacKinnon, M.; Kurk, H.K. Gains in relative cortical area during growth and their relationship to nutrition, body size, and physical activity. *Am. J. Hum. Biol.* **2023**, *182*, 177–193. [\[CrossRef\]](#)
25. Bogin, B.; Smith, B.H. Evolution of the human life cycle. *Am. J. Hum. Biol.* **1996**, *8*, 703–716. [\[CrossRef\]](#)
26. New Mexico Health Authority. New Mexico Childhood Obesity 2024 Update. 2025. Available online: <https://www.nmhealth.org/data/view/chronic/2989/> (accessed on 13 July 2026).
27. Spake, L.; Meyers, J.; Blau, S.; Cardoso, H.F.; Lottering, N. A simple and software-independent protocol for the measurement of post-cranial bones in anthropological contexts using thin slab maximum intensity projection. *Forensic Imaging* **2020**, *20*, 200354. [\[CrossRef\]](#)

28. Doube, M.; Klosowski, M.M.; Arganda-Carreras, I.; Cordelières, F.; Dougherty, R.P.; Jackson, J.; Schmid, B.; Hutchinson, J.R.; Shefelbine, S.J. BoneJ: Free and extensible bone image analysis in ImageJ. *Bone* **2010**, *47*, 1076–1079. [[CrossRef](#)] [[PubMed](#)]
29. Schneider, C.A.; Rasband, W.S.; Eliceiri, K.W. NIH Image to ImageJ: 25 years of image analysis. *Nat. Methods* **2012**, *9*, 671–675. [[CrossRef](#)] [[PubMed](#)]
30. Lucy, D. *Introduction to Statistics for Forensic Scientists*; Wiley: Chichester, UK, 2005.
31. Ruff, C.B.; Trinkaus, E.; Walker, A.; Spencer Larsen, C. Post-cranial robusticity in Homo I: Temporal trends and bio-mechanical interpretation. *Am. J. Phys. Anthropol.* **1993**, *91*, 21–53. [[CrossRef](#)] [[PubMed](#)]
32. Ruff, C.B. Body size, body shape, and long bone strength in modern humans. *J. Hum. Evol.* **2000**, *38*, 269–290. [[CrossRef](#)] [[PubMed](#)]
33. Ruff, C.B.; Garofalo, E.; Holmes, M.A. Interpreting skeletal growth in the past from a functional and physiological perspective. *Am. J. Phys. Anthropol.* **2013**, *150*, 29–37. [[PubMed](#)]
34. Macintosh, A.A.; Davies, T.G.; Ryan, T.M.; Shaw, C.N.; Stock, J.T. Periosteal versus true cross-sectional geometry: A comparison along humeral, femoral, and tibial diaphyses. *Am. J. Phys. Anthropol.* **2013**, *150*, 442–452. [[CrossRef](#)] [[PubMed](#)]
35. Davies, T.G.; Stock, J.T. The influence of relative body breadth on the diaphyseal morphology of the human lower limb. *Am. J. Hum. Biol.* **2014**, *26*, 822–835. [[CrossRef](#)] [[PubMed](#)]
36. Robbins Schug, G.; Gupta, S.; Cowgill, L.W.; Sciulli, P.W.; Blatt, S.H. Panel regression formulas for estimating stature and body mass from immature human skeletons: A statistical approach without reference to specific age estimates. *J. Archaeol. Sci.* **2013**, *40*, 3076–3086. [[CrossRef](#)]
37. Must, A.; Dallal, G.E.; Dietz, W.H. Reference data for obesity: 85th and 95th percentiles of body mass index (wt/ht²) and triceps skinfold thickness. *Am. J. Clin. Nutr.* **1991**, *53*, 839–846. [[CrossRef](#)] [[PubMed](#)]
38. Nadell, J.A.; Shaw, C.N. Phenotypic plasticity and constraint along the upper and lower limb diaphyses of Homo sapiens. *Am. J. Phys. Anthropol.* **2016**, *159*, 410–422. [[PubMed](#)]
39. Carter, D.R.; Beaupré, G.S. *Skeletal Function and Form*; Cambridge University Press: Cambridge, UK, 2001.
40. Ruff, C.B.; Hayes, W. Cross-sectional geometry of Pecos Pueblo femora and tibiae—A biomechanical investigation: I. Method and general patterns of variation. *Am. J. Phys. Anthropol.* **1983**, *60*, 359–381. [[CrossRef](#)] [[PubMed](#)]
41. Kurki, H.K.; Holland, S.; MacKinnon, M.; Cowgill, L.; Osipov, B.; Harrington, L. Appositional long bone growth: Implications for measuring cross-sectional geometry. *Am. J. Biol. Anthropol.* **2022**, *179*, 291–306. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.