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# Technical Note: The Effect of Midshaft Location on the Error Ranges of Femoral and Tibial Cross-sectional Parameters

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*ABSTRACT* In comparing long-bone cross-sectional geometric properties between individuals, percentages of bone length are often used to identify equivalent locations along the diaphysis. In fragmentary specimens where bone lengths cannot be measured, however, these locations must be estimated more indirectly. In this study, we examine the effect of inaccurately located femoral and tibial midshafts on estimation of geometric properties. The error ranges were compared on 30 femora and tibiae from the Eneolithic and Bronze Age. Cross-sections were obtained at each 1% interval from 60 to 40% of length using CT scans. Five percent of deviation from midshaft properties was used as the maximum acceptable error. Reliability was expressed by mean percentage differences, standard deviation of percentage differences, mean percentage absolute differences, limits of agreement, and mean accuracy range (MAR) (range within which mean deviation from true midshaft values was less than 5%). On average, tibial cortical area and femoral second moments of area are the least sensitive to positioning error, with mean accuracy ranges wide enough for practical application in fragmentary specimens (MAR = 40–130 mm). In contrast, tibial second moments of area are the most sensitive to error in midshaft location (MAR = 14–20 mm). Individuals present significant variation in morphology and thus in error ranges for different properties. For highly damaged fossil femora and tibiae we recommend carrying out additional tests to better establish specific errors associated with uncertain length estimates. Am J Phys Anthropol 141:325–332, 2010. ©2009 Wiley-Liss, Inc.

Despite methodological progress (see for example review in Ruff et al., 2006), biomechanical analysis remains a demanding approach for studying bone cross-sectional geometry. The reliability of biomechanical approaches has been examined in comparisons of various methods used to obtain cross-sectional properties (Ruff, 1986; Stock, 2002; O'Neill and Ruff, 2004; Stock and Shaw, 2007), for accuracy of the endosteal boundary identification (Ruff and Hayes, 1983), as well as for inter- and intra-observer variation in computed tomography (CT) scan computation of the cross-sectional properties (Sailer et al., 2003). However, reliable analysis of cross-sectional geometry also depends upon reliable location of the analyzed cross-section on the long-bone shaft (Ruff, 2000).

The most commonly employed method for locating long-bone shaft cross-sections is based on their position relative to bone length. Unfortunately, the preservation of femoral and tibial length is often poor in prehistoric samples and the position of the cross-section frequently has to be estimated (e.g., Day and Molleson, 1976; Trinkaus and Ruff, 1989, 1996; Ruff et al., 1999; Trinkaus et al., 1999a,b,c; Haeusler and McHenry, 2004; Nakatsukasa et al., 2007). Thus, there is a rational tendency to maximize the available sample for biomechanical analysis even in situations where biomechanical properties can be biased by uncertain estimation.

Several methods have been used to reconstruct the length of poorly preserved femora and tibiae (e.g., Steel and McKern, 1969; Steele, 1970; McHenry, 1974, 1991; Day and Molleson, 1976; McHenry and Berger, 1998; Trinkaus et al., 1999a; Haeusler and McHenry, 2004), but there is some concern about the reliability of the resulting length estimates (Simmons et al., 1990; Jacobs, 1992; Ernestová, 2003; Wright and Vasquez, 2003). Uncertainty also occurs when the location on the long-bone shaft is estimated indirectly by morphological features. When the length is not preserved, anatomical features must be used (e.g., maximum pilasteric development), sometimes together with other information such

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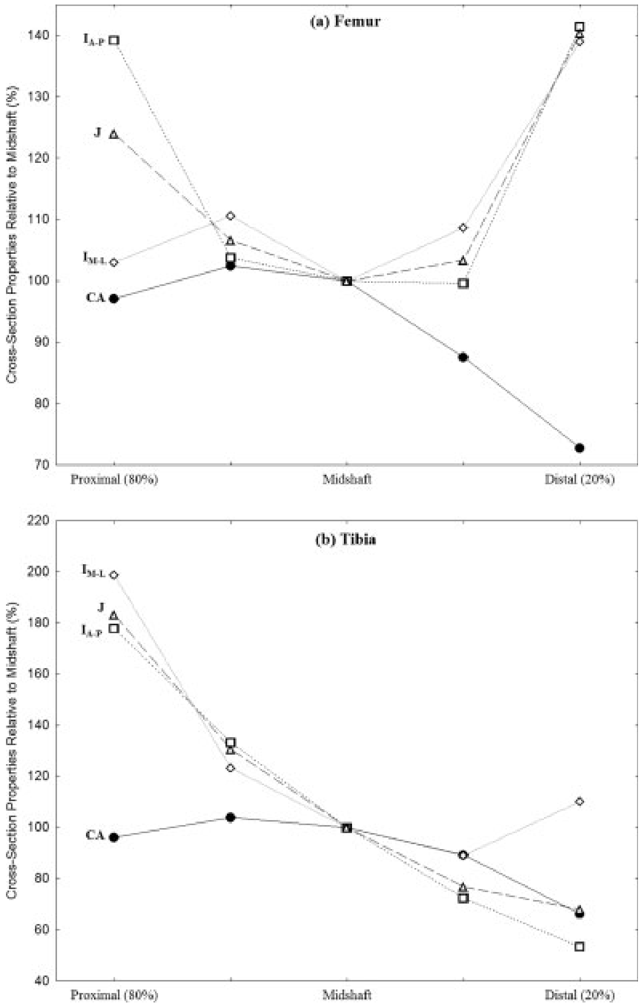

**Fig. 1.** Error prediction due to uncertain midshaft location for femora (**a**) and tibiae (**b**). Data from Ruff and Hayes (1983).

as in situ burial lengths (Trinkaus and Ruff, 1999). Unfortunately, the error for estimation of the midshaft location along the shaft is not known and reliability can only be approximated. Given the uncertainty associated with bone length estimation and the fact that the midshafts for both femora and tibiae are not directly marked by anatomical landmarks, we expect there to be error in cross-sectional properties associated with the location of cross-sections.

In light of this, we analyzed the errors in cross-sectional properties associated with variation in location of the femoral and tibial midshafts. Four cross-sectional properties were studied: cortical area (CA), antero-posterior, and medio-lateral second moments of area ($I_{A-P}$ and $I_{M-L}$), and polar moment of area ($J$). The expected error range for the cross-sectional properties is inferred from the central tendency found for Pecos femora and tibiae (Ruff and Hayes, 1983) (see Fig. 1). We hypothesized for femora that the properties most sensitive to midshaft location are CA in a distal direction from midshaft and $I_{M-L}$ in both directions (Fig. 1a). In tibiae, we hypothesized the highest error associated with midshaft location for second moments of area but minimal error for CA (Fig. 1b).

# MATERIALS AND METHODS

## Sample

The analysis is based on 30 femora and tibiae (15 females and 15 males) from the eneolithic and bronze age (see details about the sample in Sládek et al., 2006). The primary requirement was complete preservation of biomechanical length (BML) (see Ruff and Hayes, 1983). The right bone was preferred for analysis when possible.

## Measurements and cross-sections

CT scan images were taken at intervals of 1% BML in the midshaft region from 60 to 40% of BML. Details about CT scanning (e.g., definition of measurements, orientation of bones), CT scan digitizing, and computation of geometric properties were reported earlier (Sládek et al., 2006). The geometric properties obtained—cortical area (CA), second moments of area ($I_{A-P}$, $I_{M-L}$), and polar second moment of area ($J$)—were further tested for bias and error between target and particular 1% BML interval cross-sections. CA estimates cross-sectional rigidity in axial compression and tension, $I_{A-P}$ and $I_{M-L}$ evaluate resistance to bending rigidity against antero-posterior and medio-lateral loads, and $J$ estimates torsional rigidity (Ruff, 2000).

## Statistical methods

Femoral and tibial midshafts (50% of BML) represent the target cross-section. The bias and error in locating the target cross-section are expressed by the following:

1. Mean percentage difference (MD%) represents the directional bias between the target location and particular 1% of BML cross-sections. MD% varies from negative to positive values. The hypothesis of zero directional bias is examined by a paired $t$-test. MD% was calculated using the following formula:

$$\mathrm{MD\%} = \frac{\sum_{i=1}^{n}\left[(\mathrm{CS}_i - \mathrm{CStarget}_i)/\mathrm{CStarget}_i\right]\cdot 100}{n},$$

   where $\mathrm{CStarget}_i$ is a cross-sectional parameter value in the target location at 50% of BML in the $i$th individual, $\mathrm{CS}_i$ is the same parameter value at a particular 1% of BML section (e.g., 54 or 42%) and $n = 30$ is the sample size.
2. Standard deviation of percentage difference (SD%) is a measure of the random error in the location of the target reference (Altman and Bland, 1983; p 314).
3. Mean percentage absolute difference (MAD%) estimates the overall level of difference between the target location and compared cross-sections. The values of MAD% are always positive. MAD% is computed as follows:

$$\mathrm{MAD\%} = \frac{\sum_{i=1}^{n}\left[|\mathrm{CS}_i - \mathrm{CStarget}_i|/\mathrm{CStarget}_i\right]\cdot 100}{n}$$

   The symbols are described in equation for (1) above.
4. Limits of agreement (LA) represent the interval within which we would expect 95% of percentage differences to be between the target location and compared cross-sections. The limits of agreement are com-

TABLE 1. *The bias and error summary for femoral cross-sectional parameters*

| | | MD%[a] | SD | MAD%[b] | SD | 95% LA[c] |
|---|---|---|---|---|---|---|
| CA | 60% | 8.6** | 4.91 | 8.83 | 4.53 | −1.00; 18.26 |
| | 59% | 7.9** | 4.45 | 7.96 | 4.37 | −0.80; 16.64 |
| | 58% | 7.0** | 4.02 | 7.23 | 3.63 | −0.86; 14.91 |
| | 57% | 6.2** | 3.53 | 6.41 | 3.07 | −0.75; 13.10 |
| | 56% | 5.2** | 2.92 | 5.26 | 2.73 | −0.57; 10.88 |
| | 55% | 4.2** | 2.93 | 4.41 | 2.65 | −1.51; 9.98 |
| | 54% | 3.2** | 2.34 | 3.37 | 2.10 | −1.38; 7.80 |
| | 53% | 2.4** | 1.99 | 2.66 | 1.63 | −1.50; 6.31 |
| | 52% | 1.6** | 1.97 | 1.96 | 1.54 | −2.30; 5.40 |
| | 51% | 1.2** | 1.70 | 1.49 | 1.44 | −2.15; 4.53 |
| | 49% | −0.8* | 1.48 | 1.34 | 1.00 | −3.70; 2.11 |
| | 48% | −2.0** | 1.69 | 2.19 | 1.37 | −5.28; 1.35 |
| | 47% | −2.9** | 2.02 | 3.10 | 1.71 | −6.87; 1.04 |
| | 46% | −3.9** | 2.29 | 3.94 | 2.29 | −8.44; 0.56 |
| | 45% | −4.9** | 2.72 | 4.90 | 2.67 | −10.20; 0.46 |
| | 44% | −6.0** | 2.78 | 6.03 | 2.78 | −11.48; −0.57 |
| | 43% | −6.7** | 3.10 | 6.68 | 3.10 | −12.75; −0.60 |
| | 42% | −7.5** | 3.53 | 7.62 | 3.33 | −14.46; −0.61 |
| | 41% | −8.9** | 3.92 | 8.95 | 3.75 | −16.57; −1.18 |
| | 40% | −9.4** | 4.15 | 9.40 | 4.15 | −17.54; −1.26 |
| $I_{A\text{–}P}$ | 60% | 3.1* | 8.37 | 7.29 | 5.01 | −13.27; 19.53 |
| | 59% | 1.9 | 7.53 | 6.20 | 4.52 | −12.87; 16.63 |
| | 58% | 1.3 | 6.75 | 5.58 | 3.90 | −11.90; 14.57 |
| | 57% | 0.4 | 5.80 | 5.04 | 2.73 | −11.00; 11.72 |
| | 56% | −0.2 | 4.86 | 4.04 | 2.60 | −9.73; 9.33 |
| | 55% | −0.8 | 4.57 | 3.73 | 2.68 | −9.75; 8.15 |
| | 54% | −0.9 | 3.76 | 3.17 | 2.14 | −8.28; 6.46 |
| | 53% | −0.8 | 2.99 | 2.53 | 1.72 | −6.62; 5.11 |
| | 52% | −0.9 | 2.53 | 2.15 | 1.54 | −5.82; 4.11 |
| | 51% | 0.1 | 1.75 | 1.26 | 1.20 | −3.29; 3.55 |
| | 49% | 0.1 | 1.82 | 1.42 | 1.12 | −3.44; 3.70 |
| | 48% | −0.2 | 1.99 | 1.52 | 1.27 | −4.08; 3.71 |
| | 47% | 0.1 | 2.84 | 2.29 | 1.62 | −5.51; 5.61 |
| | 46% | 0.3 | 3.52 | 2.79 | 2.12 | −6.56; 7.25 |
| | 45% | 0.4 | 4.15 | 3.24 | 2.57 | −7.72; 8.56 |
| | 44% | 0.6 | 4.46 | 3.71 | 2.46 | −8.16; 9.34 |
| | 43% | 1.1 | 4.83 | 4.16 | 2.56 | −8.40; 10.53 |
| | 42% | 1.5 | 5.78 | 4.95 | 3.22 | −9.84; 12.81 |
| | 41% | 1.6 | 6.82 | 5.80 | 3.77 | −11.78; 14.94 |
| | 40% | 2.5 | 6.74 | 6.03 | 3.79 | −10.71; 15.72 |
| $I_{M\text{–}L}$ | 60% | 6.1** | 5.51 | 7.07 | 4.19 | −4.67; 16.93 |
| | 59% | 5.0** | 4.96 | 5.86 | 3.90 | −4.69; 14.75 |
| | 58% | 4.2** | 4.39 | 4.90 | 3.58 | −4.40; 12.83 |
| | 57% | 3.5** | 4.23 | 4.52 | 3.08 | −4.79; 11.81 |
| | 56% | 2.5** | 3.69 | 3.67 | 2.49 | −4.71; 9.74 |
| | 55% | 1.6* | 3.33 | 2.98 | 2.11 | −4.96; 8.10 |
| | 54% | 1.0 | 3.01 | 2.59 | 1.77 | −4.92; 6.89 |
| | 53% | 0.3 | 2.44 | 1.85 | 1.59 | −4.46; 5.10 |
| | 52% | 0.1 | 2.10 | 1.61 | 1.31 | −4.04; 4.17 |
| | 51% | 0.2 | 1.88 | 1.31 | 1.34 | −3.49; 3.87 |
| | 49% | 0.0 | 1.46 | 1.19 | 0.82 | −2.87; 2.86 |
| | 48% | −0.6 | 2.31 | 1.80 | 1.54 | −5.15; 3.90 |
| | 47% | −0.7 | 2.62 | 2.06 | 1.70 | −5.78; 4.48 |
| | 46% | −0.7 | 3.45 | 2.50 | 2.44 | −7.46; 6.07 |
| | 45% | −0.6 | 4.41 | 3.30 | 2.92 | −9.23; 8.05 |
| | 44% | −0.5 | 4.85 | 3.77 | 3.01 | −9.97; 9.02 |
| | 43% | 0.3 | 5.67 | 4.35 | 3.56 | −10.84; 11.38 |
| | 42% | 1.2 | 7.14 | 5.64 | 4.43 | −12.80; 15.20 |
| | 41% | 1.4 | 8.10 | 6.49 | 4.89 | −14.51; 17.23 |
| | 40% | 2.8 | 8.66 | 7.48 | 5.04 | −14.16; 19.80 |
| *J* | 60% | 4.6** | 5.87 | 6.00 | 4.40 | −6.87; 16.12 |
| | 59% | 3.5** | 5.22 | 4.94 | 3.80 | −6.76; 13.70 |
| | 58% | 2.8* | 4.74 | 4.39 | 3.25 | −6.50; 12.08 |
| | 57% | 1.9* | 4.25 | 3.77 | 2.69 | −6.38; 10.28 |
| | 56% | 1.2 | 3.65 | 3.12 | 2.17 | −5.99; 8.33 |
| | 55% | 0.4 | 3.45 | 2.77 | 2.03 | −6.36; 7.17 |
| | 54% | 0.1 | 2.90 | 2.37 | 1.61 | −5.61; 5.74 |
| | 53% | −0.2 | 2.36 | 1.83 | 1.45 | −4.80; 4.44 |
| | 52% | −0.4 | 2.08 | 1.72 | 1.20 | −4.47; 3.70 |
| | 51% | 0.2 | 1.62 | 1.14 | 1.14 | −3.01; 3.34 |
| | 49% | 0.0 | 1.40 | 1.08 | 0.87 | −2.70; 2.80 |
| | 48% | −0.4 | 1.71 | 1.39 | 1.06 | −3.80; 2.92 |
| | 47% | −0.3 | 2.03 | 1.69 | 1.13 | −4.32; 3.65 |
| | 46% | −0.2 | 2.75 | 2.13 | 1.71 | −5.59; 5.18 |
| | 45% | −0.1 | 3.53 | 2.69 | 2.22 | −7.04; 6.78 |
| | 44% | 0.0 | 3.78 | 2.88 | 2.40 | −7.41; 7.42 |
| | 43% | 0.6 | 4.18 | 3.23 | 2.65 | −7.60; 8.79 |
| | 42% | 1.3 | 5.26 | 4.31 | 3.17 | −9.06; 11.56 |
| | 41% | 1.3 | 6.14 | 5.13 | 3.52 | −10.69; 13.39 |
| | 40% | 2.5* | 6.20 | 5.72 | 3.33 | −9.63; 14.67 |

Femoral midshaft is used as the true value.

[a] MD%: Mean percentage difference (for computation details see Materials and Methods).

[b] MAD%: Mean percentage absolute difference (for computation details see Materials and Methods).

[c] ±95% LA: upper and lower 95% limits of agreements of MD% (Bland and Altman, 1986; see computation details in Materials and Methods).

* significance at $\alpha$-level = 0.05 of repeated measures ANOVA;

** significance at 0.0026 level (after Dunn-Šidák correction of $\alpha$-level = 0.05 for 20 test).

puted using the approach of Bland and Altman (1986):

$$\mathrm{LA} = \mathrm{MD}\% \pm 1.96 \cdot \mathrm{SD}\%.$$

5. Accuracy range is a distance, measured in % of BML and mm, above and below the midshaft where the overall error (MAD%) is less than the accepted value of 5% (see comment about accepted error below). The accuracy range is computed using the distance of the cross-sections with MAD% nearest to the accepted error and the mean length of the BML interval from midshaft to selected cross-section.

To interpret the practical importance of limits of agreement and MAD%, the accepted error must be specified. The accepted error is defined as a quantity of required reliability in the error. We expect that the accepted error also delimits the level of error that will have no impact on interpretation of the respective comparisons (e.g., comparisons between sexes or populations). It is obvious, however, that such a definition is subjective and depends on the goals of the analysis. The accepted error is frequently specified by a value derived from empirical observations (Hunter, 1980; Meloun and Militký, 1998). Such standards have not been developed for cross-sectional comparisons. The only suggestion for reasonably accurate cross-sections is the level of 5% difference established by Trinkaus and Ruff (1989). The accepted error of 5% difference was later used, for example, in other methodological studies of cross-sectional analyses (Stock, 2002; O'Neill and Ruff, 2004). Therefore, we will regard differences of 5% or lower between the target location and the compared cross-section as being practically insignificant.

All the data were prepared in Excel 2003 (Microsoft Corporation, 1985–2003). Further analyses were produced in Excel 2003 or in Statistica 6.1 (StatSoft, 1984–2003). The statistical significance of MD% was tested using paired *t*-tests with Dunn-Šidák Type I error correction (Sokal and Rohlf, 1995).

*TABLE 2. Mean accuracy range (MAR) in %BML and in millimeters for reliable location of femoral and tibial midshaft*

| | MAR (%BML) | | MAR (mm) | | |
|---|---|---|---|---|---|
| | Proximal | Distal | Proximal | Distal | Range |
| Femora | | | | | |
| CA | 56 | 45 | 23 | 21 | 43 |
| $I_{A\text{–}P}$ | 57 | 42 | 30 | 33 | 63 |
| $I_{M\text{–}L}$ | 58 | 42 | 33 | 32 | 65 |
| $J$ | 59 | 41 | 37 | 37 | 74 |
| Tibiae | | | | | |
| CA | 78 | 40 | 98 | 34 | 132 |
| $I_{A\text{–}P}$ | 52 | 48 | 8 | 6 | 14 |
| $I_{M\text{–}L}$ | 55 | 44 | 19 | 20 | 39 |
| $J$ | 53 | 47 | 11 | 9 | 20 |

The 5% difference from midshaft values is used for accepted error; mean distance of 1% BML interval is 4.04 mm for femora and 3.4 mm for tibiae.

## RESULTS

### Femoral midshaft location

Table 1 shows the directional bias and overall error for femoral geometric properties. Femoral CA has MD% values significantly different from the midshaft in the nearest 1% cross-section. By contrast, the second moments of area are significantly different only in the proximal and distal limits of the studied region. On average, there is no practical difference between error range in the proximal and distal directions except for femoral CA. The femoral CA overestimates midshaft value in the proximal direction and underestimates in the distal direction. This indicates that when midshaft is not accurately located, then the CA area is estimated on femora with lower accuracy and femoral second moments of area with higher accuracy.

Estimates for the femoral mean accuracy range are presented in Table 2. The accuracy range is calculated as an interval on the femoral shaft where the MAD% is not larger than the accepted error of 5% from the midshaft values. Femoral CA has the shortest mean accuracy range (MAR = 43 mm) and femoral $J$ has the widest accuracy range (MAR = 74 mm). On average, the femoral accuracy range is wide enough for practical application in all biomechanical parameters.

### Tibial midshaft location

The bias and error for tibial geometric properties are summarized in Table 3. Significant difference of the MD% from midshaft true values is found for CA from 47% distally but for $I_{A\text{–}P}$ and $J$ from the nearest 1% cross-section to midshaft. This result is also supported by 95% LA where 5% accepted error is reached by the LAs for CA farther from the midshaft than for second moments of area. Thus, these results indicate that tibial CA is estimated with higher reliability when midshaft is inaccurately located than are tibial second moments of area.

The mean accuracy ranges for tibial geometric properties are shown Table 2. The tibial CA has a mean accuracy range of about 132 mm, which indicates a high tolerance to the effect of inaccurate midshaft location. However, mean accuracy range for $J$ is 20 mm and for $I_{A\text{–}P}$ only 14 mm. This seems to be critical when the midshaft is located on highly damaged tibiae.

### Individual variation

The mean accuracy ranges found for the majority of the cross-sectional parameters seem to be reasonably wide for practical application. Their use in practice is brought into question, however, by visual inspection of differences between the central tendencies of geometric properties and their individual distributions (Figs. 2–4). Visual inspection indicates that individual distributions vary as to the magnitude of changes in geometric properties and in the patterns of distribution for geometric properties (i.e., rates of geometric change per mm and locations of minima and maxima within the distribution). This result is also supported by significant departures from homoscedasticity for the majority of cross-sectional parameters tested using Bartlett's and Levene's tests. Thus, inaccurate midshaft location can result in unexpectedly high individual error even in properties for which the mean accuracy range is rather wide.

Figure 5 shows three examples of femoral $I_{A\text{–}P}$ distribution near the midshaft region. According to central tendency, we would expect only slight change in the $I_{A\text{–}P}$ distribution between 55 and 45% BML (Fig. 3a). However, the selected three individuals demonstrate that geometry can remain unchanged in the midshaft region (see Individual A) but also can rapidly decrease with minimum value distally from midshaft (Individual B) as well as increase with minimum value proximally (Individual C). Thus, the mean accuracy range can underestimate as well as overestimate the individual error, which points to a disadvantage for some individuals of using the mean accuracy range for predicting expected error.

Tables 4 and 5 summarize relative frequencies for the positions of minimum and maximum values along the femoral and tibial shafts. As indicated, femoral and tibial midshafts do not represent a constant pattern as to the positions of minima and maxima. In fact, minimum is reached in midshaft for $I_{M\text{–}L}$ only in 10% and for $J$ in 13% of cases. Moreover, the minimum for the $I_{A\text{–}P}$ was not in midshaft but shifted either proximally or distally. Variation in the midshaft region is also supported by external midshaft dimensions in recent human femora (Haeusler and McHenry, 2004: Fig. 3). This variation itself is of potential interest for further paleobiological studies. It also has implications for when the impact of individual error range should be specified.

## DISCUSSION

When midshaft location is inaccurately located, then tibial second moments of area are more unreliably estimated than are femoral second moments of area. The critical geometric properties are tibial $I_{A\text{–}P}$ (MAR = 14 mm) and tibial $J$ (MAR = 20 mm). Unreliability for tibial second moments of area is associated with the more rapidly changing geometry of the tibial midshaft. Thus, if tibial length is extremely tenuous (i.e., the proximal and/or distal end is missing), then we must be cautious in interpreting tibial second moments of area and in some cases we should consider not including that bone in the analysis.

Estimation of cortical area is more sensitive to midshaft location in femora (MAR for CA = 43 mm) than in tibiae (MAR for CA = 132 mm). In both cases, however, its mean accuracy range is fairly wide for practical application and, unlike tibial second moments of area, it does not increase greatly beyond that range.

*TABLE 3. The bias and error summary for tibial cross-sectional parameters*

| | | MD% | SD | MAD% | SD | 95% LA |
|---|---|---|---|---|---|---|
| CA | 60% | −0.1 | 4.51 | 3.52 | 2.75 | −8.98; 8.72 |
| | 59% | −0.1 | 4.07 | 3.28 | 2.33 | −8.11; 7.83 |
| | 58% | 0.1 | 3.65 | 2.64 | 2.47 | −7.05; 7.25 |
| | 57% | 0.4 | 3.34 | 2.49 | 2.21 | −6.18; 6.92 |
| | 56% | −0.5 | 3.60 | 2.75 | 2.32 | −7.59; 6.51 |
| | 55% | −0.7 | 2.94 | 2.22 | 2.01 | −6.45; 5.08 |
| | 54% | −0.4 | 2.33 | 1.88 | 1.41 | −5.02; 4.13 |
| | 53% | −0.6 | 2.61 | 1.87 | 1.89 | −5.70; 4.52 |
| | 52% | −0.5 | 2.05 | 1.43 | 1.55 | −4.56; 3.47 |
| | 51% | −0.6 | 2.18 | 1.69 | 1.49 | −4.90; 3.66 |
| | 49% | −0.4 | 1.24 | 1.12 | 0.67 | −2.86; 2.02 |
| | 48% | −0.5 | 1.78 | 1.42 | 1.15 | −3.97; 3.00 |
| | 47% | −1.3** | 1.94 | 1.79 | 1.50 | −5.12; 2.47 |
| | 46% | −1.9* | 3.29 | 2.92 | 2.36 | −8.30; 4.57 |
| | 45% | −2.6** | 3.17 | 3.30 | 2.38 | −8.80; 3.62 |
| | 44% | −3.4** | 3.60 | 4.32 | 2.35 | −10.44; 3.68 |
| | 43% | −4.2** | 3.79 | 4.93 | 2.73 | −11.62; 3.22 |
| | 42% | −5.0** | 4.35 | 6.03 | 2.59 | −13.48; 3.56 |
| | 41% | −5.9** | 3.70 | 6.49 | 2.56 | −13.19; 1.33 |
| | 40% | −6.7** | 3.67 | 7.00 | 2.94 | −13.85; 0.53 |
| $I_{\mathrm{A–P}}$ | 60% | 22.7** | 7.41 | 22.72 | 7.41 | 8.19; 37.25 |
| | 59% | 20.1** | 6.61 | 20.15 | 6.61 | 7.18; 33.11 |
| | 58% | 17.9** | 6.17 | 17.88 | 6.17 | 5.79; 29.96 |
| | 57% | 15.5** | 5.73 | 15.53 | 5.73 | 4.29; 26.77 |
| | 56% | 12.9** | 4.98 | 12.94 | 4.98 | 3.19; 22.70 |
| | 55% | 10.7** | 3.74 | 10.66 | 3.74 | 3.33; 17.98 |
| | 54% | 8.9** | 3.24 | 8.86 | 3.24 | 2.50; 15.21 |
| | 53% | 6.5** | 3.14 | 6.66 | 2.81 | 0.35; 12.67 |
| | 52% | 4.2** | 2.16 | 4.40 | 1.71 | −0.03; 8.44 |
| | 51% | 2.0** | 1.51 | 2.16 | 1.32 | −0.93; 5.00 |
| | 49% | −2.9** | 1.35 | 2.86 | 1.35 | −5.51; −0.21 |
| | 48% | −5.4** | 1.91 | 5.39 | 1.91 | −9.13; −1.65 |
| | 47% | −8.2** | 2.23 | 8.21 | 2.23 | −12.59; −3.83 |
| | 46% | −10.6** | 2.86 | 10.63 | 2.86 | −16.24; −5.02 |
| | 45% | −13.2** | 3.34 | 13.25 | 3.34 | −19.80; −6.70 |
| | 44% | −15.6** | 3.39 | 15.65 | 3.39 | −22.28; −9.01 |
| | 43% | −18.2** | 3.47 | 18.25 | 3.47 | −25.05; −11.45 |
| | 42% | −20.6** | 3.72 | 20.55 | 3.72 | −27.84; −13.26 |
| | 41% | −22.8** | 3.71 | 22.75 | 3.71 | −30.02; −15.49 |
| | 40% | −24.7** | 3.84 | 24.65 | 3.84 | −32.18; −17.12 |
| $I_{\mathrm{M–L}}$ | 60% | 9.0** | 8.06 | 10.03 | 6.62 | −6.85; 24.76 |
| | 59% | 7.4** | 7.21 | 8.51 | 5.86 | −6.68; 21.57 |
| | 58% | 6.3** | 6.67 | 7.77 | 4.78 | −6.79; 19.35 |
| | 57% | 5.1** | 6.00 | 6.60 | 4.26 | −6.63; 16.89 |
| | 56% | 3.7** | 5.66 | 5.45 | 3.93 | −7.38; 14.79 |
| | 55% | 2.4* | 4.88 | 4.33 | 3.21 | −7.16; 11.96 |
| | 54% | 1.5* | 3.65 | 3.09 | 2.41 | −5.63; 8.67 |
| | 53% | 0.6 | 2.98 | 2.40 | 1.83 | −5.19; 6.48 |
| | 52% | 0.0 | 2.42 | 2.03 | 1.26 | −4.79; 4.70 |
| | 51% | −0.2 | 1.86 | 1.50 | 1.07 | −3.85; 3.42 |
| | 49% | −0.8* | 1.89 | 1.56 | 1.34 | −4.55; 2.86 |
| | 48% | −1.1* | 2.33 | 2.01 | 1.56 | −5.63; 3.52 |
| | 47% | −1.9** | 3.05 | 2.99 | 1.99 | −7.93; 4.05 |
| | 46% | −2.8** | 4.40 | 4.30 | 2.92 | −11.45; 5.78 |
| | 45% | −3.4** | 4.69 | 4.50 | 3.61 | −12.59; 5.80 |
| | 44% | −4.2** | 4.96 | 5.16 | 3.93 | −13.94; 5.49 |
| | 43% | −4.8** | 5.53 | 5.88 | 4.33 | −15.66; 6.04 |
| | 42% | −5.5** | 5.99 | 6.56 | 4.70 | −17.19; 6.28 |
| | 41% | −6.1** | 6.48 | 7.01 | 5.44 | −18.79; 6.60 |
| | 40% | −6.6** | 6.45 | 7.54 | 5.25 | −19.21; 6.06 |
| $J$ | 60% | 17.6** | 6.38 | 17.63 | 6.38 | 5.12; 30.13 |
| | 59% | 15.5** | 5.64 | 15.45 | 5.64 | 4.40; 26.51 |
| | 58% | 13.6** | 5.34 | 13.61 | 5.34 | 3.14; 24.07 |
| | 57% | 11.7** | 4.78 | 11.70 | 4.78 | 2.33; 21.08 |
| | 56% | 9.5** | 4.26 | 9.55 | 4.26 | 1.20; 17.89 |
| | 55% | 7.6** | 3.16 | 7.63 | 3.16 | 1.44; 13.82 |
| | 54% | 6.2** | 2.69 | 6.15 | 2.69 | 0.88; 11.42 |
| | 53% | 4.3** | 2.49 | 4.61 | 1.94 | −0.54; 9.22 |
| | 52% | 2.6** | 1.93 | 2.91 | 1.45 | −1.16; 6.42 |
| | 51% | 1.2** | 1.50 | 1.56 | 1.11 | −1.74; 4.15 |
| | 49% | −2.1** | 1.38 | 2.15 | 1.33 | −4.83; 0.60 |
| | 48% | −3.8** | 1.81 | 3.82 | 1.75 | −7.34; −0.25 |
| | 47% | −5.9** | 2.18 | 5.89 | 2.18 | −10.17; −1.61 |
| | 46% | −7.8** | 3.18 | 7.75 | 3.18 | −13.97; −1.53 |
| | 45% | −9.6** | 3.60 | 9.61 | 3.60 | −16.67; −2.55 |
| | 44% | −11.4** | 3.72 | 11.42 | 3.72 | −18.71; −4.14 |
| | 43% | −13.3** | 3.96 | 13.27 | 3.96 | −21.04; −5.51 |
| | 42% | −15.0** | 4.17 | 14.96 | 4.17 | −23.13; −6.80 |
| | 41% | −16.6** | 4.25 | 16.59 | 4.25 | −24.92; −8.26 |
| | 40% | −18.0** | 4.30 | 17.97 | 4.30 | −26.40; −9.54 |

Tibial midshaft is used as the true value. (For abbreviations and computation details see Table 1).

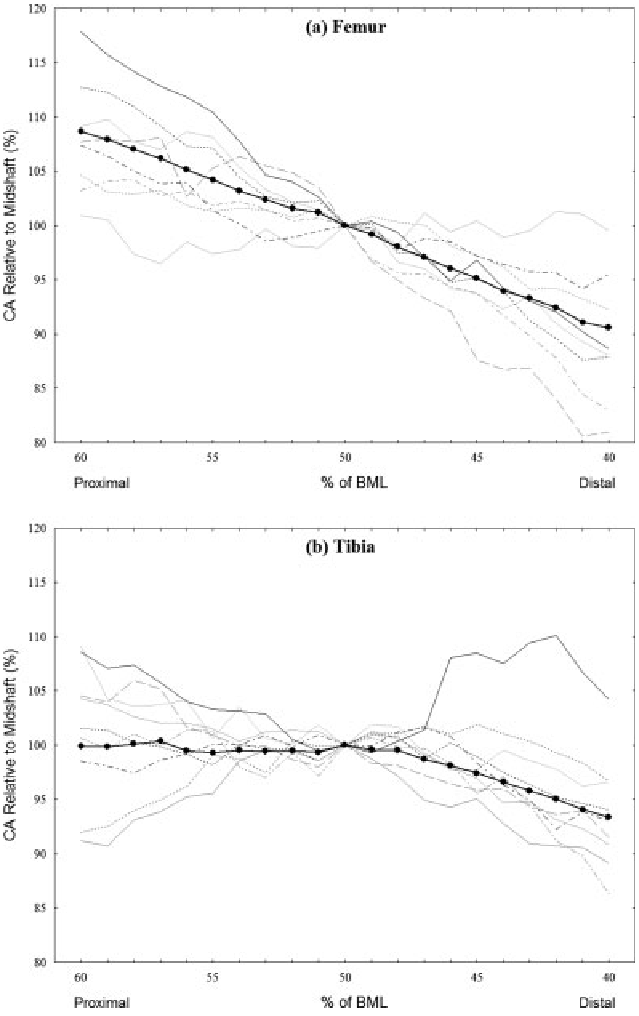

**Fig. 2.** Mean and selected individual distributions of CA relative to femoral (**a**) and tibial (**b**) midshaft. Mean distribution is indicated by solid square. (Individuals are selected to demonstrate different possibilities of obtained variations.)

There are slight contradictions between predicted (see Fig. 1) and observed (Figs. 2–4) errors for Pecos and Eneolithic or Bronze Age samples. This indicates that differences in morphology between populations, caused

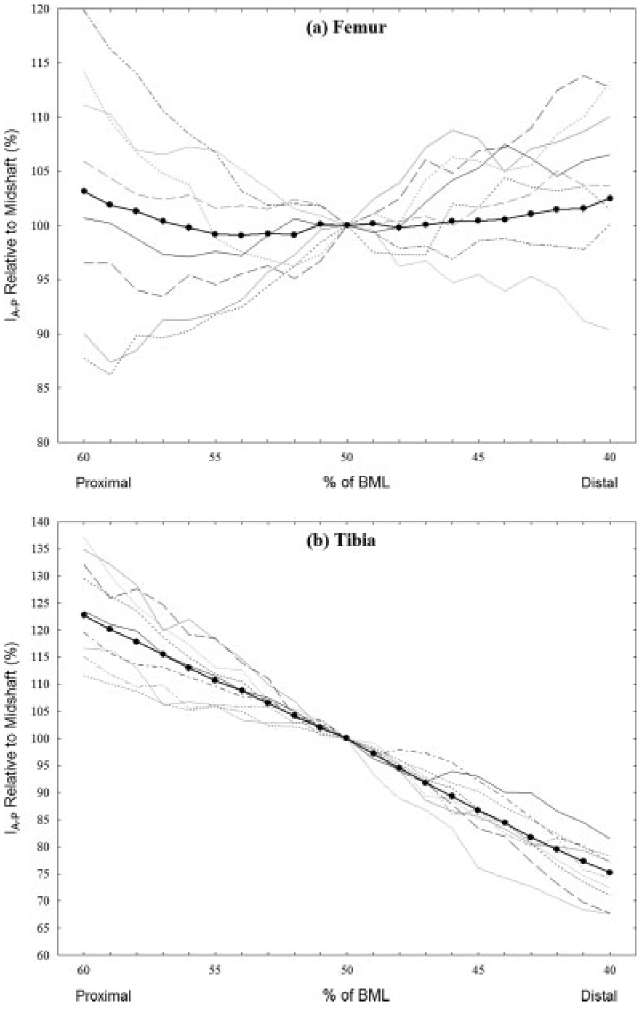

**Fig. 3.** Mean and selected individual distributions of $I_{A-P}$ relative to femoral (**a**) and tibial (**b**) midshaft. Mean distribution is indicated by solid square.

by environmental and genetic factors, would be expected to produce different mean accuracy ranges for estimated geometric properties. Similar variation has been found between individuals, which shows that obtained geometric properties can be estimated for some individuals with higher error than expected.

Individual variation in geometric properties is more important when fossil hominins with damaged bone are studied. Individual change of geometry near to midshaft can be so rapid that the wide mean accuracy range presented is unrealistic. When fossil hominins are studied, we recommend to specify how large an error we expect in locating the midshaft region by, for example, testing on a control sample with a known midshaft position as well as with simulation of the specific damage (e.g., the proximal and distal ends may be concealed in a manner that is similar to the studied individual). As the next step, we recommend to calculating error per mm from the location used for the midshaft and cross-sections 10 mm above and below the midshaft. If the error per mm indicates that properties change in the midshaft region only slowly (i.e., it results in a wide individual accepted range), then the fossil specimen can be interpreted with greater accuracy. On the other hand, if the

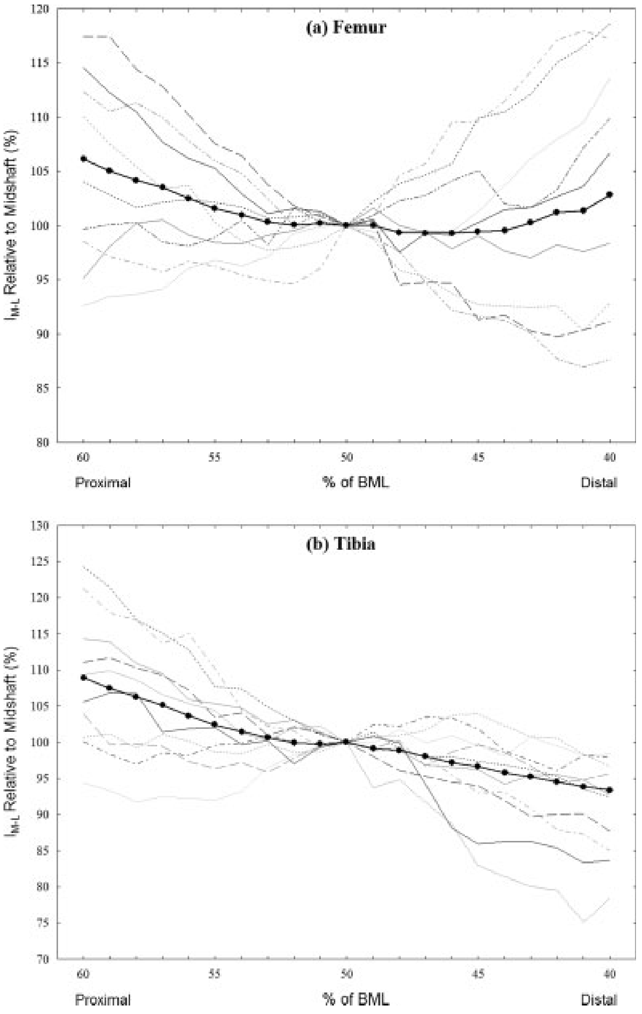

**Fig. 4.** Mean and selected individual distributions of $I_{M-L}$ relative to femoral (**a**) and tibial (**b**) midshaft. Mean distribution is indicated by solid square.

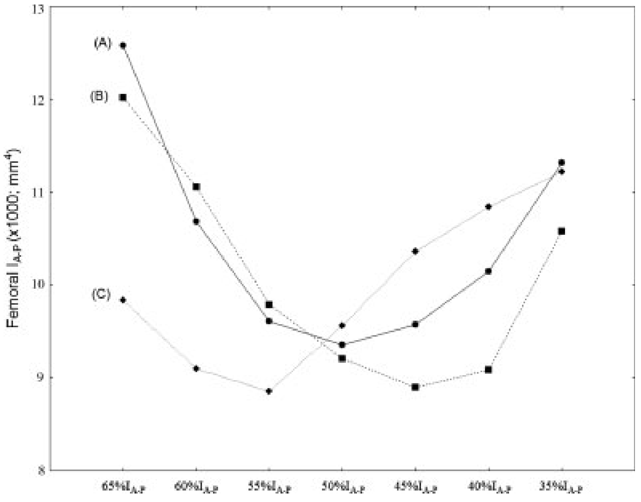

**Fig. 5.** The example of variability in pattern and magnitude near femoral midshaft for $I_{A-P}$. Three females from Late Eneolithic and Early Bronze Age are selected: Hainburg 119 (**A**); Hainburg 21 (**B**); Kněževes (BBC) 768 (**C**). The 5% BML interval is used from 65 to 35% BML.

*TABLE 4. Relative frequency for the position of minimum in the eneolithic/bronze age individuals*

| | Fe (% of individuals) | | | | Ti (% of individuals) | | | |
|---|---|---|---|---|---|---|---|---|
| %BML | CA | $I_{A–P}$ | $I_{M–L}$ | $J$ | CA | $I_{A–P}$ | $I_{M–L}$ | $J$ |
| 60% | | 3 | 7 | 3 | 3 | | 3 | |
| 59% | | 7 | | 3 | 3 | | | |
| 58% | | 3 | | | | | 3 | |
| 57% | 3 | 7 | | 3 | | | | |
| 56% | | 3 | 3 | | 3 | | | |
| 55% | | 13 | 7 | 13 | | | 3 | |
| 54% | | 3 | 3 | 7 | | | | |
| 53% | | 10 | 3 | 3 | | | | |
| 52% | | 7 | 10 | 10 | | | | |
| 51% | | | | | | | | |
| 50% | | | 10 | 13 | | | 3 | |
| 49% | | | 3 | | 3 | | | |
| 48% | | | 7 | 10 | | | | |
| 47% | | | 7 | | | | 3 | |
| 46% | | 7 | | | 3 | | 3 | |
| 45% | | | 10 | 3 | | | | |
| 44% | 3 | 7 | 3 | 7 | | | 3 | |
| 43% | | 3 | | | | | | |
| 42% | 3 | 3 | 7 | 7 | 10 | | 17 | 3 |
| 41% | 27 | 20 | 7 | 13 | 23 | 7 | 20 | 10 |
| 40% | 63 | 3 | 13 | 3 | 50 | 93 | 40 | 87 |
| Total | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |

*TABLE 5. Relative frequency for the position of maximum in the eneolithic/bronze age individuals*

| | Fe (% of individuals) | | | | Ti (% of individuals) | | | |
|---|---|---|---|---|---|---|---|---|
| %BML | CA | $I_{A–P}$ | $I_{M–L}$ | $J$ | CA | $I_{A–P}$ | $I_{M–L}$ | $J$ |
| 60% | 67 | 40 | 40 | 53 | 17 | 93 | 60 | 90 |
| 59% | 13 | 7 | 17 | 10 | 3 | 3 | 10 | 10 |
| 58% | 3 | | | | 7 | 3 | 3 | |
| 57% | 7 | | | | 10 | | 7 | |
| 56% | | | | 3 | 10 | | | |
| 55% | | | | | | | | |
| 54% | | | | | 3 | | | |
| 53% | 3 | | | | 7 | | | |
| 52% | | 3 | | | 3 | | | |
| 51% | | 7 | 3 | | 7 | | | |
| 50% | | 3 | | | 10 | | 3 | |
| 49% | | | 3 | | | | | |
| 48% | 3 | | | | 3 | | 3 | |
| 47% | | | | | 7 | | 7 | |
| 46% | | | | | | | | |
| 45% | | | | | 3 | | 3 | |
| 44% | | 10 | | | 3 | | | |
| 43% | | | | | | | | |
| 42% | 3 | | | | 7 | | 3 | |
| 41% | | 13 | 10 | 10 | | | | |
| 40% | | 17 | 27 | 23 | | | | |
| Total | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |

error per mm is large and the individual accepted range is too small then we can use error per mm for calculating an interval for respective geometric properties and use it for more accurate paleobiological comparison. Another possible approach when fossil bone length estimates are uncertain is to "bracket" section properties using a range of possible section locations in comparative samples or specimens (Ruff, 2009).

## CONCLUSION

On average, tibial CA and femoral second moments of area are the most accurately estimated cross-sectional parameters when the midshaft location is unknown. In contrast, tibial $I_{A–P}$ and $J$ are more susceptible to error due to midshaft location. Thus, for fragmentary individuals, we recommend being more cautious in interpreting tibial second moments of area. If tibial midshaft cannot be estimated within a 14- to 20-mm interval, then it should be considered whether to include the individual in the analysis. There is significant variation in the distribution of cross-sectional parameters between individuals and in central tendencies. Thus, individual error due to midshaft location may significantly vary in both pattern and magnitude compared to expected mean accuracy range. Furthermore, the position of minimum and maximum for each cross-sectional property varies between 60 and 40% of BML. We recommend for specific cases (e.g., fossil hominins with highly damaged femora or tibiae) to calculate error in midshaft location using comparative samples with similar damage patterns and error change per mm in midshaft region by three cross-sections with 10-mm distance. The resulting individual error range may help to define upper and lower limits for the cross-sectional parameters studied when a fragmentary individual is analyzed.

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## LITERATURE CITED

Altman DG, Bland JM. 1983. Measurement in medicine: the analysis of method comparison studies. The Statistician 32:307–317.

Bland JM, Altman DG. 1986. Statistical methods for assessing agreement between two methods of clinical measurement. Lancet i:307–310.

Day MH, Molleson TI. 1976. The puzzle from JK2-a femur and a tibial fragment (O.H. 34) from Olduvai Gorge, Tanzania. J Hum Evol 5:455–465.

Ernestová B. 2003. Metody rekonstrukce výšky postavy u zlomkovitých nálezů kostry. Master thesis, University of West Bohemia, Pilsen.

Haeusler M, McHenry HM. 2004. Body proportion of *Homo habilis* reviewed. J Hum Evol 46:433–465.

Hunter JS. 1980. The national system of scientific measurement. Science 210:869–874.

Jacobs K. 1992. Estimating femur and tibia length from fragmentary bones: an evaluation of Steele's (1970) method using a prehistoric European sample. J Forensic Sci 89:333–345.

McHenry HM. 1974. How large were the australopithecines? Am J Phys Anthropol 40:329–340.

McHenry HM. 1991. Femoral lengths and stature in Pliopleistocene Hominids. Am J Phys Anthropol 85:149–158.

McHenry HM, Berger LR. 1998. Limb lengths in Australopithecus and the origin of the genus Homo. S Afr J Sci 94:447–450.

Meloun M, Militký J. 1998. Statistické zpracování experimentálních dat. Praha: Plus.

Nakatsukasa M, Pickford M, Egi N, Senut B. 2007. Femur length, body mass, and stature estimates of Orrorin tugenensis, a 6 Ma hominid from Kenya. Primates 48:171–178.

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

Ruff CB. 1986. Use of computed tomography in skeletal structure research. Yrbk Phys Anthropol 29:181–196.

Ruff CB. 2000. Biomechanical analysis of archeological human skeletons. In: Katzenberg MA, Saunders SR, editors. Biological anthropology of the human skeleton. New York: Wiley-Liss. p 71–102.

Ruff CB. 2009. Relative limb strength and locomotion in *Homo habilis*. Am J Phys Anthropol 138:90–100.

Ruff CB, Hayes WC. 1983. Cross-sectional geometry of Pecos Pueblo femora and tibiae: a biomechanical investigation. I. Method and general patterns of variation. Am J Phys Anthropol 60:359–381.

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

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

Sailer R, Sládek V, Berner M. 2003. Computer tomography and calculation of bone biomechanics in cross-sections of long bones. Am J Phys Anthropol 120:182. (Abstract).

Simmons T, Jantz RL, Bass WM. 1990. Stature estimation from fragmentary femora: a revision of the Steel method. J Forensic Sci 35:628–636.

Sládek V, Berner M, Sailer R. 2006. Mobility in central European late eneolithic and early bronze age: femoral cross-sectional geometry. Am J Phys Anthropol 130:320–332.

Sokal RR, Rohlf FJ. 1995. Biometry. New York: W. H. Freeman.

Steel DG, McKern TW. 1969. A method of assessment of maximum long bone length and living stature from fragmentary bones. Am J Phys Anthropol 31:215–228.

Steele DG. 1970. Estimation of stature from fragments of long limb bones. In: Stewart TD, editor. Personal identification in mass disasters. Washington: National Museum of Natural History. p 85–97.

Stock JT. 2002. A test of two methods of radiographically deriving long bone cross-sectional properties compared to direct sectioning of the diaphysis. Int J Osteoarchaeol 12:335–342.

Stock JT, Shaw CN. 2007. Which measures of diaphyseal robusticity are robust? A comparison of external methods of quantifying the strength of long bone diaphyses to cross-sectional geometric properties. Am J Phys Anthropol 134:412–423.

Trinkaus E, Churchill SE, Ruff CB, Vandermeersch B. 1999a. Long bone shaft robusticity and body proportions of the Saint-Cesaire-1 Chatelperronian Neanderthal. J Archaeol Sci 26:753–773.

Trinkaus E, Ruff CB. 1989. Diaphyseal cross-sectional morphology and biomechanics of the Fond-de-Foret 1 femur and the Spy 2 femur and tibia. Bull Soc R Belge Anthropol Prehist 100:33–42.

Trinkaus E, Ruff CB. 1996. Early modern human remains from eastern Asia: the Yamashita-cho 1 immature postcrania. J Hum Evol 30:299–314.

Trinkaus E, Ruff CB. 1999. Diaphyseal cross-sectional geometry of near eastern middle palaeolithic humans: the femur. J Archaeol Sci 26:409–424.

Trinkaus E, Ruff CB, Conroy GC. 1999b. The anomalous archaic Homo femur from Berg Aukas, Namibia: a biomechanical assessment. Am J Phys Anthropol 110:379–391.

Trinkaus E, Stringer CB, Ruff CB, Hennessy RJ, Roberts MB, Parfitt SA. 1999c. Diaphyseal cross-sectional geometry of the Boxgrove 1 middle pleistocene human tibia. J Hum Evol 37:1–25.

Wright LE, Vasquez MA. 2003. Estimating the length of incomplete long bones: forensic standards from Guatemala. Am J Phys Anthropol 120:233–251.