Body Size Estimation of Small-Bodied Humans: Applicability of Current Methods

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KEY WORDS body mass estimation; stature estimation; Later Stone Age; southern Africa; foragers

ABSTRACT Body size (stature and mass) estimates are integral to understanding the lifeways of past populations. Body size estimation of an archaeological skeletal sample can be problematic when the body size or proportions of the population are distinctive. One such population is that of the Holocene Later Stone Age (LSA) of southern Africa, in which small stature (mean femoral length = 407 mm, n = 52) and narrow pelves (mean bi-iliac breadth = 210 mm, n = 50) produce a distinctive adult body size/shape, making it difficult to identify appropriate body size estimation methods. Material culture, morphology, and culture history link the Later Stone Age people with the descendant population collectively known as the Khoe-San. Stature estimates based on skeletal “anatomical” linear measures (the Fully method) and on long bone length are compared, along with body mass estimates derived from “morphometric” (bi-iliac breadth/stature) and “biomechanical” (femoral head diameter) methods, in a LSA adult skeletal sample (n = 52) from the from coastal and near-coastal regions of South Africa. Indices of sexual dimorphism (ISD) for each method are compared with data from living populations. Fully anatomical stature is most congruent with Olivier’s femur + tibia method, although both produce low ISD. McHenry’s femoral head body mass formula produces estimates most consistent with the bi-iliac breadth/stature method for the females, although the males display higher degrees of disagreement among methods. These results highlight the need for formulae derived from reference samples from a wider range of body sizes to improve the reliability of existing methods. Am J Phys Anthropol 141:169–180, 2010. © 2009 Wiley-Liss, Inc.
Material culture and morphological characteristics link the Holocene Later Stone Age foragers with the historic Khoe-San (Deacon and Deacon, 1999; Mitchell, 2002). Archaeological evidence for pastoralism is sometimes found in the coastal and near-coastal regions from about 2000 B.P. Despite some shifts in diet and possibly in mobility, analyses of Holocene Later Stone Age skeletons indicate homogeneity of skeletal morphology during this transition period (Stynder et al., 2007; Ginter, 2008; Stynder, 2008). Changes in skeletal morphology have been observed, subsequent to contact with Iron Age farmers (and subsequent Europeans) (Morris, 1992b). This occurred a few hundred years ago, variably through the region.

Given the importance of documenting patterns of body size in the history of human populations for our understanding of general health and physiological responses to stress, the ability to accurately estimate stature and body mass from skeletal remains is particularly important. Body size, both stature and mass, of individuals from past populations must be estimated from skeletal proxies. Stature can be estimated by “anatomical” and long bone regression (“mathematical”) methods. The best example of the anatomical approach is the Fully Technique (Fully, 1956; Raxter et al., 2006, 2007), which sums the vertical measurements of skeletal elements from a complete skeleton. Long bone regression methods, based on assumptions of proportionality, typically use lower limb length linear regression formulae (e.g., Trotter and Gleser, 1952; Olivier, 1976; Feldesman and Fountain, 1996). Two main approaches to body mass estimation are “biomechanical” methods using lower limb joint size, most commonly femoral head size (e.g., Ruff et al., 1991; McHenry, 1992), as a proxy for body mass, and “morphometric” methods which estimate mass from preserved elements that reflect body shape, including bi-iliac breadth and stature (Ruff, 1994; Ruff et al., 1997, 2005).

When estimating statures of a skeletal sample, it is important to match the body proportions of the study sample to those of the reference sample (Auerbach and Ruff, 2004); however, known-stature reference skeletal samples are few, and the variability within each is limited. Body size estimation will be less accurate when the bone sample, stature or body proportions differ from the reference samples. Later Stone Age people of southern Africa had small stature, illustrated by their short body mass and stature or body proportions differ from Ruff, 2004); however, known-stature reference skeletal samples to those of the reference sample (Auerbach and Ruff, 2004). Changes in skeletal morphology have been observed, subsequent to contact with Iron Age farmers (and subsequent Europeans) (Morris, 1992b). This occurred a few hundred years ago, variably through the region.

Because body mass and stature in life are not known for this archaeologically derived Later Stone Age sample, there are no “known” values against which to compare estimated statures. Instead, body size estimation methods will be evaluated by examining the consistency among the different methods. If similar size estimates are achieved using different methodological approaches, then the methods being compared can be considered robust with regard to differences in size and proportionality in target samples. Since living populations show sexual dimorphism with respect to stature and body mass, with larger values for males, the plausibility of stature and body mass estimates can also be assessed by examining the pattern and magnitude of sexual dimorphism that each method produces and comparing these results to the measured dimorphism of living populations. Since the body size and shape of Later Stone Age foragers is distinctive relative to those of reference samples from which stature and body mass estimation formulae have been derived, we hypothesize that our analyses will produce considerable variability in stature and body mass outcomes, reflecting the poor fit between the test sample and the reference samples. The disparities will inform our understanding of how accurate and precise such estimates can be, when target specimens are outside the normal range.

**MATERIALS AND METHODS**

Archaeologically derived, mid to late Holocene Later Stone Age (LSA) skeletons (F, n = 26; M, n = 26) from the coastal and near-coastal regions of South Africa were studied. Uncalibrated radiocarbon dates range from ca. 240 to 6180 BP (see Table 1). Skeletons dating prior to 2000 B.P. are reliably those of foragers. Skeletons with more recent dates include foragers and pastoralists, based on various combinations of archaeological context and isotopes reflecting diet. Sex and age at death estimates are based on traditional morphological indicators (e.g., Buikstra and Ubelaker, 1994). Skeletons are generally very complete and well preserved. Sex was assigned based on features of the pelvis (Phenice, 1969; Buikstra and Ubelaker, 1994) and skull (Buikstra and Ubelaker, 1994) (with preference given to pelvic indicators), and any individuals with ambiguous sex indicators were removed from the sample. Age at death was assessed using multiple methods where possible, including late fusing epiphyses (Buikstra and Ubelaker, 1994), cranial suture closure (Meindl and Lovejoy, 1985), as well as degenerative changes of the auricular surface (Lovejoy et al., 1985), sternal rib ends (Izcan et al., 1984, 1985) and pubic symphysis (Suchey and Katz, 1986; Brooks and Suchey, 1990). The overall condition of the skeleton, with respect to both age related degeneration and bone formation at the joint surfaces and the extent of dental wear, was considered in the final age estimate.

Stature was estimated using both anatomical (AN STE) and mathematical (MA STE) methods (Table 2). The Revised Fully Technique (Raxter et al., 2006, 2007) for anatomical stature estimation was applied, with age
correction. For the age correction procedure, individuals were categorized as: Young Adult (YA 20–34 years, \(n = 2\)), Middle Adult (MA 35–49 years, \(n = 13\)), and Old Adult (OA 50+ years, \(n = 2\)). Sample sizes are based on those individuals that are complete enough for anatomical stature to be calculated. Missing elements were estimated following the recommendations of Auerbach et al. (2005). Since the Revised Fully Technique reconstructs stature by summing measurements of the skeletal elements that comprise the vertical height of the individual (skull through foot), differences in body proportions are incorporated into the method (Raxter et al., 2006) making it applicable to populations whose body proportions are not represented in the reference samples used to develop the method. The need for complete and well-preserved skeletons is a limitation for the application of this method to archaeologically derived skeletal samples.

Three mathematical stature formulae based on linear regressions were also applied: Trotter and Gleser's

### TABLE 1. Uncalibrated radiocarbon dates and age categories of specimens in study sample

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Sex</th>
<th>Age category</th>
<th>C14 Date (B.P.)</th>
<th>Lab #</th>
<th>Citation</th>
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<tr>
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<td>YA</td>
<td>2010 ± 50</td>
<td>Pta-4376</td>
<td>3, 5</td>
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<tr>
<td>UCT 396</td>
<td>F</td>
<td>MA</td>
<td>2090 ± 60</td>
<td>Pta-4965</td>
<td>6</td>
</tr>
<tr>
<td>ALB 139</td>
<td>F</td>
<td>YA</td>
<td>5100 ± 70</td>
<td>Pta-8626</td>
<td>7</td>
</tr>
<tr>
<td>ALB 177</td>
<td>F</td>
<td>OA</td>
<td>390 ± 40</td>
<td>Pta-8584</td>
<td>7</td>
</tr>
<tr>
<td>ALB 178</td>
<td>F</td>
<td>OA</td>
<td>240 ± 45</td>
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<td>OA</td>
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<td>7, 10</td>
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<tr>
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<td>F</td>
<td>MA</td>
<td>430 ± 45</td>
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<td>YA</td>
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<td>MA</td>
<td>3754 ± 35</td>
<td>OxA-V-2055-4</td>
<td>9</td>
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<tr>
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<td>OA</td>
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<td>OA</td>
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<td>MA</td>
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<td>MA</td>
<td>2110 ± 45</td>
<td>Pta-8721</td>
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</tr>
<tr>
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<td>F</td>
<td>YA</td>
<td>1957 ± 26</td>
<td>OxA-15077</td>
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<td>Pta-2309</td>
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<td>2360 ± 20</td>
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<td>2310 ± 25</td>
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<td>3210 ± 70</td>
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<td>UCT 390</td>
<td>M</td>
<td>MA</td>
<td>ca. 2100</td>
<td></td>
<td>6</td>
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<td>UCT 254</td>
<td>M</td>
<td>MA</td>
<td>1270 ± 50</td>
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<td>UCT 386</td>
<td>M</td>
<td>MA</td>
<td>2000 ± 50</td>
<td>Pta-5283</td>
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<td>M</td>
<td>YA</td>
<td>540 ± 50</td>
<td>Pta-8677</td>
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<td>M</td>
<td>MA</td>
<td>4700 ± 60</td>
<td>Pta-5979</td>
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</tr>
<tr>
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<td>M</td>
<td>YA</td>
<td>5105 ± 20</td>
<td>Pta-8638</td>
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<td>YA</td>
<td>2640 ± 60</td>
<td>Pta-8636</td>
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<td>M</td>
<td>MA</td>
<td>350 ± 50</td>
<td>Pta-8671</td>
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<td>M</td>
<td>MA</td>
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<td>4445 ± 50</td>
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<td>UCT 199</td>
<td>M</td>
<td>MA</td>
<td>6180 ± 70</td>
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<td>1, 12</td>
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<tr>
<td>UCT 220</td>
<td>M</td>
<td>YA</td>
<td>2100 ± 21</td>
<td>Pta-5678</td>
<td>2</td>
</tr>
<tr>
<td>UCT 331</td>
<td>M</td>
<td>YA</td>
<td>2100 ± 70</td>
<td>Pta-3869</td>
<td>3</td>
</tr>
<tr>
<td>ALB 174</td>
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<td>YA</td>
<td>430 ± 50</td>
<td>Pta-8574</td>
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<tr>
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<td>MA</td>
<td>400 ± 50</td>
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<td>MA</td>
<td>1550 ± 20</td>
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<td>M</td>
<td>MA</td>
<td>2150 ± 60</td>
<td>Pta-4199</td>
<td>2, 3</td>
</tr>
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</table>

a Specimens housed at the following institutions: SAM: Iziko Museums of Cape Town; UCT: University of Cape Town; ALB: Albany Museum, Grahamstown; NMB and SS: Florisbad Research Station, National Museum, Bloemfontein.

b Age categories: YA, Young Adult (20–34 years); MA, Middle Adult (35–49 years); OA, Old Adult (50+)

**TABLE 2. Body mass and stature estimation formulae**

<table>
<thead>
<tr>
<th>Source</th>
<th>Estimation formula</th>
</tr>
</thead>
</table>
| Ruff et al., 2005                          | Females: \(BM = 0.504 \times ST + 1.804 \times LBIB - 72.6\)  
Males: \(BM = 0.422 \times ST + 5.126 \times LBIB - 92.9\) |
| McHenry, 1992                               | \(BM = 2.239 \times FH - 39.9\) |
| Ruff et al., 1991                          | Females: \(BM = (2.426 \times FH - 35.1) \times 0.9\)  
Males: \(BM = (2.741 \times FH - 54.9) \times 0.9\) |
| Raxter et al., 2006                        | \(ST = 1.009 \times SKH - 0.0426 \times age + 12.1\) |
| Trotter and Gleser, 1952                   | "White" Females: \(ST = 2.47 \times FLm + 54.10\)  
"Black" Females: \(ST = 2.28 \times FLm + 59.76\)  
"White" Males: \(ST = 2.38 \times FLm + 61.41\)  
"Black" Males: \(ST = 2.11 \times FLm + 70.35\)  
ST = 3.019390 \times FLm + 31.263362  
ST = 1.31 \times (FLm + TLm) + 55.3 |
| Feldesman and Fountain, 1996               |                    |
| Olivier, 1976                              |                    |

(1952) sex-specific femur formulae, Feldesman and Fountain’s (1996) “Generic” formula for the femur, and Olivier’s (1976) femur + tibia formula. Since the study sample cannot be categorized as “black” or “white,” stature was estimated using the Trotter and Gleiser method by averaging the statures calculated from their sex-specific “black” and “white” formulae (as per Pfeiffer and Sealy, 2006). Holliday (2002) and Auerbach and Ruff (2004) suggest that an average stature should be calculated when utilizing these formulae for North African and other mid-latitude populations. The LSA populations inhabited the coast of southern Africa at ~34° South, so this group represents a mid-latitude population from the Southern Hemisphere. As well, they display body proportions more similar to North Africans than to other low-latitude Sub-Saharan populations (Kurki et al., 2008).

None of the mathematical stature equations applied in this study are derived from samples with the body proportions of the LSA sample. The short femora of the LSA sample are generally outside the range of the samples used by Trotter and Gleiser, although there is some overlap between the smallest individuals of the reference samples and the largest individuals of the LSA sample. The stature estimates derived here all require extrapolation beyond the regression line. However, as comparable femur-based equations for mid-latitude populations are not available, the Trotter and Gleiser average approach may help address body proportion issues. Feldesman and Fountain’s (1996) “generic” formula (not their femur/stature ratio) was derived using a worldwide reference sample that, importantly for application to small-bodied samples, included Pygmy groups. The use of a worldwide reference sample including both sexes also means that differences in body proportionality among populations from differing geographical regions and between sexes are not accounted for. This provides an opportunity to compare the stature estimates based on a “generic” formula to stature equations derived from more specific reference samples. Olivier’s (1976) femur + tibia formula is used in this study because it was derived using a sample of African Pygmy males, representing a population more similar in body size and proportionality to the LSA and Khoi-san populations than other known-stature reference samples (although see Kurki et al., 2008).

Body mass was estimated for the skeletal sample using both biomechanical (FH BME) and morphometric (BIBST BME) methods (Table 2). Two biomechanical body mass estimation methods based on femoral head diameter were used: McHenry’s (1992) formula (as given in Auerbach and Ruff, 2004) and Ruff et al.’s (1991) formulae. McHenry’s reference sample included some Khoi-San skeletons, and was generated specifically for use in estimating mass of small-bodied hominins; it does not include sex-specific formulae, and is based on sex and population means. The LSA sample falls at the low end or outside the range of body mass encompassed by the reference sample used by Ruff et al. (1991) to derive their femoral head equations, therefore the application to this sample does represent extrapolation beyond the regression line. Because their body mass equation represents one of a very few alternatives to McHenry’s equation and was generated using a larger sample, examination of its applicability in this context is warranted. Morphometric body mass was estimated using Ruff et al.’s (2005) bi-iliac breath and stature formula. These formulae were generated using a worldwide reference sample that includes small-bodied Pygmy groups (Ruff, 1994, 1997; Ruff et al., 2005). Bi-iliac breath/stature body mass estimates were generated using each of the four stature estimation methods.

Stature and body mass were estimated for each individual in this sample using all of the applicable methods based on the skeletal elements preserved. Variability in sample sizes in the analysis reflects differences in element representation.

Several approaches were used to examine agreement between the stature and body mass estimates generated by the various formulae. For each individual in the LSA sample, the differences between each estimate of stature and of body mass were calculated, and the mean and range of differences in the sample were examined. Raw differences were calculated as (AN STE – MA STE) and (FH BME – BIBST BME); percentage differences were
TABLE 3. Summary statistics and raw and percentage differences among methods for stature estimation

<table>
<thead>
<tr>
<th></th>
<th>Anatomical-Mathematical</th>
<th>Fully Anatomical</th>
<th>Trotter and Gleser Mathematical</th>
<th>Feldesman and Fountain Mathematical</th>
<th>Olivier Mathematical</th>
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<tbody>
<tr>
<td></td>
<td>Mean (cm)</td>
<td>(SD)</td>
<td>N</td>
<td>Mean (cm)</td>
<td>(SD)</td>
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<tr>
<td>Living Khoe-San*</td>
<td>150.1</td>
<td>74</td>
<td>156.9</td>
<td>79</td>
<td>148.3</td>
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<tr>
<td>Females</td>
<td>1.4 (2.4)</td>
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<td>2.3 (1.3)</td>
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<td>3.5 (1.9)</td>
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<td>3.0 (2.0)</td>
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</tbody>
</table>

* Indicates difference between AN STE and MA STE is significant at P < 0.05 in the paired t-tests.

TABLE 4. Summary statistics and raw and percentage differences among methods for body mass estimation

<table>
<thead>
<tr>
<th></th>
<th>Femoral Head—Bi-iliac Breadth/Stature</th>
<th>Femoral Head</th>
<th>McHenry Femoral Headb</th>
<th>Trotter and Gleser Bi-iliac Breadth/Stature</th>
<th>Feldesman and Fountain Bi-iliac Breadth/Stature</th>
<th>Olivier Bi-iliac Breadth/Stature</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean (kg)</td>
<td>(SD)</td>
<td>N</td>
<td>Difference (kg)</td>
<td>% Difference</td>
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<td>3.2</td>
<td>19</td>
<td>0.6*</td>
<td>3.2</td>
<td>19</td>
</tr>
<tr>
<td>Males</td>
<td>1.5*</td>
<td>5.8</td>
<td>18</td>
<td>1.5*</td>
<td>5.8</td>
<td>18</td>
</tr>
</tbody>
</table>

* Indicates difference between FH BME and BIBST BME is significant at P < 0.05 in the paired t-tests.

RESULTS

Tables 3 and 4 provide the average differences for the stature and body mass estimations and the results of the paired t-tests, as well as body size data on historic Khoe-San taken from the literature. The anatomical and mathematical stature estimates are compared in Figures 1 and 2. The femoral head body mass estimates are compared with the bi-iliac breadth/stature body mass estimates in Figures 3 and 4. In each of the bivariate graphs (Figs. 1 and 3), the line of equivalency represents where an individual data point would fall if both methods of stature or body mass being compared produced the same value.

In the bivariate graphs (Fig. 1a–c) of stature estimation, all individuals fall below the line of equivalency, indicating that the stature estimates based on long bone lengths (MA STE) are larger than the anatomical stature estimates (AN STE). This is also illustrated in the box plot of percent differences (see Fig. 2) which indicates that overall the patterns of differences are similar for all formulae. The paired t-tests of the AN STE and MA STE are all significant, except for the male Olivier MA STEs, indicating that stature estimates using the mathematical approach are in general larger than those estimated with the anatomical approach. The females show slightly larger mean raw and percentage differences for the Feldesman and Fountain and Olivier MA STEs, although male differences are greater for Trotter and Gleser MA STEs. However, compared with the body mass analysis (see below), the raw and percentage differences between the estimates are relatively low; the largest difference for the males is –9.1 cm (–6.0%) using the Trotter and Gleser stature estimate, and for the females is –9.0 cm (–5.9%) using the Feldesman and Fountain stature estimate.

For body mass, the femoral head formulae (FH BME) tend to produce larger absolute values than the bi-iliac breadth/stature body mass estimates (BIBST BME), except for the females using McHenry’s FH BME formula. The BIBST BMEs usually fall above the line of equivalent body mass for the males of both FH BME formulae and the females of the Ruff FH BMEs (Fig. 3a-d). The mean raw and percentage differences are near zero.
for the female McHenry FH BMEs versus all of the BIBST BMEs (except using the Fully stature formula) (Table 4). In contrast, mean raw and percentage differences are all above zero, and all paired t-tests are significant for the male McHenry FH BMEs and both sexes of the Ruff FH BMEs. The males show considerable disagreement between FH BMEs and BIBST BMEs with mean percentage differences greater than 20% for all FH-BIBST BME comparisons. The box plots of percent differences between FH BMEs and BIBST BMEs (Fig. 4a,b) illustrate the large range of percent differences generated for the male comparisons in particular. The greater congruence between McHenry's FH BMEs and the Trotter and Gleser, Feldesman and Fountain, and Olivier BIBST BMEs of the females is also clearly demonstrated.

Examination of the level and pattern of sexual dimorphism in stature and body mass produced by the formulae provide another means of examining the reliability of these methods. The indices of sexual dimorphism (ISD) for each stature and body mass estimation method applied to the LSA sample are provided in Tables 5 and 6, respectively. These ISD values were calculated using the total sample of individuals for which stature could be estimated using the particular stature formula (compare mean statures from Table 3). These indices can be compared with levels of sexual dimorphism for other populations, including the historic Khoe-San, based on living stature (Table 5) and body mass data (Table 6).

The index of sexual dimorphism in stature for the historic Khoe-San sample (ISD = 0.069) is greater than the indices based on all of the estimated statures used in this study for the LSA sample (range = 0.033–0.050). The Feldesman and Fountain and Olivier stature estimation methods produce the lowest ISD values for all the groups compared in Table 5. Further, an
examination of the degree of overlap or separation of female and male data scatters in the bivariate graphs of stature (see Fig. 1) suggest very low levels of sexual dimorphism based on the estimated statures. However, an examination of the ISD values for other populations in Table 5 indicates that although LSA sexual dimorphism in stature is low for all stature estimation methods, several other populations (Mbuti, Bhutanese, Tolai, Highland, and Ok) fall within the LSA range, and that the overall range of ISD values for human groups is moderate but variable (range = 0.040–0.113 based on living stature data). In no living group examined, is mean female stature greater than mean male stature.

The indices of sexual dimorphism in body mass (Table 6) display a somewhat different pattern that more clearly identifies issues with some of the body mass estimation methods. The most apparent anomaly is that for all of the bi-iliac breadth/stature body mass estimation methods mean female body mass estimates are actually larger than male mean body mass estimates, resulting in ISD values of −0.017 to −0.075. Similarly, body mass estimated using Ruff and colleagues’ femoral head method results in a relatively low ISD (0.034). Although the Inuit index is also very low (ISD = 0.013), in none of the living groups is mean female body mass larger than mean male body mass. McHenry’s FH BMEs result in an ISD value (0.178) more comparable with those based on living group data (ISD range = 0.013–0.236). However, McHenry’s FH BME formula also increases the level of sexual dimorphism in the LSA sample relative to that of the raw skeletal measurements. For example, ISD values for the LSA sample femoral head diameter (0.096), femoral length (0.040) and bi-iliac breadth (0.004) are all lower than body mass ISD values when using this formula. In comparison, Ruff’s FH BME sex-specific formulae ISD are more consistent with skeletal element dimorphism.

Examining the data scatter pattern of individual body mass estimates, McHenry’s femoral head formula (see Fig. 3) produces more distinct female and male
groupings, suggesting a higher degree of sexual dimorphism in body mass, than do the Ruff FH BMEs. All of the bi-iliac breadth/stature body mass estimates produce considerable overlap of values between male and female groups. This high degree of overlap of male and female body masses illustrates the very low levels of sexual dimorphism in the sample, when using these body mass estimates.

**DISCUSSION AND CONCLUSION**

The applicability of various body size estimation methods to skeletal samples of unknown stature and body mass can be assessed by examining the consistency among stature and body mass estimation approaches that are based on different skeletal proxies. Comparisons of the stature estimation methods in this study have identified significant differences in the mean statures between the AN STE and all three MA STEs (except male Olivier MA STEs), yet the actual mean differences are relatively small (≤4.6 cm or 3.0%). Greater differences between body mass estimates relative to stature estimates are not unexpected since mass is proportional to stature cubed. The Fully anatomical stature method typically produces shorter stature estimates than the mathematical stature formulae.

In the estimation of body mass, the McHenry female FH BME shows a high degree of agreement with the BIBST BMEs for all four stature methods, although the males do not. The Ruff FH BME formulae produce significantly larger body mass estimates for both sexes. If we assume that BIBST BME is a good estimator of body mass, as suggested by Ruff and coworkers (Ruff, 1994; Ruff et al., 1997; Auerbach and Ruff, 2004), then the strong congruence between the McHenry FH BME and BIBST BMEs suggests that McHenry's formula is appropriate for the LSA females. The mean raw and percentage differences between FH BME and BIBST BME are generally high (except for the females using McHenry's FH method) in this study compared with a previous study using different and diverse samples (Auerbach and Ruff, 2004), although it is relevant to note that percentage differences were calculated in a different manner in that study, and so direct comparisons of values are not possible.

In that study, Auerbach and Ruff (2004) examined a worldwide collection of skeletal samples. Although most of the populations represented in their samples are large-bodied, two skeletal samples of small-bodied populations were included: the Andaman Islanders and African Pygmies. Although samples sizes are small (Andaman Islander female $n = 5$, male $n = 3$; Pygmy female $n = 4$, male $n = 1$), their study showed that these two small-bodied samples followed a similar pattern to that of the LSA sample in the current study. Namely, as with the LSA, McHenry's femoral head formula produced the most agreement between body mass estimates for the female Andaman Islander and African Pygmy samples (see their Fig. 2). Small-bodied individuals in their total sample show a lower difference between McHenry's FH BME and BIBST BMEs, relative to other FH formulae (see their Table 4). They concluded that McHenry's femoral head formula is the best for skeletal samples from populations at the small end of the body size range, if bi-iliac breadth/stature body mass estimates are not possible. The suggested explanation is that McHenry's samples included small bodied Khoe-San and Pygmy groups, whereas Ruff et al.'s (1991) sample was generally larger-bodied, therefore estimating body mass for small-bodied individuals using the Ruff FH formulae would require extrapolating beyond the reference sample range (Auerbach and Ruff, 2004). Since Ruff et al. (Ruff, 1988; Ruff et al., 1991, 1993) have shown the relationship between body mass and femoral head size is positively allometric, one would expect body mass estimations from femoral head size to overestimate true body mass in small-bodied people. Auerbach and Ruff (2004) did not address why the male and female samples of the small-bodied samples do not show the same pat-
TABLE 6. Indices of sexual dimorphism (ISD) in body mass for estimated body mass from skeletal samples and living groups of known body mass

<table>
<thead>
<tr>
<th>Sample</th>
<th>Male (kg)</th>
<th>Female (kg)</th>
<th>n</th>
<th>ISD</th>
</tr>
</thead>
<tbody>
<tr>
<td>S. African Later Stone Age</td>
<td>50.9 24</td>
<td>42.6 25</td>
<td>25</td>
<td>0.178</td>
</tr>
<tr>
<td>McHenry Femoral Head</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ruff Femoral Head</td>
<td>50.6 24</td>
<td>48.9 25</td>
<td>25</td>
<td>0.034</td>
</tr>
<tr>
<td>Trotter and Gleser</td>
<td>41.8 24</td>
<td>42.5 25</td>
<td>25</td>
<td>0.017</td>
</tr>
<tr>
<td>Bi-iliac breadth/stature</td>
<td>40.8 24</td>
<td>42.5 25</td>
<td>25</td>
<td>0.041</td>
</tr>
<tr>
<td>Bi-iliac breadth/stature</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Olivier Bi-iliac breadth</td>
<td>38.6 15</td>
<td>41.6 16</td>
<td>25</td>
<td>0.076</td>
</tr>
<tr>
<td>Fully Bi-iliac breadth</td>
<td>40.0 7</td>
<td>40.8 8</td>
<td>20</td>
<td>0.020</td>
</tr>
</tbody>
</table>

Living Groups

Khoi-San | 47.9 79 | 40.1 74 | 20 | 0.177 |
Sara | 66.8 na | 58.3 na | 17 | 0.136 |
Tutsi | 56.6 na | 52.8 na | 18 | 0.069 |
Mbuti Pygmy | 43.4 na | 38.2 na | 20 | 0.127 |
W. Aka Pygmy | 48.3 na | 42.7 na | 20 | 0.123 |
Sahalians | 59.3 na | 52.2 na | 18 | 0.127 |
Sudanic | 58.4 na | 51.4 na | 17 | 0.128 |
Bagandu/Isson | 54.6 na | 50.4 na | 18 | 0.080 |
Belgian | 66.9 na | 56.2 na | 17 | 0.142 |
Bulgarian | 67.0 na | 58.7 na | 17 | 0.132 |
Rumanian | 60.7 na | 53.9 na | 17 | 0.119 |
Inuit | 67.2 na | 66.3 na | 17 | 0.013 |
Aleut | 67.7 na | 53.4 na | 17 | 0.236 |
Japanese | 58.9 na | 49.9 na | 17 | 0.186 |
Kurdish Jews | 66.0 na | 59.7 na | 17 | 0.100 |
Yemenite Jews | 61.7 na | 51.1 na | 17 | 0.188 |
Karkar | 56.4 na | 47.0 na | 17 | 0.182 |
Lafa | 58.5 na | 49.2 na | 17 | 0.173 |
Austral. Aborig. | 56.7 na | 45.4 na | 17 | 0.221 |

a Index of Sexual dimorphism = (male − female)/(male + female)/2.
b Skeletal sample. Body mass reconstructed as indicated in text.
c Body mass estimation method.
d Living groups—data on body mass from: a. Truswell and Hansen (1976); b. Eveleth and Tanner (1976); c. Vincent et al. (1962) and Bailey (personal communication, cited in Ruff, 1994); d. Cavalli-Sforza (1986); e. Froment and Hiernaux (1984); f. Laughlin (1951) and Laughlin (personal communication, cited in Ruff et al., 2005); g. Abbie (1956–57).

All four stature estimation methods produce levels of sexual dimorphism that are similar to that reported for living groups. For body mass estimation, McHenry’s femoral head formula produces a level of sexual dimorphism that best reflects those of living groups, whereas several of the other body mass formulae (BIBST BME) produce unrealistic patterns (i.e., females > males) or very low levels of sexual dimorphism (Ruff’s FH BME) relative to living groups. The difference in the ISD values between McHenry’s femoral head formula and Ruff’s may be amplified by the fact that McHenry’s formula is used for both sexes, whereas Ruff’s formulae are sex-specific. Given the positive allometry of femoral head size relative to body mass (see above), using the same formula for both sexes would have the effect of exaggerating the body mass of the males, since they tend to have larger femoral head diameters relative to the females. When the pooled sexes formulae provided by Ruff et al. (1991) is applied to the LSA sample, the resulting ISD (0.136; male mean body mass = 56.5, female mean body mass = 49.3) is closer to the ISD of McHenry’s formula.
Because of the small number of specimens in the LSA sample that are complete enough for Fully Anatomical stature to be calculated, it is pertinent to consider how representative these individuals are of the total sample for each sex. If these Fully individuals are skewed toward the larger or smaller ends of the female or male body size range of the total LSA sample, then this could have a significant impact on the results, particularly the indices of sexual dimorphism. This was investigated (results not shown) by dividing the females and males into two groups, the Fully individuals and non-Fully individuals (the rest of the specimens) for each sex, and comparing mean estimated stature and body mass. While the Fully individuals of both sexes are scattered throughout the body size ranges, mean stature and body mass are slightly larger relative to the non-Fully individuals. Because both sexes show the same pattern, the indices of sexual dimorphism would not be affected.

The goal of this study was to examine whether current body mass and stature estimation methods can produce consistent and accurate results when applied to the Later Stone Age sample given that most estimation formulae have been generated using reference samples of larger body size and differing body proportions. The results suggest the following:

1. On the basis of the criterion of repeatability in stature estimation using different skeletal proxies, the Fully and Olivier formulae are most appropriate for the small-bodied LSA population of southern Africa. However, the differences among all four stature estimation methods in general, while statistically significant, are not large.

2. Although there is often a high degree of variability in the body mass estimates generated by the various formulae for a given specimen, McHenry’s femoral head formulae is most appropriate for application to this sample. These results validate the recommendations made by Auerbach and Ruff (2004) for very small-bodied individuals.

3. Although McHenry’s femoral head formula is generally the best for application to small-bodied samples based on the factors outlined above, it appears to overemphasize sexual dimorphism relative to raw skeletal measures. This may be an important consideration where body mass estimates are used to investigate sexual dimorphism, either to standardize other measurements to body size, or in allometric comparisons.

Several questions arise from these results. What role does the very narrow pelvic breadths of the LSA sample (female mean = 209 mm (SD = 15.7), n = 26; male mean = 210 mm (SD = 18.1), n = 24) play in influencing the reliability of bi-iliac breadth/stature body mass methods? Would this factor also apply to estimations for other small-bodied human samples? A recent study by Kurki (2007) suggests that narrow pelves are not characteristic of all smaller bodied populations. When the data from Auerbach and Ruff (2004) is considered, a similar pattern is found for the Andaman Islander sample to that seen in the LSA sample in this study. Is there a systematic difference in the relationship between body mass and body breadth in the small/narrow males, such as those of the LSA and Andaman Islander samples? It is important to note that the bi-iliac-breath/stature body mass estimation formulae were developed using a worldwide sample, including small-bodied, but not narrow-bodied, African Pygmy samples (Ruff, 1994). These questions may be addressed through an examination of the relationship between body mass and body breadth at the small end of the human body size range to help us to better characterize the range of human variation and improve our understanding of early hominins.

It is always appropriate to compare methods with consideration of accuracy and reliability in mind, since most methods will work better for some samples than for others. The results of this study, when considered in combination with the patterns seen for small-bodied populations in the study by Auerbach and Ruff (2004), suggest that body mass estimation for individuals from small-bodied populations is particularly problematic. This study highlights the challenges associated with the absence of body mass and stature estimation formulae that have been generated from reference samples of smaller overall body size, and of varying body proportions.

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