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PAPER

ANTHROPOLOGY

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The Effect of Weight on the Femur: A Cross-Sectional Analysis*

ABSTRACT: This study assessed whether obesity significantly affects femoral shape. Femora of 121 white men were divided into two weight classes based on body mass index (BMI) of the deceased. Five external anteroposterior (AP) and mediolateral (ML) measurements were taken at consistent percentages of diaphyseal length. These were then subject to statistical tests. After controlling for age, multivariate statistics show a significant ($p < 0.05$) effect of BMI on the femur, with the greatest significance in ML measurements. *T*-tests confirm these dimensions are significantly larger in the overweight ($p < 0.05$). The effect of BMI on size-transformed and shape-transformed variables was also evaluated, with ANOVA results showing a significant BMI effect on ML size ($p < 0.05$), but not shape. Significant size-transformed ML variables were then subject to discriminate function analyses with a cross-validation correction. Results show a correct classification rate of 88% in normal weight and 77% in overweight individuals.

KEYWORDS: forensic science, forensic anthropology, obesity, long bones, cross-section, bone functional adaptation

For the last 30 years, obesity has increased steadily and rapidly in all age and sex categories among white, black, and Hispanic people of Mexican origin in the United States (1,2) despite widespread knowledge of associated health effects (3,4). Some reports state the percentage of overweight Americans is as high as 66% (5) with no indication these rates will decline (6). Growing attention has been paid to the impact that obesity has on biomechanical action with regard to both mechanical load and to the compensatory acts utilized to deal with this increased load. However, aside from noting correlations between obesity and osteoarthritis (7,8) or general attempts to estimate body mass (9–11), little attention has been paid to the observable pattern that obesity may leave on the human skeleton. The high prevalence of obesity, a condition that clearly affects how an individual appeared in life, has ramifications that extend into both public health sectors and forensic biological profile determinations. Therefore, any information regarding weight that could be gleaned from skeletal remains has great promise to aid in identification efforts.

This project sought to assess the relationship between weight and external properties of the femur. Specific attention was spent searching for any key differences in bone shape between weight categories grouped by body mass index (BMI). Although there remains some debate regarding the impact of genetics on bone shape (12), a theory of bone functional adaptation or "BFA" is generally accepted and was used as the model for this research (13). Key hypotheses of BFA hold that when a bone is subject to strain levels that exceed bone design threshold, cellular components can enact synchronized resorption and deposition of bony matrix. This process results in an altered bone shape designed to best handle strains placed upon it (13,14). Therefore, if stresses associated with biomechanical modifications of the obese surpass the strain threshold of a bone or bony location, it is possible that discernible differences in long-bone morphology could be observed between different weight categories as a direct result of long-term, *abnormal* mechanical compensation.

Materials and Methods

Sample

The Hamann–Todd collection (dating from 1912 to 1938) was selected for analysis because of the large number of individuals for which both weight and stature were recorded, allowing calculation of BMI. Because bone density (and presumably, cross-sectional geometry) is known to be influenced by many factors including age, sex, pathology, pregnancy, nutritional deficiencies, genetics, and activity level (15), it was necessary to restrict the sample to avoid as many biases as possible. Therefore, only men of European ancestry were examined as they were best represented in this collection. Skeletons displaying pathology were not included for analysis, and both BMI categories had very similar age distributions.

BMI was calculated according to a standard equation provided by the Centers for Disease Control (16):

$$\mathrm{BMI} = \text{weight in kg}/(\text{height in m})^2$$

To maintain sample sizes large enough for statistical analysis, individuals who were classified as obese or overweight were collapsed into one category. Because BMI scores occur on a continuous scale and because of questions regarding the validity of BMI for use in the determination of fitness, individuals given

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"intermediate" BMI scores (the highest normal weight or lowest overweight values) were excluded from analysis to ensure each sample group was distinct. Therefore, the designation "overweight" was used for individuals with a calculated BMI greater than or equal to 26.5. Individuals with a BMI between 19.5 and 24.5 were classified as "normal weight." The total sample size was 121 individuals, 64 of whom were overweight and 57 normal weight. The mean age of the sample is 49.89 with a range of 24–82.

Measurements

To evaluate possible changes in diaphyseal shape or size between BMI classes, cross-sectional geometry of the femoral shaft was evaluated. These geometric properties have been popular in anthropological activity assessments since a standardized means of analysis was introduced by Ruff in 1981 (11,17–25). Although previous cross-sectional analyses have utilized numerous techniques (e.g., physical sectioning, radiographic measurements, or computed tomography) and properties (e.g., total area, cortical area, ratios, minimum and maximum dimensions), this project was designed to use noninvasive techniques that were easily employed with instruments common in both laboratory and field settings. While interior geometry of the diaphysis is often included in cross-sectional analyses, a review of the literature indicates a strong correlation between external measurements and interior morphology (26–28). Therefore, only external measurements of the diaphyseal anteroposterior (AP) and mediolateral (ML) dimensions were used.

The femur was positioned according to Ruff (17) by placing the dorsal surface directly onto an osteometric board with the distal aspect of the lesser trochanter and the area immediately proximal to the femoral condyles aligned in the same plane when viewed medially (Fig. 1). Clay was used to properly orient and secure the bone. To create a series of measurement locations that were consistent between femora, diaphyseal length was determined to run from the distal-most point of the femur to the site at which the femoral neck contacts the greater trochanter. Because this length does not include the femoral head and neck, measured locations avoid the morphological complexities of the proximal-most and distal-most ends. Sliding calipers were used to measure the AP and ML dimensions at 20%, 35%, 50%, 65%, and 80% diaphyseal length, measuring from the distal end proximally. These calipers were also equipped with a small T-shaped level to ensure the dimensions measured were exact and consistent between femora.

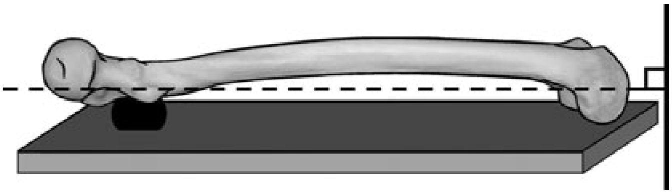

FIG. 1—*Orientation of the femur.*

Statistics

A Pearson's product-moment correlation coefficient was used to examine the relationship between weight (lbs) and stature.

An analysis of variance (ANOVA) was conducted to examine the effect of age, BMI, or an interaction on cross-sectional properties of the femur. Locations for which a significant effect of either age or BMI was reported were then subject to a *t*-test using Fisher's protected least significant difference (LSD) correction for uneven sample sizes to evaluate which BMI or age classes were significantly different.

Because of the confounding effect of size, the properties of size and shape were evaluated to determine whether they were significantly affected by age, BMI, or both. Using standards devised by Mosimann and James and Darroch and Mosimann (29,30), size and shape variables were computed; however, they were not log transformed. These were then subjected to ANOVA tests to examine the effect of age and BMI on these variables. A canonical discriminant function was performed on significant size-transformed variables to further examine differences among BMI classification. The leave-one-out or cross-validation method was used for classifying normal weight and overweight individuals. All statistical tests were performed using the SAS System for Windows Version 9.1.3 (SAS Institute) (31).

Results

The Pearson's product-moment correlation coefficient results show no correlation between weight and stature ($r = -0.114$,

TABLE 1—*ANOVA results for femoral anteroposterior (AP) and mediolateral (ML) dimensions.*

			AP Femur		ML Femur	
Location (%)	Variable	d.f.	*F*	*p*-Value	*F*	*p*-Value
20	Age	2	0.96	0.328	2.42	0.093
	BMI	2	0.77	0.465	3.58	0.061
	Age × BMI	4	1.10	0.337	0.27	0.766
35	Age	2	0.58	0.448	2.93	0.057
	BMI	2	0.92	0.402	7.69	**0.007
	Age × BMI	4	0.59	0.555	0.54	0.585
50	Age	2	2.38	0.126	1.98	0.143
	BMI	2	2.39	0.096	7.22	**0.008
	Age × BMI	4	2.83	0.063	0.65	0.525
65	Age	2	2.14	0.147	2.75	0.068
	BMI	2	3.59	*0.031	6.43	*0.013
	Age × BMI	4	1.27	0.284	0.32	0.727
80	Age	2	3.37	0.069	1.40	0.251
	BMI	2	2.86	0.062	6.24	*0.014
	Age × BMI	4	0.64	0.530	1.33	0.268

BMI, body mass index.
*Significant at *p*-value <0.05, **significant at *p*-value <0.01.

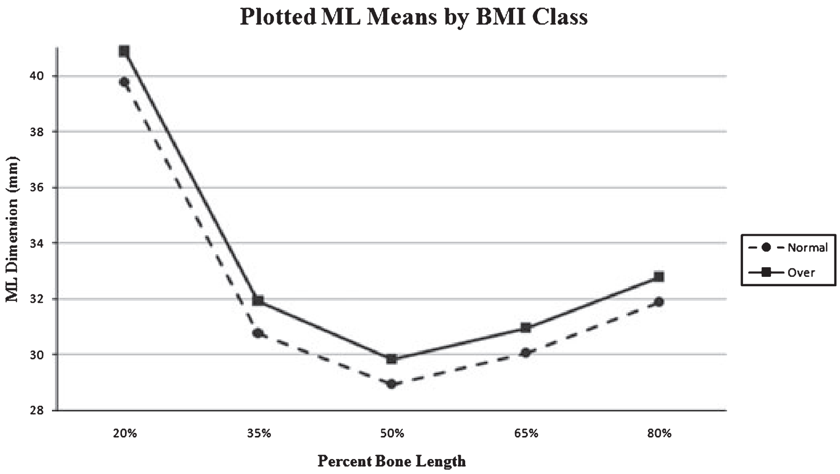

FIG. 2—*Mean ML measurements of the femur from distal (20%) to proximal (80%) locations.*

$p = 0.215$). Results of the ANOVA for AP and ML dimensions are summarized in Table 1. At all 10 sites evaluated (AP 20%, 35%, 50%, 65%, 80% and ML 20%, 35%, 50%, 65%, and 80%), there was no significant age × BMI interaction, allowing each effect to be analyzed separately. Additionally, no significant effect of age was reported for any dimension.

Results of the ANOVA showed a significant BMI effect at the 35% ($F = 7.69$, $p = 0.007$), 50% ($F = 7.22$, $p = 0.008$), 65% ($F = 6.43$, $p = 0.013$), and 80% ($F = 6.24$, $p = 0.014$) ML regions, and only the 65% AP region ($F = 3.59$, $p = 0.031$). Results of *t*-tests confirm these dimensions are significantly larger in the overweight BMI category (*p*-value <0.05) when compared to the normal weight category. See Fig. 2 for plotted ML measurement means by BMI class.

The ANOVA results on size-transformed and shape-transformed variables show that BMI has a significant effect on overall ML size ($F = 9.31$, $p = 0.003$) but not AP size ($F = 2.62.$, $p = 0.077$). However, results of the MANOVA on shape-transformed variables show no significant effect of BMI on bone shape in either AP or ML dimensions.

One significant canonical root was derived using two highly significant ML dimensions (ML50 and ML35) and size (Table 2). Approximately 100% of variation is accounted for in CAN1. The total canonical structure presented in Table 3 indicates that the variation on the first canonical axis is mainly associated with size, followed by ML shape at the 50% (mid-shaft) region. The total classification accuracy is 82.5% (88% for normal weight and 77% for overweight).

Discussion and Conclusion

Femoral ML increases have been previously reported in the literature. Stein et al. (32) found that after controlling for height, only the ML dimension of the femoral mid-shaft displayed significant weight effects. Ruff (20) also found ML increases in proximal femora of women, presumably because of alterations of the femur to compensate for increased pelvic width. Interestingly, research has also shown elongation of the proximal ML dimension of the femur in pregnant women (33). As ML diameter measures resistance to ML bending, these results suggest that as weight increases, alterations to the femoral angle result in greater ML pressures, forcing the femur to adapt or risk failure. To evaluate whether these changes were consistent with biomechanical differences between BMI classes, research from biomechanical studies was evaluated to discern alterations made by overweight individuals, specifically targeting those behaviors that might result in increased ML loading of the femur.

TABLE 3—*Total canonical structure for transformed variables (ML35, ML50) and size.*

Variable	Can1
ML35	0.820
ML50	0.931
Size	−0.971

Biomechanical Research on Obesity

Biomechanical studies of the obese centered on two main actions: sit-to-stand (STS) movements and gait analyses. When evaluating the differences in STS motions of obese individuals rising from a chair without use of their arms, researchers found that overweight individuals slide their feet dorsally before rising to limit flexion of the torso and lighten loads on the lower back (34–36). This is in contrast to normal weight individuals, who decreased the angle of the torso and refrained from moving their feet. Because higher trunk flexion correlates with higher hip joint forces (34), the tendency of obese individuals to decrease trunk angle actually reduces hip torque when compared to normal weight individuals. This makes BMI remodeling of the femur difficult to explain, as hypothetically, if strain is limited then bone stress thresholds will not be surpassed and will not trigger remodeling responses.

In an analysis of gait in normal and overweight men, Spyropoulos et al. (37) found that overweight individuals displayed several key

TABLE 2—*Significant canonical axes for transformed variables (ML35, ML50) and size.*

No.	Eigenvalue	Cumulative %	Proportion	Canonical Correlation	Likelihood Ratio	Approximate *F*	d.f.	Pr > *F*
1	0.0839	1.000	1.000	0.278	0.9226	3.27	117	0.024

differences in walking strategy. For example, obese individuals had a step width twice that of normal weight individuals, resulting from greater abduction of the hip throughout all stages of the walking cycle. Increased step width in the obese was also found in gait-speed analyses (38). Increased hip abduction presumably occurs to cope with excess adipose tissue of the inner thigh and/or to maintain balance (37–39).

Gait analyses using pressure mats have also concluded ground reaction forces (GRF) in obese individuals were greater than normal controls in both vertical, AP, and ML directions, with the most extreme differences in the latter (38). While increase in the AP plane of obese individuals would be expected because of greater force impacting the heel as it strikes and required of the toe for pushing off, changes in the ML direction are more difficult to explain on the basis of carrying weight alone. In fact, an increase in the ML plane suggests that obese individuals strike the ground in an entirely different manner than do normal weight individuals. An increase in ML force could be associated with some of the aforementioned biomechanical differences, most notably increased step width. Additionally, it has been reported that obese individuals have increased ankle eversion at many stages throughout the walking cycle, resulting in greater loads on the medial side of the foot (1).

Studies have also found that obese individuals spend more time in stance and less time in swing motion than did normal weight individuals (1,40), therefore exposing lower limb bones to longer periods of stress. Browning and Kram (38) found that while vertical and AP GRF increased linearly with weight, ML forces exceeded this proportion, with obese individuals having an ML GRF over 80% greater than those observed in normal weight controls. This drastic increase in ML GRF caused by adiposity, coupled with increased loading, associated kinematic alterations of step width, knee torque, increased stance length, and ankle eversion may all help explain ML elongation of the femur in the overweight.

Although research shows that obese individuals alter angles of joint placement to cope with added weight (1), gait analyses also show that while walking, knee and hip flexion/extension is not as strong in obese individuals as in normal weight individuals (40). While it would seem acceptable to assume that greater muscular contraction (resulting in more forceful joint movements) would result in more rapidly pronounced changes to bone structure, past research in bone remodeling shows that very little change is required to begin the remodeling process. In fact, Rubin and Lanyon (41) found that as few as four cycles per day of under-average, abnormal load was sufficient to maintain bone mineral rates and that 36 cycles was sufficient to enact peak bone remodeling rates of the periosteum in rooster ulnae. The influence of abnormal loads and stress-induced remodeling thresholds is also addressed in other bone remodeling research (14,42). Therefore, because obese people display abnormally high rates of hip abduction owing to increased step width, it is possible that even subaverage levels of mechanical action (as might be expected given greater expectation of inactivity in the overweight) with associated "buffering" compensations to torque might be strong enough to elicit a remodeling response in the femoral shaft. This might also explain the lack of response in the distal-most femur as knee joint angle and torque did not significantly differ between obese and normal weight individuals (40).

An exploration into biomechanical research in obesity shows numerous significant differences in walking strategy between overweight and normal weight individuals. These compensatory acts may alter force movement pathways and magnitudes through the femoral diaphysis, triggering ML elongation through BFA. While this research is still intended to be a first step, these results do show promise in future efforts to identify obesity using skeletal remains and further highlight the multifaceted nature of long-bone cross-sectional properties. Given these results, future research on a more contemporary or forensically appropriate sample is warranted.

In conclusion, results of the cross-sectional analysis show that ML dimensions of the femur in overweight individuals are significantly larger. In addition, the high-percent correct classification for the transformed ML dimensions suggests that normal weight and overweight individuals can be classified correctly, which would add an important aspect to our current biological profile tool kit.

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