

Bone and fat relationships in postadolescent black females: a pQCT study

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Abstract

Summary Despite adolescent black females experiencing the highest rates of obesity, the effect of excess fat mass on bone structure and strength in this population is unknown. Our findings in postadolescent black females suggest that excess weight in the form of fat mass may adversely influence cortical bone structure and strength.

Introduction Although adolescent obesity has been associated with reduced bone structure and strength in white females, this relationship has not been studied in adolescent black females, a population experiencing the highest rates

of obesity. Our objective was to compare bone structure and strength between postadolescent black females with normal and high levels of adiposity.

Methods Black females with $\leq 32\%$ body fat were classified as normal body fat (NF; $n=33$, aged 19.3 ± 1.3 years); females exceeding this cutoff were classified as high body fat (HF; $n=15$, aged 19.0 ± 1.1 years). Using peripheral quantitative computed tomography, tibial and radial bones were scanned at the 4% (trabecular) and 20% (cortical) sites from the distal metaphyses. Fat-free soft-tissue mass (FFST) and %body fat were assessed by dual-energy X-ray absorptiometry.

Results After controlling for either FFST or body weight, the HF vs. NF group had lower total cross-sectional area (CSA; 9–17%), cortical CSA (6–15%), and strength–strain index (SSI; 13–24%) at the cortical site of the tibia (all $p<0.05$). At the cortical site of the radius, the HF vs. NF group had lower total CSA (14%, $p=0.03$), cortical CSA (9%, $p=0.04$), and SSI (15%, $p=0.07$) after control for body weight. There were no group differences in either the FFST-adjusted cortical bone values at the radius or in the trabecular bone parameters (body weight- or FFST-adjusted) at the tibia and radius.

Conclusions Consistent with our adiposity and bone data in late-adolescent white females, our findings in black females entering adulthood also suggest that obesity may adversely influence cortical bone strength.

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Introduction

As the evidence linking childhood obesity to skeletal fractures is mounting [1–7], being overweight may be

associated with suboptimal bone growth and development. Determining whether adiposity is either beneficial or detrimental to the growing skeleton has been challenging. For instance, some reports indicate that childhood obesity is associated with greater bone mass at the spine, hip, and total body, even after adjustment for height, sexual maturation, and lean mass [8–11]. Others conclude that obesity is linked to lower bone mass or that extra weight from fat mass had no effect on bone mass [12–14]. Discrepancies in these results may be attributed, in part, to the limitations of using dual-energy X-ray absorptiometry (DXA) when studying the pediatric skeleton [15]. Since DXA-derived bone outcomes are two-dimensional and measure only integral bone, they are confounded by differences in bone and body size and do not differentiate between trabecular and cortical compartments.

Using three-dimensional bone-imaging techniques, such as quantitative computed tomography (QCT) or peripheral QCT (pQCT) to assess skeletal strength in the study of pediatric bone–fat relationships, researchers have shown that fat mass does not provide additional weight-loading benefits to either trabecular bone density at the spine [16] or cortical bone geometry at appendicular skeletal sites [17, 18]. In a 16-month investigation, Wetzsteon et al. [19] found that change in strength–strain index, a pQCT-derived measure of torsional bone strength [20], was associated with change in muscle mass, but not fat mass in overweight children. Taken together, these findings support Frost’s mechanostat theory that the bone adapts primarily to dynamic forces produced by muscle and not static forces imposed by the extra weight of fat [21]. Why bone seems to adapt only to muscle mass and not fat mass is unclear.

Because obesity rates are highest in young African American females, a limitation of the aforementioned bone–fat investigations was that study participants were predominately white children and adolescents. The National Health and Nutrition Examination Survey, 2003–2006, estimated that the overweight prevalence among black females, aged 12 to 19 years, was almost double the rate for white females (28% versus 15%) [22]. If obesity has a negative impact on bone, skeletal health in this population could be a public health concern. However, this notion might seem incongruous given that postmenopausal black females experience fewer fragility fractures than do white females [23]. Racial differences in fragility fractures are thought to be the result of a stronger skeleton in black vs. white individuals that seems to be present in childhood and tracks into adulthood [24–26]. It is possible that the high obesity rates in blacks could be a contributing factor to the racial differences in fracture risk. Since fat mass is a component of body weight, it is plausible that adiposity could induce a stronger bone in blacks because of the extra

weight it imposes on the skeleton [27]; however, this proposition warrants further investigation.

In the only investigation to date of the bone–fat relationship in African American youth, Afghani and Goran [28] linked visceral obesity, assessed by QCT, to lower total body bone mass, measured by DXA, in prepubertal black children. Although this finding proposes a potential concern for bone health in a population experiencing high rates of obesity, further work is warranted. In a previous investigation [17], we determined associations between adiposity and pQCT-derived bone parameters in 115 late-adolescent females; however, only two of the participants were of the African American race. As a result, we sought to investigate in a larger sample of black females entering adulthood the effect of adiposity on bone structure and strength. Therefore, in this study, we compared tibial and radial bone structure and strength parameters between two adiposity groups defined as having normal and high levels of body fat. Since muscle size and skeletal size are known to be strong predictors of bone [29–32], it is possible that they may confound the connection between fat and bone. Accordingly, we took into consideration muscle and/or skeletal size as potential confounders in this investigation of the bone–fat relationship.

Methods

Study participants

African American female college students ($N=48$; aged 18 to 22 years) attending University of Georgia (UGA) were used in this investigation. We elected to include black females only and the specific age range in order to minimize any confounding effects from race, sex and pubertal maturation on the bone outcome variables. Black or African American race was determined by self-report, in accordance with the National Institutes of Health Policy and Guidelines on the Inclusion of Women and Minorities as Subjects in Clinical Research [33]. All participants must have reported normal menstruation (e.g., greater than or equal to four menstrual periods in the last 6 months) for inclusion in the study. Participants were excluded if they reported significant weight loss or gain in the past 6 months ($\pm 10\%$ initial body weight), participation in competitive high-school (grade 9–12) or college athletics, diagnosis of eating disorders, prior skeletal fracture, present illness or chronic disease and/or use of oral contraceptives, dietary supplements or medications known to affect body weight, body fat, or bone metabolism. Procedures were approved by the Institutional Review Board for Human Subjects at UGA, and all participants provided written consent.

Anthropometry

Height and body weight measurements were collected by a trained laboratory technician. Participants were measured for height and weighed in light indoor clothing following the removal of shoes. Height was measured to the nearest 0.1 cm using a wall-mounted stadiometer (Novel Products Inc., Rockton, IL). Body weight was measured to the nearest 0.1 kg using an electronic scale (Seca Bella 840, Columbia, MD). Prior to testing each week, the scale was checked for accuracy using known weights. Recalibration of the scale was not required during the testing sessions. Limb lengths were measured with anthropometric tape (Rosscraft, Inc) to the nearest 0.10 mm at the forearm (distance between the ulnar styloid process and olecranon) and tibia (the distal edge of the medial malleolus to the tibial plateau).

Dual-energy X-ray absorptiometry

Body composition variables [fat mass (kg), fat-free soft-tissue mass (FFST) mass (kg) and percentage body fat] and bone outcomes of the total body [bone mineral content, BMC (g) and bone area (cm²)] were measured using DXA (Delphi A; S/N 70467; Hologic Inc., Bedford, MA). The same technician analyzed all scans using Hologic software, version 11.2. Quality assurance for DXA was performed via calibration against the manufacturer's three-step soft-tissue wedge (model TBAR; SN 2275) and anthropomorphic spine phantom (model DPA/QDR-1; SN 9374) composed of different thickness levels of aluminum and lucite, calibrated against stearic acid (100% fat) and water (8.6% fat). In our laboratory, a coefficient of variation of 0.36% was observed from 648 scans of the spine phantom over a 3-year period. For determination of measurement reproducibility, one-way random effects model, single measure intraclass correlation coefficients (ICCs) were calculated in females 18–30 years of age ($n=10$) scanned twice in our lab during a 7-day period for total body fat mass, FFST mass and %fat (all $R \geq 0.87$) and for BMC of the whole body ($R=0.98$).

Peripheral quantitative computed tomography

Peripheral QCT (XCT-2000; Stratec Medizintechnik, Pforzheim, Germany) measurements were taken of the nondominant radius and tibia. Radial and tibial measures were taken at the 4% and 20% sites for bone outcomes, proximal to the articular surface of the distal end of the tibia and radius. The 4% and 20% sites represent areas high in trabecular and cortical bone, respectively. Each scan was acquired with a 0.4 mm voxel size and a slice thickness of 2.4 mm. The anatomic reference line (for determination of

the distal end of the radius or tibia) was identified by acquisition of a 30-mm planar scout view of the joint line and automatically set by the software at 4% or 20% sites. Image processing and calculation of the various bone measures were determined using the Stratec software (version 5.50d), which allows modal options for the following: Contour Mode for detecting the outer bone edge, Peel Mode for defining the way subcortical and trabecular bone are separated, and Cort Mode for separating cortical bone from trabecular bone.

At the trabecular site of the radius and tibia, total and trabecular vBMD (mg/cm³) and total cross-sectional area (CSA, mm²) were measured using Contour Mode 2 (200 mg/cm³), Peel Mode 2 (400 mg/cm³), and Cort Mode 3 (169 mg/cm³). Using total vBMD and total CSA, bone strength index (mg²/mm⁴, Eq. 1) was calculated, which reflects the strength of bone against compression [34, 35]. The following bone variables were assessed at the radial and tibial cortical sites: cortical vBMD (mg/cm³), cortical CSA (mm²), total CSA, cortical BMC (mg/mm), cortical thickness (mm), endosteal circumference (mm), and polar strength–strain index (mm³). Cortical bone variables for the 20% site were assessed using Contour Mode 1 (710 mg/cm³), Peel Mode 2 (540 mg/cm²), and Cort Mode 1 (480 mg/cm³). The strength–strain index (mm³), an estimate of torsional bone strength, is calculated as the integrated product of the section modulus and the density of cortical bone Eq. 2. Section modulus is calculated as $(a \times d^2)/d_{\max}$, where a is the CSA of a voxel, d is the distance of the voxel from the center of gravity, and d_{\max} is the maximum distance of one voxel to the center of gravity. The ratio of cortical vBMD and normal physiological density (ND=1,200 mg/cm³) provides an estimate of the modulus of elasticity [20].

$$\text{Bone strength index (mg}^2\text{/mm}^4\text{)} = \text{total CSA} \times \text{total vBMD}^2 \quad (1)$$

$$\text{Strength – strain index (mm}^3\text{)} = \frac{\sum_i (a_i \times d_i^2) (\text{Cortical vBMD/ND})}{d_{\max}} \quad (2)$$

A third measurement, muscle CSA (mm²), was also assessed at the 66% site of the tibia and radius. All pQCT measures were assessed and analyzed by the same trained operator. The pQCT operator scanned the phantom daily to maintain quality assurance. Test–retest measurements were performed on five females, aged 18 to 24 years, to determine reliability of the pQCT in our laboratory. The one-way random effects model, single measure ICCs for all pQCT measurements were calculated to be $R \geq 0.97$.

Definition of adiposity groups

Participants were dichotomized by the DXA-derived percentage body fat cutoff suggested by Going, Lohman, and Falls (Fitnessgram/Activitygram 3rd Edition, The Cooper Institute, Dallas, TX) [36]. Going, Lohman, and Falls [36] indicate that, regardless of race and age (6–18 years), a normal range of percentage body fat for females is 18–32%, while levels >32% body fat are associated with cardiovascular disease risk factors (i.e., hypertension, dyslipidemia, and impaired glucose tolerance) [37–39]. Therefore, females with $\leq 32\%$ body fat were classified as normal body fat; females exceeding this cutoff were classified as high body fat.

Statistical analyses

Statistical analyses were performed using SPSS version 18.02 for Mac OS X (PASW Statistics, Chicago, IL). A P value ≤ 0.05 was considered statistically significant for all analyses. Normal distribution and homogeneity of variances were confirmed by Shapiro–Wilks W and Levene's tests, respectively. Pearson's bivariate correlations were used to examine the associations of body weight, fat mass, and FFST mass with bone variables. Partial Pearson's correlation coefficients were performed to determine the associations of fat mass with the bone variables, with control for FFST mass. Group differences for anthropometric, body composition, and unadjusted bone variables were determined using unpaired (i.e., independent samples) two-tailed t tests. Descriptive statistics for raw variables are presented as mean \pm SD. An F test was performed to test the assumption of homogeneity of regression slopes with regard to the interaction between the independent variables (i.e., adiposity groups) and the covariate (i.e., FFST mass or body weight). Because there were no interactions, analysis of covariance was used to compare the differences in bone response variables between the normal body fat and high body fat groups after adjusting for either FFST mass or body weight differences. Estimated means of bone variables in the adjusted analyses are reported as mean (95% CI).

Sample size determination was estimated using data previously collected in our laboratory [17]. From these data in white females, aged 18–19 years, the mean \pm SD tibial bone values in the lowest quartile for total vBMD, cortical CSA, and strength–strain index are 287 ± 35 mg/cm³, 177 ± 15 mm², and 1101 ± 97 mm³, respectively. Radial bone values in the lowest quartile for total vBMD, cortical CSA, and strength–strain index were 307 ± 40 mg/cm³, 63 ± 7.9 mm², and 189 ± 20 mm³, respectively. Based on these tibial and radial bone data in white late-adolescent females, we estimated that 12–15 subjects in each adiposity group

would provide 81–84% power ($\alpha=0.05$) to detect at least a 10% difference in total vBMD, cortical CSA, and strength–strain index at the tibia and radius between adiposity groups (Sample Power, software version 2.0, SPSS, Chicago, IL).

Results

Participant characteristics

Mean age, weight, height, BMI, menarche, FFST, fat mass, percentage body fat, total body BMC, total body bone area, tibial and forearm lengths and muscle CSA, and pQCT-derived bone variables of the participants are provided in Table 1. Age, height, and menarche were not different between adiposity groups. The high body fat group, however, was found to have greater body weight, BMI, FFST mass, and percentage body fat than the normal body fat group (all $p < 0.05$). There were no significant differences between groups in total body BMC, total body bone area, tibial length, tibial muscle CSA, forearm length, forearm muscle CSA, or the pQCT-derived bone parameters.

Bivariate correlations of body weight, fat mass, and FFST mass with bone measurements

Total body BMC was positively related with weight ($r=0.69$, $p < 0.01$), fat mass ($r=0.52$, $p < 0.01$), and FFST mass ($r=0.79$, $p < 0.01$). Total body bone area was also positively associated with weight ($r=0.72$, $p < 0.01$), fat mass ($r=0.55$, $p < 0.01$), and FFST mass ($r=0.82$, $p < 0.01$).

Among the pQCT-derived bone parameters, body weight was not associated with total vBMD or trabecular vBMD at the trabecular site of the tibia and radius, although it was positively associated with total CSA (tibia; $r=0.26$, $p=0.07$ and radius; $r=0.33$, $p=0.02$) and bone strength index (tibia; $r=0.58$, $p < 0.01$ and radius; $r=0.29$, $p=0.05$). At the cortical bone site, body weight was negatively associated with cortical vBMD at the tibia ($r=-0.31$, $p=0.04$) but not at the radius. At the other cortical sites, however, body weight was positively correlated with cortical CSA, total CSA, cortical BMC, cortical thickness, and strength–strain index at the tibia and radius ($r=0.42$ – 0.63 , all $p < 0.05$). Positive relations were observed between fat mass and bone strength index (radius only), cortical CSA, total CSA (cortical site of tibia only), cortical BMC, cortical thickness (tibia only), and strength–strain index ($r=0.30$ – 0.47 , all $p < 0.05$). Positive associations were also found between FFST mass and total CSA (4% and 20% bone sites), bone strength index, cortical CSA, cortical BMC, cortical thickness (tibia only), endosteal circumference, and strength–strain index ($r=0.42$ – 0.63 , all $p < 0.05$). Cortical

Table 1 Characteristics of the participants

	Total sample (N=48)	Normal body fat group ^a (n=33)	High body fat group ^a (n=15)
Age (years)	19.2±1.2	19.3±1.3	19.0±1.1
Weight (kg)	65.2±14.9	59.6±8.9	77.6±18.1 ^b
Height (cm)	163.4±7.3	163.3±6.2	163.9±6.2
Body mass index (kg/m ²)	24.4±5.3	22.4±3.1	28.9±6.4 ^b
Menarche (years)	11.9±1.7	11.8±1.7	12.1±1.8
FFST mass (kg)	44.2±6.7	42.9±5.8	47.1±7.8 ^b
Fat mass (kg)	20.8±9.5	16.3±3.9	30.8±10.6 ^b
Fat mass (%)	29.8±6.9	26.2±3.4	37.7±4.3 ^b
Total body BMC (g)	2273±325	2238±298	2349±377
Total body bone area (cm ²)	2018±173	1995±161	2069±193
Tibial length (mm)	388.1±28.5	384.5±29.4	395.9±25.8
Forearm length (mm)	269.1±13.5	268.3±13.9	270.9±13.1
Tibial muscle CSA (mm ²)	6209±1069	6127±1127	6379±954
Forearm muscle CSA (mm ²)	2699±548	2657±569	2781±515
pQCT bone parameters			
4%, trabecular site			
Total vBMD (mg/cm ³)			
Tibia	391.1±68.7	384.2±62.8	406.4±79.9
Radius	414.0±97.8	405.7±108.9	431.6±68.5
Trabecular vBMD (mg/cm ³)			
Tibia	234.0±40.9	234.1±39.9	234.0±44.2
Radius	224.7±32.8	221.1±33.1	232.4±31.9
Total CSA (mm ²)			
Tibia	748.8±184.0	755.8±177.9	734.1±200.9
Radius	260.9±59.8	262.1±62.9	258.4±54.6
Bone strength index (mg ² /mm ⁴)			
Tibia	1116±300	1086±250	1180±388
Radius	434±125	417±132	471±103
20%, cortical site			
Cortical vBMD (mg/cm ³)			
Tibia	1191±20.8	1193±18.6	1187±25.1
Radius	1181±42.0	1180±39.3	1185±47.9
Total CSA (mm ²)			
Tibia	359.4±52.9	361.9±51.0	354.1±58.3
Radius	107.6±20.4	107.8±21.7	107.4±17.9
Cortical CSA (mm ²)			
Tibia	214.6±30.9	214.1±26.2	215.7±40.4
Radius	74.2±9.6	73.6±9.7	75.4±9.6
Cortical BMC (mg/mm)			
Tibia	255.4±35.2	255.3±29.9	255.7±45.7
Radius	87.7±11.5	86.8±11.3	89.4±12.0
Cortical thickness (mm)			
Tibia	3.94±0.5	3.91±0.4	4.00±0.7
Radius	2.64±0.3	2.61±0.3	2.69±0.3
Endosteal circumference (mm)			
Tibia	42.3±5.6	42.7±5.6	41.3±5.7
Radius	20.1±4.3	20.2±4.5	19.7±3.9
Strength–strain index (mm ³)			
Tibia	1454±292	1469±283	1422±319
Radius	246.1±62.0	242.2±62.4	254.4±62.3

All values are means ± SD

FFST fat-free soft tissue, BMC bone mineral content, CSA cross-sectional area, pQCT peripheral quantitative computed tomography, vBMD volumetric BMD

^a Normal body fat (≤32% body fat); high body fat (>32% body fat)

^b Significantly different from normal body fat group, $p < 0.05$ (two-tailed independent t tests)

vBMD at the tibia only was inversely related with fat mass ($r=-0.25$, $p=0.07$) and FFST mass ($r=-0.33$, $p=0.03$).

Partial correlations between fat mass and bone measurements after controlling for FFST mass

After controlling for FFST mass, fat mass was inversely related with cortical CSA (radius only), total CSA (20% site), endosteal circumference (radius only), and strength–strain index ($r = -0.31$ to -0.45 , all $p<0.05$). There were no significant relations between fat mass and DXA bone variables or pQCT variables at the trabecular bone site (total vBMD, trabecular vBMD, total CSA, and bone strength index) and the following bone parameters at the cortical bone site: cortical vBMD, cortical CSA (tibia only), cortical BMC, cortical thickness, and endosteal circumference (tibia only).

Bone comparisons between normal- and high fat groups after adjustment for either body weight or FFST mass

Peripheral QCT

Tibia After controlling for body weight, the high body fat vs. normal body fat group had significantly lower total CSA [319.5 (295.6–343.5) vs. 378.1 (362.7–393.4), $p<0.01$], cortical CSA [193.0 (180.5–205.6) vs. 224.7 (216.7–232.7), $p<0.01$], cortical BMC [230.3 (215.5–244.7) vs. 267.2 (258.0–276.5), $P<0.01$], and strength–strain index [1,224 (1,096–1,353) vs. 1,562 (1,480–1,644), $p<0.01$]. Table 2 shows similar tibial bone findings between groups at the 20% site after controlling for FFST mass. Specifically, the cortical bone strength (strength–strain index) of the high body fat group was 13% lower than the normal body fat group ($p<0.01$; Fig. 1). In the high body fat group, the lower cortical bone strength was due to smaller bone dimensions [total CSA (9%, $p=0.01$) and cortical CSA (6%, $p=0.05$)] compared to the normal body fat group. No significant differences were observed between adiposity groups at the trabecular bone site of the tibia after controlling for either body weight or FFST mass.

Radius After controlling for body weight, the high body fat vs. normal body fat group had significantly lower total CSA [97.4 (86.6–108.2) vs. 112.5 (105.6–119.4), $p=0.03$] and cortical CSA [69.8 (65.1–74.5) vs. 76.2 (73.2–79.2), $p=0.04$] at the cortical site. In the high body fat group, the smaller cortical bone dimensions for a given amount of body weight reflected a 15% weaker bone (strength–strain index) compared to the normal body fat group, but the difference did not reach significance [221.2 (189.7–252.8) vs. 257.7 (237.6–277.9), $p=0.07$]. There were no significant radial bone differences between groups at the

trabecular site after control for body weight. Table 2 displays radial bone values, controlling for FFST mass, of the normal body fat and high body fat groups. At the cortical site, the FFST-adjusted radial bone values tended to follow a similar pattern as the FFST-adjusted tibial bone values, but the differences were smaller in magnitude and did not reach significance (Fig. 1). There were no significant differences between groups at the trabecular bone site after control for FFST mass. Adjusted radial and tibial bone outcomes were also determined for the adiposity groups after control for muscle CSA for each respective bone site, but no significant differences in tibial or radial bone parameters at the trabecular or cortical sites were found between groups (data not shown).

Discussion

In this study of postadolescent black females, we compared bone structure and strength parameters of the tibia and radius between two adiposity groups defined as having normal and high levels of percentage body fat. The unadjusted tibial and radial bone measurements were not significantly different between adiposity groups, even though the high body fat group was carrying significantly greater soft-tissue loads (an average of 14-kg fat mass and 4-kg of FFST mass) than the normal body fat group. After controlling for either the higher FFST mass or the greater body weight in the high body fat group, we observed smaller cortical bone dimensions at the tibia and radius in the high body fat group compared to the normal body fat group. Consistent with our adiposity and bone data in late-adolescent white females [17], our findings in black females entering adulthood also suggest that obesity may adversely influence cortical bone strength.

It has recently been proposed that race may modify the relationship between adiposity and bone. In postmenopausal women, Castro et al. [40] demonstrated that for each unit increase in BMI, the odds ratio for having low aBMD were lower for white women, while black women had slightly higher odds for low aBMD. In prepubertal black and white children, Afghani and Goran [28] observed total abdominal adipose tissue, assessed by QCT, was negatively associated with total body BMC, measured using DXA. However, there were racial differences in the associations of total body BMC with subcutaneous abdominal adipose tissue (SAAT) and visceral adipose tissue (VAT). For instance, an inverse correlation between SAAT and total body BMC was observed in white, but not in black children [28]. Conversely, an inverse association between VAT and total body BMC was found in black, but not in white children [28]. The results in this study and in our analogous work

Table 2 Tibial and radial bone parameters at trabecular and cortical sites in postadolescent black females with normal- and high body fat levels

pQCT bone parameters	Normal body fat group ($n=33$)	High body fat group ($n=15$)	p value
4%, trabecular site			
Total vBMD (mg/cm^3)			
Tibia	386.6 (361.9, 411.3)	401.7 (365.0, 438.4)	0.50
Radius	403.8 (368.2, 439.5)	435.6 (382.7, 488.5)	0.33
Trabecular vBMD (mg/cm^3)			
Tibia	235.3 (220.4, 250.2)	231.2 (209.2, 253.3)	0.76
Radius	222.2 (210.4, 234.0)	230.3 (212.8, 247.8)	0.45
Total CSA (mm^2)			
Tibia	767.1 (702.7, 831.4)	709.9 (614.5, 805.3)	0.33
Radius	267.8 (248.3, 287.2)	246.3 (217.5, 275.1)	0.23
Bone strength index (mg^2/mm^4)			
Tibia	1120 (1030, 1209)	1107 (974, 1240)	0.89
Radius	424.6 (381.7, 467.5)	454.1 (390.6, 517.7)	0.45
20%, cortical site			
Cortical vBMD (mg/cm^3)			
Tibia	1191 (1185, 1199)	1190 (1179, 1201)	0.76
Radius	1178 (1163, 1194)	1189 (1167, 1212)	0.45
Total CSA (mm^2)			
Tibia	369.4 (356.0, 382.9)	337.9 (318.0, 357.8)	0.01
Radius	110.4 (104.5, 116.2)	101.9 (93.2, 110.5)	0.11
Cortical CSA (mm^2)			
Tibia	218.8 (211.5, 226.1)	205.7 (194.8, 216.5)	0.05
Radius	75.0 (72.5, 77.5)	72.5 (68.8, 76.2)	0.29
Cortical BMC (mg/mm)			
Tibia	260.6 (252.1, 269.0)	244.4 (231.9, 257.0)	0.04
Radius	88.3 (85.0, 91.5)	86.3 (81.5, 91.2)	0.51
Cortical thickness (mm)			
Tibia	3.95 (3.78, 4.12)	3.91 (3.66, 4.17)	0.80
Radius	2.62 (2.51, 2.74)	2.66 (2.49, 2.84)	0.70
Endosteal circumference (mm)			
Tibia	43.1 (41.2, 45.1)	40.5 (37.6, 43.3)	0.13
Radius	20.6 (19.1, 22.0)	19.0 (16.8, 21.1)	0.23
Strength-strain index (mm^3)			
Tibia	1514 (1446, 1583)	1326 (1225, 1427)	<0.01
Radius	250.2 (232.9, 267.6)	237.3 (211.6, 263.0)	0.41

Presented as estimated marginal mean (95%CI) adjusted for fat-free soft-tissue mass. Normal body fat ($\leq 32\%$ body fat); high body fat ($>32\%$ body fat) *pQCT* peripheral quantitative computed tomography, *BMC* bone mineral content, *CSA* cross-sectional area, *vBMD* volumetric BMD

[17] suggest similar relations between total body adiposity and bone structure and strength parameters in young black and white females. We are unable to determine whether race plays a part in the influence of central body adiposity on bone structure and strength, as VAT and SAAT were not assessed in this study or in our previous work [17]. Since obesity-related metabolic abnormalities are more strongly related to visceral adiposity rather than total adiposity, it is worthy to explore whether the influence of visceral

adiposity on bone structure and strength is modified by race, as it may provide some insight into why older black females experience fewer fragility fractures than do white females [23].

In developing females, high levels of adipose tissue are associated with an increased production of sex steroids such as estrogen and testosterone [41, 42], although their impact on cortical and trabecular bone in the presence of obesity is unclear. Our data in postadolescent black females suggest

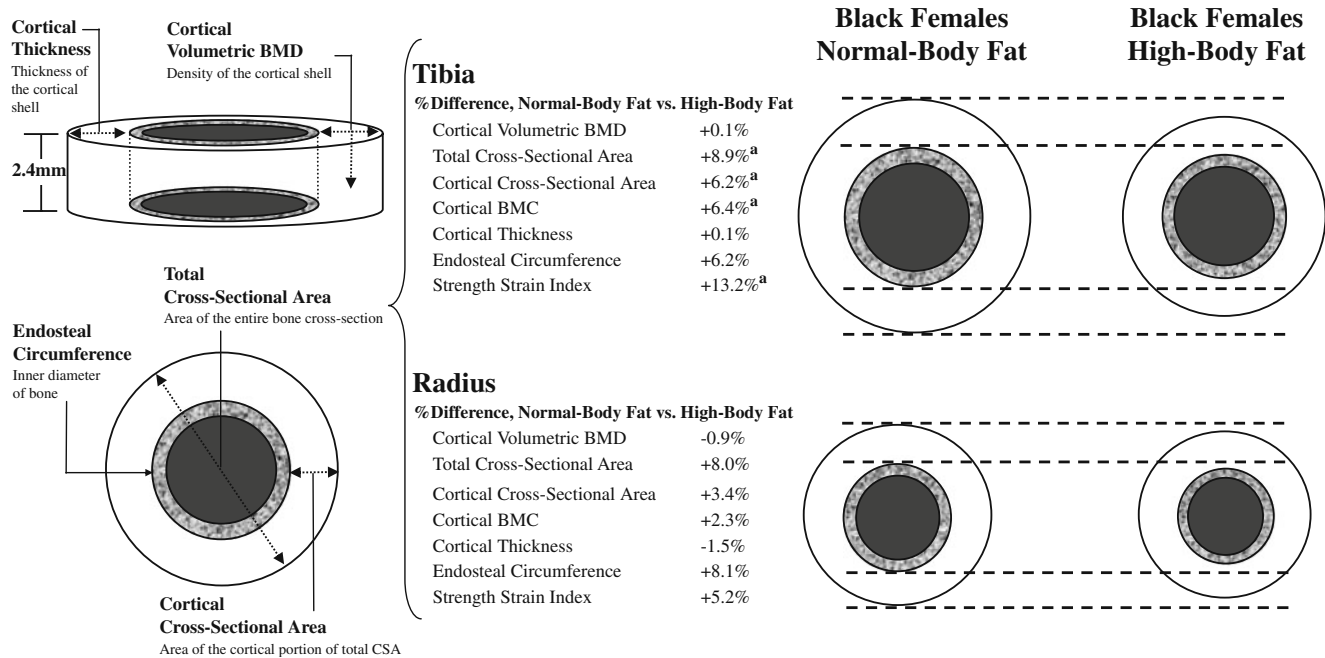


Fig. 1 Schematic representation of the average magnitude of difference $[A - B/(A + B)/2 \times 100]$ at the cortical site of the tibia and radius, after controlling for either fat-free soft-tissue mass (FFST), in normal body fat ($n=33$) vs. high body fat ($n=15$) postadolescent

black females. The *outer white circles* represent cortical bone, the *textured circles* represent trabecular bone and the *gray circles* represent the medullary cavity. ^a $P < 0.05$

that, for a given amount of FFST mass, cortical bone size is more strongly and inversely associated with increasing fat mass compared to the relations that we observed between trabecular bone and adiposity. This lack of relationship between trabecular bone and fat mass was also observed in our previous study in late adolescent white females [17]. In a sample of 677 men, 25–45 years of age, Taes et al. [43] found that fat mass was inversely associated with pQCT-derived cortical bone parameters at both the radius and tibia, after controlling for either body weight or FFST mass. In contrast to our findings, however, the investigators observed negative relations between fat mass and trabecular bone parameters at the radius (trabecular bone parameters at the tibia were not assessed) [43]. One could speculate that because of the variation in estrogen and testosterone concentrations between males and females, these sex steroids may have differential effects on trabecular and cortical bone in the presence of obesity. However, Khosla et al. [44, 45] found that the effects of estrogen and testosterone on trabecular and cortical bone parameters, assessed by pQCT, are similar between young adult males and females. Furthermore, the authors noted that having high levels of estrogen provided no extra skeletal strength benefits for either trabecular or cortical bone, but having low levels of estrogen was more detrimental to trabecular than cortical bone [45]. Estrogen is thought to reduce the bone remodeling threshold on the endosteal surface of cortical bone, thereby sensitizing bone next to marrow to the effect of weight-

bearing loads, resulting in greater storage of bone mineral and an increase in bone area [46]. Therefore, it is possible that the lack of association between adiposity and trabecular bone parameters could be attributed to FFST mass being more strongly associated with cortical bone rather than the trabecular bone. Since young overweight black females take part in limited physical activities [47], it is possible that our findings between adiposity and cortical bone size could be the result of low levels of physical activity associated with high levels of body fat. Thus, when we statistically control for surrogates of skeletal loading (e.g., FFST mass or body weight), the observed effect would be greater in (1) cortical vs. trabecular bone and in (2) weight-loaded (tibia) vs. non-weight-loaded (radius) bone. That was the case in both instances in our investigation and in similar studies that assessed cortical and trabecular bone at the tibia and radius [17, 18]. Though we excluded participants who participated in competitive high-school and collegiate sports, we did not collect any information on the types and frequencies of physical activities performed from early to late puberty or any weight history documentations from the participants. Therefore, we are unable to identify which participants engaged in (non-competitive) high impact activities or gained excessive weight due to reduced physical activity during adolescence.

Figure 1 shows a visual representation of the overall effect by which smaller cortical bone dimensions, as was observed in the high body fat group compared with the

normal body fat group, had on estimated bone strength (strength–strain index) relative to FFST mass. It is worth noting that in the simple correlation analyses, we found not only FFST mass but also fat mass and body weight to be positively associated with bone parameters at the tibia and radius. Studies have reported positive associations between bone outcomes and body weight or fat mass [9, 12, 48–50]. In our study, however, the strength of these associations was generally greater between the bone parameters and FFST mass rather than fat mass or body weight. FFST mass is predominately muscle and that our bone outcomes were more strongly related to FFST mass is consistent with the Frost mechanostat theory of bone development, which suggests bone adaptation is driven primarily by changes in mechanical load [21]. Since fat mass is a component of body weight, it is indeed possible that adiposity may have a protective effect on the skeleton due to the extra weight it imposes on bone as a mechanical load [27]. Therefore, in addition to our bone analyses controlling for FFST mass differences, we also present bone data between adiposity groups, controlling for body weight. The magnitude of differences between adiposity groups (lower in high body fat vs. normal body fat group) seems to be greater in the body weight-adjusted bone outcomes compared to the FFST mass-adjusted bone outcomes. Similarly, Zhao et al. [51], studying 6,477 Chinese and Caucasian adults ranging in age from 19–90 years of age, found that fat mass was negatively correlated with DXA-derived bone mass, when the mechanical loading effect of body weight was statistically removed. Beck et al. [52] reported similar findings between fat mass and DXA-derived hip structural parameters, after controlling for body weight, in 4,642 postmenopausal women in the Women’s Health Initiative Observational Study. Using pQCT, Ducher et al. [18] showed that, once controlling for forearm length and body weight differences, overweight children had a smaller cortical bone at the radius than normal-weight children. These study findings along with our data would suggest that bone strength of heavier individuals might not be adequate for their higher body weight. However, these bone findings, controlling for body weight, must be interpreted with caution, as the negative association between fat mass and bone outcomes may just be due to the FFST mass having a larger positive effect on bone outcomes than fat mass [53].

The present study has several strengths. First, this study evaluated the effect of excess fat mass on bone structure and strength parameters, assessed by pQCT, at weight-bearing (tibia) and non-weight-bearing (radius) skeletal sites that have not been previously reported in postadolescent black females. In addition, studying only postadolescent black females minimized the degree of variability in factors known to influence bone such as race, sex, and

maturational status. Lastly, by grouping the black females by percent body fat (rather than BMI), we exclude the possibility of misclassification of those with high levels of body fat that may have otherwise been classified as normal weight if BMI had been used for the grouping procedure. In contrast, we acknowledge several limitations. In addition to not having historical information on weight-bearing activities and weight status history, another limitation was that our study utilized cross-sectional data and thus was not specifically designed to examine the longitudinal effects of adiposity and bone development. It is also important to note that we did not assess biochemical parameters indicative of metabolic abnormalities, which could have had an effect on bone independent of adiposity. For instance, obese individuals suffer from hyperleptinemia rather than leptin deficiency [54]. Animal studies reveal that leptin treatment elicits a bimodal response, where low doses of leptin can stimulate bone formation and prevent bone loss, but high concentrations of leptin suppress bone formation and increase bone resorption [55]. Obesity is also associated with other metabolic disturbances such as insulin resistance and increased inflammation, which both conditions have shown to hinder bone growth [56]. Future studies should include an assessment of endocrine factors to explore these issues.

In summary, our results suggest that excess fat mass may adversely influence cortical bone structure and strength in African American females entering adulthood. Thus, the negative contribution of adipose tissue seems to offset its potential benefit as a mechanical load. Although our study suggests a concern for bone health in a population experiencing the highest rates of obesity, prospective research is needed to confirm a cause and effect relationship that considers physical inactivity, metabolic abnormalities, and environmental influences.

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Conflicts of interest None.

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