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Better Skeletal Microstructure Confers Greater Mechanical Advantages in Chinese-American Women Versus White Women

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Abstract

Despite lower areal bone mineral density (aBMD), Chinese-American women have fewer fractures than white women. We hypothesized that better skeletal microstructure in Chinese-American women in part could account for this paradox. Individual trabecula segmentation (ITS), a novel image-analysis technique, and micro-finite-element analysis (μ FEA) were applied to high-resolution peripheral quantitative computed tomography (HR-pQCT) images to determine bone microarchitecture and strength in premenopausal Chinese-American and white women. Chinese-American women had 95% and 80% higher plate bone volume fraction at the distal radius and tibia, respectively, as well as 20% and 18% higher plate number density compared with white women ($p < .001$). With similar rodlike characteristics, the plate-to-rod ratio was twice as high in the Chinese-American than in white trabecular bone ($p < .001$). Plate-rod junction density, a parameter indicating trabecular network connections, was 37% and 29% greater at the distal radius and tibia, respectively, in Chinese-American women ($p < .002$). Moreover, the orientation of the trabecular bone network was more axially aligned in Chinese-American women because axial bone volume fraction was 51% and 32% higher at the distal radius and tibia, respectively, than in white women ($p < .001$). These striking differences in trabecular bone microstructure translated into 55% to 68% (distal radius, $p < .001$) and 29% to 43% (distal tibia, $p < .01$) greater trabecular bone strength, as assessed by Young's moduli, in the Chinese-American versus the white group. The observation that Chinese-American women have a major microstructural advantage over white women may help to explain why their risk of fracture is lower despite their lower BMD.

Keywords

BONE MICROSTRUCTURE; HIGH-RESOLUTION PERIPHERAL QUANTITATIVE COMPUTED TOMOGRAPHY; INDIVIDUAL TRABECULA SEGMENTATION; RACE; CHINESE-AMERICAN; WHITE

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Disclosures

Drs. Liu and Guo are inventors of the ITS analyses software used in the study. All the other authors have no conflicts of interest.

Introduction

Osteoporosis is characterized by low bone mineral density (BMD) and microarchitectural deterioration that compromises bone strength and increases fracture risk.⁽¹⁾ Measurement of BMD by dual-energy X-ray absorptiometry (DXA) correlates highly with risk of fragility fracture, which is the clinical endpoint of osteoporosis. Despite its widespread use and clinical utility, DXA has a number of limitations. DXA provides a two-dimensional (2D) depiction of BMD [areal BMD (aBMD) in g/cm²] rather than a true volumetric density (g/cm³). Areal BMD, therefore, is influenced by bone size and is underestimated in smaller bones and overestimated in larger bones.^(2–4) Moreover, DXA does not distinguish between cortical bone, the outer dense envelope of bone, and trabecular bone, the inner compartment containing individual distinct trabeculae. Furthermore, DXA cannot assess bone microarchitecture, which is being recognized increasingly as an important determinant of bone strength.^(5–8)

DXA's limitations become apparent when assessing bone density in Asian populations. Asian women tend to have lower aBMD, as measured by DXA, when compared with white women and other racial groups.^(9–13) Despite lower aBMD in Asian women, however, numerous studies indicate lower rates of hip and wrist fractures than in white women.^(9,14–16) These seemingly incongruent findings are not completely explained by the smaller bones of Asian women. We and others^(17,18) recently reported that premenopausal Chinese-American women have greater cortical and trabecular bone density and thickness but smaller bone area at the radius and tibia compared with premenopausal white women when measured using high-resolution peripheral quantitative computed tomography (HR-pQCT), a new technology that enables noninvasive visualization and quantification of bone microstructure in the forearm and distal tibia of human subjects.⁽¹⁹⁾ Prior to the advent of this technology, only the percutaneous bone biopsy, an invasive procedure, could provide this information. DXA failed to identify these differences.⁽¹⁷⁾

To delineate the microarchitectural characteristics of trabecular bone that are key determinants of bone strength, we have developed a novel analytic technique, individual trabecula segmentation (ITS), by which the HR-pQCT image can be resolved into individual trabeculae and assessed with regard to their topographic orientation.^(20–22) Trabecular elements appear as either rodlike or platelike. The platelike orientation is the primary determinant of strength.^(21,23) More plates and/or a higher plate/rod ratio are associated with stronger bone.⁽²²⁾ The ITS analysis technique that we have developed and confirmed by evaluation of ex vivo bone samples^(21,23) now has been applied to the images obtained by HR-pQCT. Our recent study using HR-pQCT and ITS analyses of trabecular bone showed their potential as sensitive tools to distinguish between premenopausal osteoporotic and normal subjects and to detect subtle differences in trabecular plate and rod microstructure between groups.⁽²⁰⁾ We also have shown recently that HR-pQCT and ITS analysis can discriminate postmenopausal fragility fracture status independent of aBMD measurements.⁽²⁴⁾ The preceding studies suggest that ITS-based analysis of HR-pQCT scans in human subjects can serve as a useful index of bone quality.^(20,24) HR-pQCT also permits a direct assessment of the mechanical competence of bone by using high-resolution image-based microstructural finite-element analysis (μ FEA).^(25,26) By simulating bone under deformation conditions, estimated mechanical competence of bone can be determined noninvasively and has been shown to identify those with osteoporosis^(23,27) and those who have sustained a fragility fracture.^(28–32)

In this study, we have used ITS and μ FEA of HR-pQCT images to determine trabecular morphology and strength in premenopausal Chinese-American and white women. The

results provide a microarchitectural and biomechanical context for understanding why Chinese-American women are at reduced fracture risk compared with white women.

Material and Methods

Subjects

Ninety-five premenopausal women (46 white and 49 Chinese-American women) were studied. In this article, the term *Chinese-American* defines a group having all four grandparents of Chinese descent and who reside in the United States; the term *white* indicates white race/non-Hispanic ethnicity with residence in the United States. We chose to study Chinese-American women because Chinese-Americans have been reported to have the lowest rates of hip fracture among any Asian-American subgroups.⁽¹⁴⁾ Participants were recruited by newspaper and Internet advertisements, flyers, and directly at primary-care physician offices. Inclusion criteria were self-reported full Chinese or white descent (all four grandparents) with residence in the United States, regular menses, and age between 29 and 40 years. This age range was selected to study women who had reached peak bone mass and in whom a perimenopausal transition or menopause had not influenced bone and mineral metabolism. Women were screened by history and biochemical evaluation [i.e., thyroid-stimulating hormone (TSH), creatinine, liver function tests, phosphorus, calcium, parathyroid hormone (PTH), and 25-hydroxyvitamin D] for conditions or medications known to affect bone metabolism. Exclusion criteria included amenorrhea for 6 months or more, current pregnancy or lactation, current hyperthyroidism (TSH < 0.5 μ IU/mL), kidney dysfunction (GFR < 60 mL/min), liver dysfunction (AST or ALT > 2 $\times$ the upper limit of normal), intestinal malabsorption owing to any cause, history of malignancy other than nonmelanomatous skin cancer, metabolic bone diseases, primary or secondary hyperparathyroidism, human immunodeficiency virus (HIV) infection, organ transplantation, and current or past use of antiepileptic medications, glucocorticoids > 3 months, tacrolimus, cyclosporine, methotrexate, bisphosphonates, teriparatide, raloxifene, calcitonin, or aromatase inhibitors. All patients gave written informed consent. Patients were compensated for study participation and travel expenses. This study was approved by the Institutional Review Board of Columbia University Medical Center. In both groups, all subjects resided in the New York tristate area. The current study group represents subjects described in the article by Walker and colleagues⁽¹⁷⁾ plus additional participants recruited after publication of the article of Walker and colleagues.⁽¹⁷⁾

Clinical evaluation

Information regarding past medical and surgical history, medications, tobacco and alcohol use, and reproductive history was collected. Daily dietary calcium was assessed with a standardized food frequency questionnaire.⁽³³⁾ Physical activity was evaluated with the Modified Baecke Questionnaire.⁽³⁴⁾ Alcohol intake was assessed as number of drinks (1 drink = 12 ounces of beer, 5 ounces of wine, or 1 ounce of liquor) per day. Participants were considered alcohol users if they had 1 or more drinks per day. Tobacco use was quantified as current, past, and never use. Weight and height were measured by balance beam and a wall-mounted, calibrated Harpenden stadiometer.

Biochemical evaluation

Screening biochemistries such as calcium and phosphorus were determined by standard automated biochemical techniques. Serum intact PTH was measured by chemiluminescence assay, and 25-hydroxyvitamin D was measured by liquid chromatography tandem mass spectrometry.

Bone mineral density by DXA

Areal BMD was measured at the lumbar spine (LS, L₁–L₄), total hip (TH), femoral neck (FN), and one-third radius ($\frac{1}{3}$ Rad) using a QDR 4500A (Hologic, Inc., Waltham, MA, USA) dual-energy X-ray absorptiometer. Participants were measured on the same densitometer using the same software, scan speed, and technologist certified by the International Society of Clinical Densitometry. In vivo precision, determined according to the standard method at this facility, is 1.28% at the lumbar spine, 1.36% at the hip, and 0.70% for the distal radius ($\frac{1}{3}$ Rad).⁽³⁵⁾

HR-pQCT scan

HR-pQCT (XtremeCT, Scanco Medical AG, Bassersdorf, Switzerland) of the nondominant distal radius and distal tibia was performed as described previously.^(19,30,36) The HR-pQCT measurement included 110 slices, corresponding to a 9.02-mm section along the axial direction, with a nominal voxel size of 82 μ m. The region of interest and representative images of HR-pQCT are shown in Fig. 1. Quality control was provided by scanning the European forearm phantom at the time subjects were scanned. The mean cross-sectional area and cortical thickness (Ct.Th) of whole-bone segments were evaluated, and the mineralized phase was thresholded according to the standard patient evaluation protocol.⁽³⁷⁾

Individual trabecula segmentation (ITS)–based morphological analyses

A $5.7 \times 5.7 \times 5.7$ mm³ cubic subvolume and a $9.0 \times 9.0 \times 9.0$ mm³ cubic subvolume were extracted from the center of the trabecular bone compartment of each HR-pQCT image of the distal radius and distal tibia. All trabecular bone subvolumes then were subjected to ITS-based morphological analyses. As shown in Fig. 2A, a complete volumetric decomposition technique was applied to segment the trabecular network into individual plates and rods.⁽²¹⁾ Briefly, digital topological analysis (DTA)–based skeletonization⁽³⁸⁾ was applied first to transform a trabecular bone image into a representation composed of surfaces and curves skeleton while preserving the topology (i.e., connectivity, tunnels, and cavities),^(39,40) as well as the rod and plate morphology of the trabecular microarchitecture. Then digital topological classification was applied in which each skeletal voxel was uniquely classified as either a surface or a curve type.⁽⁴¹⁾ Using a newly developed iterative reconstruction method, each voxel of the original image can be classified as belonging to either an individual plate or rod (Fig. 2A). Based on the 3D evaluations of each individual trabecular plate and rod (Fig. 2A), bone volume and number of plates and rods were evaluated by plate and rod bone volume fraction (pBV/TV and rBV/TV), as well as plate and rod number densities (pTb.N and rTb.N, 1/mm). Plate/rod ratio (P/R ratio), a parameter of plate versus rod characteristics of trabecular bone, was defined as plate bone volume divided by rod bone volume. The average size of plates and rods was quantified by plate and rod thickness (pTb.Th and rTb.Th, mm), plate surface area (pTb.S, mm²), and rod length (rTb. ℓ , mm). Intactness of the trabecular network was characterized by plate-rod junction density (P-R Junc.D, 1/mm³), calculated as the total junctions between trabecular plates and rods normalized by the bulk volume. Orientation of the trabecular bone network was characterized by axial bone volume fraction (aBV/TV), defined as axially aligned bone volume divided by the bulk volume. Trabecular bone volume fraction, mean number density, and mean thickness (BV/TV, Tb.N, and Tb.Th) for all trabeculae also were calculated. Detailed methods of the complete volumetric decomposition technique and ITS-based measurements can be found in our recent publications.^(21,22)

Micro–finite element analysis (μ FEA)

Each thresholded HR-pQCT whole-bone segment image and trabecular bone subvolume image of the distal radius and distal tibia was converted to a μ FE model. Bone tissue was

modeled as an isotropic linear elastic material with a Young's modulus (E_s) of 15 GPa and a Poisson's ratio of 0.3.⁽⁴²⁾ For each model of trabecular bone subvolume, six μ FE analyses representing three uniaxial compression tests and three shear tests were performed to derive the full orthotropic stiffness tensor in a new coordinate system representing the best orthotropic symmetry. Three axial elastic moduli then were derived and sorted such that E_{11} and E_{22} represented the in-plane elastic moduli and E_{33} was the modulus in the axial direction ($E_{11} < E_{22} < E_{33}$).⁽⁴³⁾ For each model of whole-bone segment, a uniaxial compression test was performed to calculate the reaction force under a displacement equal to 1% of bone segment height along the axial direction. Whole-bone stiffness, defined as the reaction force divided by the applied displacement, characterizes the mechanical competence of both cortical and trabecular compartments and is closely related to whole-bone strength⁽⁴⁴⁾ and fracture risk.^(31,32,45) The percentage of load carried by the cortical compartment at the distal surface of bone segments also was calculated. All the μ FE analyses were performed by using a customized element-by-element preconditioned conjugate gradient solver.⁽⁴⁶⁾

Statistical analysis

Data are expressed as mean $\pm$ SD. Comparisons of clinical and biochemical variables between the Chinese-American and white groups were evaluated by independent two-sided Student's t test. Criterion values were adjusted for unequal variances where appropriate. Pearson correlation coefficients were computed for bone density, ITS variables, and mechanical parameters with each potential covariate. Sets of covariates with p values of less than .05 and independent from each other were selected. These included weight, calcium intake, sport index, and 25-hydroxyvitamin D. In general, weight, calcium intake, and sport index had positive correlations with one or more outcome variables within each group and in the combined data. 25-Hydroxyvitamin D level had positive correlations within each group but negative correlations in the combined data. Bone density, ITS, and μ FEA results for each site were first compared between the two racial groups without adjustment using two-sided t tests and then compared again after adjustment for the preceding covariates using generalized linear mixed models. To investigate the trabecular bone structure-function relationship, linear regression analyses were performed for BV/TV and E_{33} , the elastic modulus in the principal daily loading direction, at each site for each group, respectively. The slopes of linear correlations for the two racial groups were compared statistically.⁽⁴⁷⁾ For all analyses, a two-tailed $p < .05$ was considered to indicate statistical significance. Statistical analysis was performed using NCSS software (NCSS 2007; NCSS Statistical Software, Kaysville, UT, USA).

Results

As shown in Table 1, Chinese-American and white women did not differ in age, but Chinese-American women were 2% shorter and had 10% lower body weight than white women. White women were more physically active than Chinese-American women. There was no difference in current tobacco or alcohol use in Chinese-American versus white women and no difference in age at menarche. 25-Hydroxyvitamin D levels were 31% lower and PTH levels 19% higher in Chinese-American compared with white women (Table 1).

Areal BMD by DXA did not differ between the groups at the lumbar spine, total hip, femoral neck, or $\frac{1}{3}$ radius before adjustment for covariates (Table 2). After adjustment for covariates, aBMD was higher at the lumbar spine (1.061 ± 0.139 versus 0.989 ± 0.137 g/cm², $p = .02$) in Chinese-American women compared with white women but not different at other sites.

By HR-pQCT, cross-sectional bone area was 9% lower at the radius and 6% lower at the tibia in Chinese-American women compared with white women. Cortical thickness was 18% and 10% greater in Chinese-American women versus white women at the distal radius and tibia, respectively. Chinese-American women had 22% and 13% greater BV/TV but similar Tb.N at the distal radius and tibia as white women. Tb.Th was 3% greater at the distal radius but similar at the tibia in Chinese-American women. ITS and μ FE analyses of HR-pQCT images revealed marked differences between the two groups (Table 2, Fig. 2B, and Fig. 3). Remarkably, Chinese-American women had 95% and 80% higher plate bone volume fraction (pBV/TV) at the distal radius and tibia, respectively, as well as 20% and 18% higher plate number density (pTb.N), compared with white women ($p < .001$). In contrast, rodlike characteristics (i.e., the amount and number of trabecular rods, rBV/TV and rTb.N) were similar. Thus the plate/rod ratio was two times higher in Chinese-American than in white trabecular bone (0.62 versus 0.30 at the distal radius, 0.70 versus 0.35 at the distal tibia, $p < .001$). Additionally, the size of individual trabecular plates was significantly greater in Chinese-American women versus Caucasian women: Trabecular plates were 9% and 4% greater in thickness and 11% greater in surface area at the distal radius and tibia ($p = .001$). In contrast, the size of individual trabecular rods, in terms of both thickness and length, was not different in Chinese-American and white women, except for a 3% greater rod thickness at the distal radius in Chinese-American women. Plate-rod junction density (P-R Junc.D), a parameter indicating the trabecular network connections, was 37% and 29% greater at the distal radius and tibia in Chinese-American women ($p < .002$). Moreover, the orientation of the trabecular bone network was more axially aligned in Chinese-American women because axial bone volume fraction (aBV/TV) was 51% and 32% higher at the distal radius and tibia, respectively, compared with white women ($p < .001$; Table 2, Fig. 2B, and Fig. 3).

These striking differences in trabecular bone microstructure translated into 55% to 68% (distal radius, $p < .001$) and 29% to 43% (distal tibia, $p < .01$) higher trabecular mechanical competence (Young's moduli E_{11} , E_{22} , and E_{33}) in the Chinese-American women versus the white women, as estimated by μ FEA of HR-pQCT images (Table 2, Fig. 3). Although Chinese-American women have smaller bone size than white women, thicker cortices and more platelike trabecular bone led to 14% and 8% greater whole-bone stiffness at the radius and tibia, respectively ($p < .05$). The relative contributions of cortical and trabecular compartments for carrying the mechanical loading were similar in the two racial groups.

In addition, the difference in trabecular structure type also translated into significantly different bone microstructure-function relationships between Chinese-American and white women (Fig. 4). The slope of the E_{33} versus BV/TV curve is significantly greater in Chinese-American women than in white women at both sites ($p < .05$), suggesting that Chinese-American women have a greater axial elastic modulus than white women given the same amount of trabecular bone. Adjustment for covariates in general did not influence the direction or significance of the differences in ITS and μ FEA variables between the two racial groups (Table 2).

Discussion

To our knowledge, this is the first study to use noninvasive measurements of trabecular and cortical bone micromechanics to study racial differences between Asian and white women. We describe major differences between Chinese-American and white premenopausal women in trabecular structural type (i.e., plate versus rod characteristics) that contribute to greater biomechanical strength in Chinese-American women, as measured by ITS and μ FE analyses of HR-pQCT images. Our results extend the findings of Marshall and colleagues and Walker and colleagues, who recently described greater trabecular density, smaller bone

area, and greater cortical thickness at the proximal femur, distal radius, and distal tibia in Asian compared with white populations.^(17,48) The data in this study provide insightful mechanistic evidence that more trabecular plates contribute to stronger trabecular bone in Chinese-American women. Additionally, we were able to evaluate the biomechanical contributions of cortical and trabecular compartments at two different skeletal sites and discern the difference in integrated bone stiffness between the two racial groups.

Although Chinese-American women have smaller bone size than white women, thicker cortices and more platelike trabecular bone lead to greater integral bone stiffness at both the distal radius and tibia. In contrast, there was no difference in aBMD at any site by DXA between the Chinese-American and white women. Areal BMD at the lumbar spine became greater in Chinese-American than white women after adjustment for weight and other covariates. This is consistent with the known effect that DXA underestimates volumetric bone density in those with small bone size.⁽²⁻⁴⁾ Previous studies have shown that the technology of HR-pQCT could offer clear advantages over DXA in the measurement of bone density in Chinese-American women because HR-pQCT measures volumetric bone mineral density (vBMD), which is not influenced by bone size.^(17,18)

ITS and μ FE analyses are validated methods for assessing microarchitectural and mechanical properties based on HR-pQCT images.^(25,26,49) Our previous study based on HR-pQCT images of normal and osteoporotic premenopausal women suggested that at a fixed bone mass, platelike trabeculae contributed positively to the mechanical properties of trabecular bone.⁽²⁰⁾ The results of this study indicate that although Chinese-American and white women have similar rodlike trabecular structure, Chinese-American women have significantly more and larger trabecular plates than white women. In addition, Chinese-American women have greater junction densities between plate and rod elements and more axially aligned trabeculae, which together provide a dramatic advantage in platelike structure. The mechanical advantage of a more platelike trabecular structure was further supported by a significantly greater slope in a structure-function curve (E_{33} versus BV/TV) in Chinese-American women than in white women, indicating a faster rise in mechanical competence given a similar increase in the amount of bone for Chinese-American women. Altogether, these results account for the greater mechanical competence of trabecular bone. Moreover, Chinese-American women had a thicker cortical compartment than white women. Although the difference in cortical thickness was not as striking quantitatively as the differences observed in trabecular bone microstructure, both the cortical and trabecular compartments contributed equally to the greater mechanical strength in the Chinese-American women. Adjustments for covariates did not substantially alter the findings. In general, microstructural and mechanical differences between Chinese-American and white women were more apparent at the radius rather than tibia. The differences in the distal tibia may be attenuated by effects of weight bearing at the tibia.

Currently, there are no data regarding the mechanism by which trabecular plate versus rod morphology is physiologically determined. We speculate that both platelike and rodlike trabeculae are essential in stabilizing trabecular bone structure, withstanding external loading, and dissipating mechanical energy.⁽²³⁾ Therefore, the platelike or rodlike structure may be determined in part through mechanical adaptation. Differences in trabecular structure type between Chinese-American and white women also may be due to genetic factors.

Several limitations of this study should be noted. The cohort studied was a relatively small convenience sample of women, and thus the results could have been influenced by selection bias. However, the demographic and DXA-based data are consistent across other studies. Since race/ethnicity was self-reported, we cannot exclude the possibility of racial diversity

within the groups, although, if present, this would have been expected to diminish the ability to detect between-group differences. We did not study postmenopausal women in order to avoid the potential confounding effects of racial differences in postmenopausal and age-related bone loss, as well as other factors (including medication usage) that would have to be taken into account in the context of an aging population. Additional studies in postmenopausal women will be an important focus for testing whether the results of this study apply to postmeno-pausal women. Other limitations include those imposed by μ FE analysis. Cortical and trabecular bone tissues were assumed to be constant and homogeneous for all the subjects. Therefore, the resulting mechanical measurements of μ FE analysis reflect only the influence of bone microstructure but not intrinsic mineral quality. It is unclear whether Chinese-American and white women differ in intrinsic bone tissue properties, such as collagen cross-link and degree of mineralization. It will be of future interest to derive subject-specific cortical and trabecular tissue properties from HR-pQCT images and integrate them into μ FE analysis.

With advanced in vivo skeletal imaging and novel ITS morphologic analytical techniques, conspicuous differences in trabecular bone microstructure and mechanical competence have been observed between premenopausal Chinese-American and white women. The greater platelike structure of bone in Chinese-American women offers mechanical advantages over the relatively greater rodlike structure of bone in white women. These results may help to account for the paradoxically lower fracture rates seen in Chinese-American women compared with white women.

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Fig. 1.

(A) HR-pQCT scout views of the tibia (*left*) and radius (*right*) illustrating the placement of the reference line at the endplate of the tibia or radius. The first slice of the region of interest is 22.5 and 9.5 mm proximal to the reference line at the tibia and radius, respectively. A stack of 110 parallel CT slices provides a 3D image of approximately 9 mm in the axial direction (*dashed lines*). (B) Representative HR-pQCT reconstructed 3D images of the distal tibia (*left*) and radius (*right*) after the trabecular compartment was separated from the cortical compartment.

Fig. 2.

(A) Schematics of individual trabecula segmentation (ITS)-based morphological analyses of trabecular plates and rods. Orientation, thickness, and surface area/length of each plate and rod were derived based on each segmented individual trabecula. (B, top) Bigger bone size, thinner cortex, and less dense trabecular bone volume of (left) white compared with (right) Chinese-American women illustrated by representative 3D cortical and trabecular bone microarchitecture imaged by HR-pQCT. (Bottom) A cubic trabecular bone volume was extracted and decomposed into individual trabecula represented by different colors. The same trabecular bone volume also was illustrated by green and red to represent platelike and rodlike trabeculae, respectively. Chinese-American women have significantly more platelike trabeculae than white women.

Fig. 3.

Percentage difference in bone area, cortical thickness (Ct.Th), plate and rod bone volume fraction (pBV/TV and rBV/TV), plate and rod number density (pTb.N and rTb.N), plate and rod thickness (pTb.Th and rTb.Th), plate surface area (pTb.S), rod length (rTb.ℓ), plate-to-rod junction density (P-R Junc.D), axial bone volume fraction (aBV/TV), whole-bone stiffness, Young's moduli (E_{11} , E_{22} , and E_{33}), and percentage of load carried by cortical bone (% cort load) between Chinese-American and white women at the distal radius and tibia. *Significant difference between the two racial groups.

Fig. 4.

Relationships between BV/TV and E_{33} of trabecular bone for white and Chinese-American women at (A) the distal radius and (B) the distal tibia. The slope of the structure-function curve (E_{33} versus BV/TV) is significantly greater in Chinese-American women than in white women at both sites ($p < .05$).

Table 1

Anthropometric, Lifestyle Factors, and Biochemical Data

	White, mean $\pm$ SD	Chinese-American, mean $\pm$ SD	<i>p</i> Value, Chinese-American versus white
<i>N</i>	46	49	
Age (years)	35.0 $\pm$ 3.9	35.8 $\pm$ 6.5	.4
Height (cm)	165 $\pm$ 7	162 $\pm$ 5	.01
Weight (kg)	63.3 $\pm$ 16.8	56.9 $\pm$ 9.9	.03
Daily calcium intake (mg)	1394 $\pm$ 1570	885 $\pm$ 557	.04
Physical activity (Baecke Sport Index)	1.59 $\pm$ 0.70	1.08 $\pm$ 0.61	<.001
Alcohol use (%)	6%	11%	.5
Current smokers (%)	4%	6%	.6
Age at menarche (years)	13.0 $\pm$ 1.6	12.7 $\pm$ 1.2	.3
25-Hydroxyvitamin D (ng/mL)	35.9 $\pm$ 13.5	24.7 $\pm$ 8.9	<.001
PTH (pg/mL)	31.2 $\pm$ 12.5	37.2 $\pm$ 13.2	.02

Table 2**Racial Comparison of Bone Density and Microarchitecture**

	White, mean $\pm$ SD	Chinese-American, mean $\pm$ SD	p Value before adjustment
DXA			
Lumbar spine (g/cm ²)	1.020 $\pm$ 0.120	1.027 $\pm$ 0.142	0.79 **
Femoral neck (g/cm ²)	0.818 $\pm$ 0.114	0.783 $\pm$ 0.102	0.12
Total hip (g/cm ²)	0.931 $\pm$ 0.122	0.905 $\pm$ 0.112	0.28
1/3 Radius (g/cm ²)	0.702 $\pm$ 0.051	0.698 $\pm$ 0.057	0.79
HR-pQCT			
Radius			
Bone area (mm ²)	231 $\pm$ 37	210 $\pm$ 50	0.03
Cortical thickness (mm)	0.82 $\pm$ 0.15	0.97 $\pm$ 0.15	0.03 *
TB bone volume fraction (%)	19.6 $\pm$ 6.1	23.9 $\pm$ 7.2	0.002 *
TB number (1/mm)	1.92 $\pm$ 0.23	1.98 $\pm$ 0.23	0.21
Tb thickness (mm)	0.21 $\pm$ 0.01	0.22 $\pm$ 0.01	0.001 *
TB plate bone volume fraction (%)	4.7 $\pm$ 3.5	9.2 $\pm$ 5.2	<0.001 *
TB rod bone volume fraction (%)	14.9 $\pm$ 3.4	14.8 $\pm$ 3.6	0.85
TB plate-to-rod ratio	0.30 $\pm$ 0.20	0.62 $\pm$ 0.35	<0.001 *
TB plate number (1/mm)	1.12 $\pm$ 0.28	1.34 $\pm$ 0.26	<0.001 *
TB rod number (1/mm)	1.78 $\pm$ 0.18	1.74 $\pm$ 0.19	0.35
TB plate thickness (mm)	0.19 $\pm$ 0.02	0.21 $\pm$ 0.02	<0.001 *
TB rod thickness (mm)	0.21 $\pm$ 0.01	0.22 $\pm$ 0.01	<0.001 *
TB plate surface area (mm ²)	0.14 $\pm$ 0.01	0.16 $\pm$ 0.02	<0.001 *
TB rod length (mm)	0.70 $\pm$ 0.05	0.69 $\pm$ 0.05	0.53
TB plate-rod junction density (1/mm ³)	2.30 $\pm$ 1.22	3.15 $\pm$ 1.30	0.002 *
TB axial bone volume fraction (%)	6.9 $\pm$ 3.2	10.3 $\pm$ 4.2	<0.001 *
Tibia			
Bone area (mm ²)	663 $\pm$ 82	625 $\pm$ 122	0.08
Cortical thickness (mm)	1.10 $\pm$ 0.21	1.21 $\pm$ 0.25	0.03 *
TB bone volume fraction (%)	17.7 $\pm$ 4.9	20.2 $\pm$ 4.3	0.01 *
TB number	1.83 $\pm$ 0.22	1.88 $\pm$ 0.16	0.27
TB thickness (mm)	0.21 $\pm$ 0.01	0.22 $\pm$ 0.01	0.34
TB plate bone volume fraction (%)	4.4 $\pm$ 2.7	8.0 $\pm$ 3.9	<0.001 *
TB rod bone volume fraction (%)	13.3 $\pm$ 3.7	12.2 $\pm$ 2.7	0.09
TB plate-to-rod ratio	0.35 $\pm$ 0.22	0.70 $\pm$ 0.42	<0.001 *
TB plate number (1/mm)	1.10 $\pm$ 0.21	1.30 $\pm$ 0.19	<0.001 *
TB rod number (1/mm)	1.68 $\pm$ 0.22	1.63 $\pm$ 0.16	0.26
TB plate thickness (mm)	0.20 $\pm$ 0.01	0.21 $\pm$ 0.01	0.001 *
TB rod thickness (mm)	0.22 $\pm$ 0.01	0.22 $\pm$ 0.01	0.67

	White, mean $\pm$ SD	Chinese-American, mean $\pm$ SD	<i>p</i> Value before adjustment
TB plate surface area (mm ²)	0.14 $\pm$ 0.02	0.16 $\pm$ 0.02	<0.001 *
TB rod length (mm)	0.70 $\pm$ 0.05	0.69 $\pm$ 0.03	0.18
TB plate-rod junction density (1/mm ³)	2.02 $\pm$ 0.87	2.61 $\pm$ 0.76	<0.001 *
TB axial bone volume fraction	6.8 $\pm$ 2.3	8.9 $\pm$ 3.0	<0.001 *
μ FEA			
Radius			
Whole-bone stiffness (kN/mm)	82.6 $\pm$ 15.5	94.0 $\pm$ 16.8	0.001 *
Cortical load distribution (%)	43 $\pm$ 11	46 $\pm$ 11	0.25
<i>E</i> ₁₁ (anteroposterior) (MPa)	312 $\pm$ 196	485 $\pm$ 244	<0.001 *
<i>E</i> ₂₂ (mediolateral) (MPa)	472 $\pm$ 342	791 $\pm$ 496	<0.001 *
<i>E</i> ₃₃ (longitudinal) (MPa)	935 $\pm$ 610	1527 $\pm$ 777	<0.001 *
Tibia			
Whole-bone stiffness (kN/mm)	231 $\pm$ 42	250 $\pm$ 45	0.05
Cortical load distribution (%)	31 $\pm$ 7	34 $\pm$ 6	0.10
<i>E</i> ₁₁ (anteroposterior) (MPa)	217 $\pm$ 114	279 $\pm$ 128	0.01
<i>E</i> ₂₂ (mediolateral) (MPa)	337 $\pm$ 183	482 $\pm$ 216	<0.001 *
<i>E</i> ₃₃ (longitudinal) (MPa)	925 $\pm$ 444	1266 $\pm$ 484	<0.001 *

* *p* Value remained significant after adjustment for weight, sport index, calcium intake, and 25-hydroxyvitamin D level.

** For lumbar spine aBMD, *p* value became significant after adjustment for weight, sport index, calcium intake, and 25-hydroxyvitamin D level.