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Age and sex differences in estimated tibia strength: influence of measurement site

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Abstract

Variability in peripheral Quantitative Computed Tomography (pQCT) measurement sites and outcome variables limit direct comparisons of results between studies. Further, it is unclear what estimates of bone strength are most indicative of changes due to aging, disease, or interventions. The purpose of this study was to examine age and sex differences in estimates of tibia strength. An additional purpose of this study was to determine which tibia site or sites are most sensitive for detecting age and sex differences in tibia strength.

Methods—Self-identifying Caucasian men (n=55) and women (n=59) ages 20–59 years had their tibias measured with pQCT from 5%–85% of limb length in 10% increments distal to proximal. Bone strength index (BSI), strength strain index (SSI), moments of inertia (Ip, Imax, Imin), and strength-to-mass ratios (Ip:Tot.BMC, SSI:Tot.BMC) were quantified.

Results—There were significant ($p<0.01$) site effects for all strength variables and strength to mass ratios. Site*sex interaction effects were significant ($p<0.05$) for all strength variables. Men had greater ($p<0.01$) values than women for all strength variables. Sex differences in Ip, Imax, Ip:Tot.BMC, SSI, and SSI:Tot.BMC ratio were smallest at the 15% site and peaked at various sites, depending on variable. Site*age interactions existed for Imax, Ip:Tot.BMC, and SSI:Tot.BMC. There were significant age effects Imax, Ip:Tot.BMC and SSI:Tot.BMC, as values were lowest in the 20–29 age group.

Conclusion—Age and sex differences varied by measurement site and variable and larger sex differences existed for moments of inertia than SSI. Strength-to-mass ratios may reflect efficiency of the whole bone architecture.

Keywords

pQCT; SSI; bone strength

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Introduction

The ability to resist fracture depends on the ability to accommodate greater mechanical loads than those placed upon the bone (1,2). Bone adapts to loads that are routinely placed on it, and part of bone adaptation is the optimal arrangement of material to improve stiffness, toughness, and strength (2–4). An effective mechanostat, mechanistic pathways for local detection of mechanical loading, should allow for the most efficient arrangement of bone tissue (2–4). Losses in mechanostat sensitivity, either due to aging, altered hormone status or other pathological or idiopathic conditions, may result in bone strength that is not necessarily proportionate to the bone tissue loss due to suboptimal geometry adaptations (1–5). Conversely, it is not clear that the age of peak bone mass coincides with the age of peak bone strength.

Peripheral Quantitative Computed Tomography (pQCT) assesses total, cortical, and trabecular content and tissue distribution in cross-sectional slices of long bones. These data can then be used to calculate section moduli and 2nd moments of inertia to provide information about resistance to fracture from bending and torsional loading. pQCT-assessed bone variables have been shown to strongly predict breaking strength (6–8). Polar strength strain index (SSI), a cortical-weighted section modulus, is the most commonly reported pQCT strength variable. The term bone strength index (BSI) has been used both interchangeably with SSI and as a separate measure of compressive strength at distal tibia sites using a different equation from SSI (6,8–11). Polar, maximum and minimum moments of inertia (I_p , I_{max} , I_{min}) values are sometimes reported in mechanical loading studies (9,12,13), and recently, the use of bone strength-to-bone mass ratios were proposed as an indicator of mechanostat effectiveness (14).

There are data to suggest that pQCT strength variables can predict nonvertebral fractures and discriminate between previously fractured versus nonfractured limbs (15,16). However, to date, there are no recommendations for using strength estimates for bone health assessment or hip fracture risk prediction (17), since a paucity of reference data exists for these measures. Variability in which tibia sites are utilized in studies limits direct study comparison and impedes the development of reference databases. It is currently unclear whether certain tibia site(s) are superior or even ideal for detecting group differences in bone strength estimations. A consensus has not been made as to whether SSI or I_p should be interchangeably used as indicators of bone quality or fracture resistance. Finally, little is known about the distribution of and variability in strength-to-mass ratios in any population (14). Accordingly, the purpose of this study was to examine age and sex differences in tibia strength estimates, and the effects of measurement site on age and sex differences.

Methods

Research Design and Participants

This cross-sectional study employed a mixed factorial research design with two between subject variables (sex and age decade) and one within subject variable (limb site). This study tested healthy, self-identified Caucasian men and women ages 20–59 years who were grouped by decade. Participants had their non-dominant tibia scanned with pQCT at 9 cross-

sectional sites, ranging from 5% to 85% of the limb length. The University of Oklahoma Institutional Review Board approved all methods.

Both pre and postmenopausal women were recruited for this study, but premenopausal women were eumennorrheic, and none were taking sex steroids for at least the previous 12 months. Menstrual cycle characteristics, menopausal status, and history of oral contraceptive or hormone replacement therapy use were self-reported. Potential participants were excluded if they were taking sex steroids, if they weighed more than 300 lbs., had any conditions or were taking medications known to cause significant BMD change, or if they had any metal devices implanted in the tibia. A Block 2005 food frequency questionnaire was used to estimate average daily caloric, macro and micro nutrient intake, and the Bone Specific Physical Activity Questionnaire (BPAQ) was used to determine current, past, and total physical activity (18).

Body Composition

Body weight and height were measured using a wall stadiometer and a Tanita BWB-800 digital scale (Tanita Corporation of America, Inc., Arlington Heights, IL). Bone free lean body mass (BFLBM) and fat mass (FM) of the total body were measured using DXA (GE Lunar Prodigy, Prodigy enCORE software version 13.31.016, Madison, WI). Scan speeds were determined by the measured thickness of the subject at the naval (Thick = >25 cm and Standard = 13 – 25 cm). Urine specific gravity for hydration status was measured using a refractometer (VEE GEE®, Model CLX-1) prior to being scanned on the DXA. All subjects were within our predetermined hydration range (1.004~1.029).

Peripheral Quantitative Computed Tomography (pQCT)

A pQCT scanner XCT 3000 with software version 6.00 (Stratec Medizintechnik GmbH, Pforzheim, Germany) was used to measure and analyze tibia slices at 9 sites of the nondominant tibia from 5–85% (distal to proximal) of the tibia length in 10% increments. Compressive, bending and torsional strength was estimated from these scans and were represented as bone strength (BSI), strength-strain indices (SSI), moments of inertia (I_{max} , I_{min} , I_p), and SSI:Total BMC and I_p :Total BMC ratios. A threshold of 480 mg/cm³ was used for determining strength measures, except for BSI. An outer threshold of 169 mg/cm³ and an inner threshold of 650 mg/cm³ were used for the 5% site for determining BSI because of the thin cortical shell. Since the 15% has a cortical thickness greater than the resolution of the pQCT, the 710 mg/cm³ outer threshold was used.

The Stratec software provided information about mass moments of inertia (I) in the x-y plane; however, the axes of the image were rotated with respect to the principal axes of the tibia slice. To obtain the rotated I_x and I_y , the following translation was used:

$$\alpha = \frac{\tan^{-1} \frac{2I_{xy}}{I_x - I_y}}{2} \quad I_{rotatedx} = \frac{I_x + I_y}{2} + \frac{I_x - I_y}{2} \cos 2\alpha - I_{xy} \sin 2\alpha \quad I_{rotatedy} = \frac{I_x + I_y}{2} - \frac{I_x - I_y}{2} \cos 2\alpha + I_{xy} \sin 2\alpha$$

The larger value was denoted as I_{max} , and the smaller value was denoted as I_{min} (12). Bone strength index (BSI) is a compressive strength index that was calculated for the 5% and 15%

sites because of high relative amounts of compressive loading seen at these sites. BSI was calculated as $\text{Total vBMD}^2 \times \text{Total Area}$ (6). For ease of interpretation, values were divided by 10^6 . SSI, Ip, Imax, and Imin are not reported at the 5% site because this site is particularly influenced by partial volume effects when performing cortical-based analyses because of the thin cortical shell relative to the resolution of the scan (19). In the Bone Density Research Laboratory, the *in vivo* (%CV) precision for measuring total BMC and area and strength measures ranged from 0.3–1.5%. All pQCT scans were performed by the same qualified technician.

Statistical Analyses

Data are reported as mean $\pm$ SE for all dependent variables. Statistical analyses were performed using SPSS for Windows version 18.0 (SPSS, Inc., Chicago, IL). Four (decade) by two (sex) by n (site) repeated measures ANOVAs were used to detect significant interaction (site*age*sex, site*age, site*sex, age*sex) and main (site, age, sex) effects on all tibia variables at each site. When a site*sex interaction was significant, independent t-tests were performed to determine sex differences at each site. When a significant site*age interaction occurred, one-way ANOVAs were used to determine age group differences at each site. When a significant age*sex interaction occurred, sex differences were determined for each age group, and age group differences were determined within each sex. Bonferroni post hoc tests were used for pairwise age-group and site comparison when testing for main effects. Specifically, SSI, Imax, Imin, SSI:Total BMC, and Ip:Total BMC were compared between sites 15%–85%. BSI was compared between sites 5% and 15%. The level of significance was set at $p = 0.05$. The assumption of sphericity was violated in every pQCT-related repeated measures ANOVA, so the Greenhouse-Geisser adjustment was used to determine significance.

Results

Participants

Table 1 presents the age and body composition of the participants. There were a total of 55 women and 59 men. There were 19 postmenopausal women (time since menopause: 1–20 years), 2 perimenopausal women and 38 premenopausal women ($n = 38$). Twenty-seven premenopausal women (71%) were previous oral contraceptive users, and 4 of the postmenopausal women were previous hormone replacement therapy (HRT) users. The time since last hormone usage ranged from 1 year to 31 years.

Physical Activity and Diet

Bone-specific physical activity levels throughout the lifespan were assessed by questionnaire, and are reported in Table 2. Those in the 20s had significantly ($p < 0.05$) greater total and past physical activity scores than those in the 50s, and women had greater total and past scores than men ($p < 0.05$). There were no significant group differences in current bone loading physical activity. There were significant ($p < 0.01$) sex differences in average daily total intake, protein intake and percentage of total intake as protein, where men ate more than women. Calcium intake declined with age in men, and increased with age in women. Nearly half (55/114: 48%) had an average daily calcium intake below the

recommended dietary allowance of 1000 mg/day (20). Over half of the participants (64/114) had an average daily vitamin D intake below the estimated average requirement of 400 IU/day, and 95/114 participants were below the recommended dietary allowance of 600 IU/day (20).

Bone Strength Assessments

Bone strength index data for the tibia 5% and 15% sites are presented in Table 3. BSI had significant ($p < 0.05$) site, sex, age, and site*sex effects. Women had 33.2% and 42.1% lower BSI values than men at the 5% and 15% sites, respectively. The 50–59 group had 28% and 17% lower ($p < 0.05$) BSI values than the 20–29 group.

Figures 1 and 2 present the SSI and Ip at each tibia site. Strength and strength to mass ratios were greatest at the most proximal sites. Site, sex and site*sex effects were significant ($p < 0.01$) for SSI. SSI of the 15% and 25% sites were not significantly different from each other, but all other sites were significantly different. Men had 28.1–31.2% higher SSI values than women. Correcting for BFLBM made the site*sex, age*sex, and site*age*sex interactions nonsignificant ($p = 0.056, 0.061$, and 0.064), and sex differences were reduced to 9.4–14% higher in men. Correcting for FM did not affect the SSI results.

Site*sex interaction, site, and sex effects were significant ($p < 0.01$) for Ip. All sites were significantly ($p < 0.01$) different from each other. Ip values in women were 36–42% lower than values in men, with the smallest differences at the ends of the tibia. When using BFLBM as a covariate, the site*age*sex and age*sex interactions became significant ($p < 0.05$), and the site*age interaction neared significance ($p = 0.067$). The sex difference was largest (26.6% lower in women) in the 40–49 year age group, and was smallest (1.4% higher in women) in the 20–29 year age group. Within each decade, the smallest sex difference was at the 75% site, except for in the 20–29 year group. Using FM as a covariate did not change the results from the ANOVA.

Figures 3 and 4 show the I_{max} and I_{min} values at each site. There were significant ($p < 0.01$) site, site*age, site*sex, and sex effects for I_{max}. The 15% and 25% sites were not significantly different from each other; all other sites were significantly different from the other sites. I_{max} values lowest in the 20–29 group, and were 12.2%–14.2% lower than the 40s age group. The 50–59 group had 6.2% (65)–16.4% (85) lower I_{max} values than the 40s group. I_{max} values were 36.5% (15) – 46.7% (65) lower in women, and sex difference were significant at all sites. Correcting for BFLBM made the age*site interaction not significant, and made the age*sex and age*sex*site interactions significant. In this analysis, sex differences were smallest in 20–29 (<1%) and largest in 40–49 (33%), followed by 30–39 (23%). Further, when correcting for BFLBM, I_{max} was lowest in 20–29 men and highest in 40–49 men, but lowest in 40–49 women and highest in 50–59 women. Age and sex interactions varied by site.

I_{min} had significant ($p < 0.01$) site, site*sex, and sex effects. When correcting for BFLBM, site, sex and site*sex effects were no longer significant. Using FM as a covariate did not affect the I_{min} results. Sex effects were significant ($p < 0.01$) at all sites, where men had

38.2% (85 site) – 62.9% (25 site) greater values than women. Correcting for BFLBM reduced these differences to 0.3–18.4%.

An SSI:Total BMC and an Ip:Total BMC ratio was calculated at each site to determine the bone strength relative to bone mass. Figure 5 presents SSI:ToC ratios at each tibia site. Strength to mass ratio, as represented as SSI:Total BMC, had significant ($p < 0.01$) site, site*age, site*sex, age, and sex effects. All sites were significantly different. The 20–29 age group had significantly lower ($p < 0.05$) SSI:Total BMC than 30–39 (1.3–11.3%) and 50–59 (3.6–10%), and there was a trend ($p = 0.075$) to have lower SSI:Total BMC than 40–49 (1.2–9.2%). Women had 4.8–12.5% lower SSI:Total BMC than men. Site*sex ($p = 0.096$) and sex ($p > 0.10$) were no longer significant when correcting for BFLBM, and sex differences were reduced to being 4.8% lower (at 85% site) to 1.2% greater (at 15% site) in women. Correcting for fat mass did not remove any significant effects.

Site, age, sex, age*site, and sex*site effects were significant ($p < 0.01$) for Ip:Tot.BMC, presented in Figure 6. All sites were significantly different from each other ($p < 0.01$). The 20–29 group had 4–15% lower Ip:Tot.BMC than all other age groups ($p < 0.05$), where differences were largest at the tibia 85% site. Women had 17–25% lower values than men ($p < 0.01$) and differences were significant at all sites. Correcting for BFLBM resulted in the age*sex and age*sex*site interactions becoming significant ($p < 0.05$), but the site*sex interaction became nonsignificant. Values were 2–3% higher in 20–29 women than 20–29 men, but were 9–11% lower in women in the other decade groups.

Calcium intake was not significantly ($p > 0.05$) correlated with any bone strength variables. Vitamin D had sporadic significant weak correlations (0.18–0.22, $p < 0.05$), as SSI, SSI:Tot.BMC, Imin, Imax, and Ip were each correlated with vitamin D at only 1 site, and the site of correlation varied depending on the relationship assessed. Relative protein intake significantly correlated ($r = 0.19–0.31$, $p < 0.05$) with all strength measures at all sites except for SSI:Tot.BMC, where sites 15%, 25%, and 85% were not significant. Protein intake was related to Ip, Imax, and SSI ($r = 0.18–0.28$, $p < 0.05$). Total and past BPAQ scores were typically negatively related to bone strength (SSI, SSI:Tot.BMC, Ip, Imax, Ip:Tot.BMC) values ($r = -0.17–0.28$, $p < 0.05$).

Discussion

The primary finding of this study is large differences in strength and strength-to-mass ratios between men and women were mostly, but not entirely, explained by differences in muscle mass. Fat mass generally did not affect the ANOVA model results. Bone strength and strength to mass ratios were lowest in the 20–29 year old decade. The 30–39 and 40–49 year old decades had the highest estimated bone strength, depending on the strength measurement, and the magnitude of age differences depended on the measurement site. Most tibia sites measured in this study had significantly different amounts of estimated strength and strength-to-mass ratios.

Increased fragility fracture risk in women after middle age may be a result of differences in both the strength and efficiency of whole bone architecture (21–24). Men had greater

SSI:Total BMC ratios than women at all sites except for the 15% site, and greater Ip:Total BMC ratios at all sites. Dividing SSI values by total BMC values to assess strength-to-weight ratios is a slight departure from Capozza et al., where they divided cross-sectional moment of inertia by total BMC. The calculation of a strength-to-weight ratio can be indicative of the efficiency of whole-bone tissue arrangement (14). Thus, it appears from these data that men have a more effective arrangement of bone mass. Even though the SSI:Total BMC ratio appeared to have larger group divergence, the method proposed by Capozza et al. may be as effective of an assessment of wholebone architecture efficiency, but further studies are needed to determine if either assessment are beneficial for assessing bone health (14).

Age-related findings were less consistent and less pronounced than sex differences. Inconsistent age effects and a general lack of age*sex interaction effects were likely related to the lack of age differences in BFLBM and the finding of peak fat mass values in the 40–49 age group. It was expected that fat mass would increase with each decade, and that BFLBM would either remain stable or potentially decrease with each decade, if we found large physical activity differences between age groups (25–28). Age group differences in muscle mass may have resulted in more age group differences in bone strength because of reduced force exerted on the bone. Another plausible reason for fewer age effects than sex effects is that most of these sites contain predominately cortical tissue, which is thought to decline more rapidly at ages older than measured in our sample (29–31).

Calcium and vitamin D were not related to bone characteristics, which is interesting considering such a high proportion of the sample was not ingesting recommended amounts according to Institute of Medicine (20). The proportion of calories ingested as protein, however, was related to bone health. Higher protein intakes have previously been associated with increased BMD and IGF-1 levels and with reduced rates of bone resorption (32,33). Also, since serum samples were not obtained, we cannot state for certain that the participants were vitamin D deficient. Wide ranges of physical activity levels were included to adequately reflect the general healthy population. Specific sports or physical activities were not excluded, as this would have limited to applicability of the findings. While some physical activities have been positively associated with bone characteristics (10,12,13,34–37), some physical activities have been negatively associated with bone health (38–40) but the reasons for the negative association are unclear.

Inconsistencies in tibia measurement sites and outcome variables between studies limit the progression of pQCT into a clinical or diagnostic tool (6,9,11,14,22,36,41). Multiple sites were found to be the peak site for sex differences, depending on the strength variable evaluated. However, the 15% site was routinely the site with the smallest differences. Diaphyseal sites were routinely within 2% of each other's values, however, this is still at or above a difference that can be considered real in some laboratories. The 5% and 85% had the largest age group differences in strength, likely due to the higher trabecular content compared to other sites. These findings illustrate the need for more uniform testing sites between studies.

The cross-sectional design is a limitation of this study because it precludes the ability to address rates of bone strength changes. Longitudinal studies are needed to confirm which sites are most sensitive for detecting change related to fragility fracture risk. Also, further research will be needed to determine whether strength to mass ratios are better indicators of bone health than bone strength or bone mass measures separately.

Conclusion

Sex and age group differences existed in strength and strength to mass ratio estimates in the tibia of healthy men and women, and the degree of difference depended on the measurement site. These data support the need for standardization of measurement sites. More studies are needed to determine fracture risk prediction with strength estimates.

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References

1. Bouxsein ML. Determinants of skeletal fragility. *Best Practice Res Clin Rheumatol*. 2005; 19:897–911.
2. Frost HM. From Wolff's Law to the Utah Paradigm: insights about bone physiology and its clinical applications. *Anat Rec*. 2001; 262:398–419. [PubMed: 11275971]
3. Bouxsein ML. Bone quality: where do we go from here? *Osteoporos Int*. 2003; 14(Suppl 5):S118–S127. [PubMed: 14504716]
4. Frost HM. A 2003 update of bone physiology and Wolff's Law for clinicians. *Angle Orthod*. 2004; 74:3–15. [PubMed: 15038485]
5. Mulvihill BM, Prendergast PJ. An algorithm for bone mechanoresponsiveness: implementation to study the effect of patient-specific cell mechanosensitivity on trabecular bone loss. *Comput Methods Biomech Biomed Engin*. 2008; 11(5):443–451. [PubMed: 18608340]
6. Kontulainen SA, Johnston JD, Liu D, Leung C, Oxland TR, McKay HA. Strength indices from pQCT imaging predict up to 85% of variance in bone failure properties at tibial epiphysis and diaphysis. *J Musculoskelet Neuronal Interact*. 2008; 8(4):401–409. [PubMed: 19147978]
7. Liu D, Manske SL, Kontulainen SA, Tang C, Guy P, Oxland TR, McKay HA. Tibial geometry is associated with failure load ex vivo: a MRI, pQCT, and DXA study. *Osteoporos Int*. 2007; 18:991–997. [PubMed: 17268944]
8. Siu WS, Qin L, Leung KS. pQCT bone strength index may serve as a better predictor than bone mineral density for long bone breaking strength. *J Bone Miner Metab*. 2003; 21:316–322. [PubMed: 12928834]
9. Evans RK, Negus C, Antczak AJ, Yanovich R, Israeli E, Moran DS. Sex differences in parameters of bone strength in new recruits: beyond bone density. *Med Sci Sports Exerc*. 2008; 40(11S):S645–S653. [PubMed: 18849870]
10. Heinonen A, Sievanen H, Kyrolainen H, Perttunen J, Kannus P. Mineral mass, size, and estimated mechanical strength of triple jumpers' lower limb. *Bone*. 2001; 29(3):279–285. [PubMed: 11557373]
11. Macdonald H, Kontulainen S, Petit M, Janssen P, McKay H. Bone strength and its determinants in pre- and early pubertal boys and girls. *Bone*. 2006; 39:598–608. [PubMed: 16600704]
12. Rantalainen T, Nikander R, Heinonen A, Suominen H, Sievanen H. Direction-specific diaphyseal geometry and mineral mass distribution of tibia and fibula: a pQCT study of female athletes representing different exercise loading types. *Calcif Tissue Int*. 2010; 86:447–454. [PubMed: 20383493]

13. Warden SJ, Bogenschutz ED, Smith HD, Gutierrez AR. Throwing induces substantial torsional adaptation within the midshaft humerus of male baseball players. *Bone*. 2009; 45:931–941. [PubMed: 19647807]
14. Capozza RF, Feldman S, Mortarino P, et al. Structural analysis of the human tibia by tomographic (pQCT) serial scans. *J Anat*. 2010; 210:470–481. [PubMed: 20136670]
15. Mikkola T, Sipila S, Portegijs E, et al. Impaired geometric properties of tibia in older women with hip fracture history. *Osteoporos Int*. 2007; 18:1083–1090. [PubMed: 17323107]
16. Sheu Y, Zmuda JM, Boudreau RM, et al. Bone strength measured by peripheral quantitative computed tomography and the risk of nonvertebral fractures: the osteoporotic fractures in men (MrOS) study. *J Bone Miner Res*. 2011; 26(1):63–71. [PubMed: 20593412]
17. Baim S, Binkley N, Bilezikian JP, Kendler DL, Hans DB, Lewiecki EM, Silverman S. Official positions of the International Society for Clinical Densitometry and executive summary of the 2007 ISCD Position Development Conference. *J Clin Densitom*. 2008; 11(1):75–91. [PubMed: 18442754]
18. Weeks BK, Beck BR. The BPAQ: a bone-specific physical activity assessment instrument. *Osteoporos Int*. 2008; 19(11):1567–1577. [PubMed: 18414964]
19. Binkley TL, Specker BL. PQCT measurement of bone parameters in young children: validation of technique. *J Clin Densitom*. 2000; 3(1):9–14. [PubMed: 10745298]
20. Ross, AC.; Taylor, CL.; Yaktine, AL.; Del Valle, HB. Institute of Medicine. Washington DC: The National Academies Press; 2011. Dietary reference intakes for calcium and vitamin D.
21. Cauley, JA.; Ensrud, KE.; Hillier, TA.; Hochberg, M.; Stone, KL.; Cummings, SR. The study of osteoporotic fractures: major findings and contributions. In: Marcus, R.; Feldman, D.; Nelson, DA.; Rosen, CJ., editors. *Osteoporosis Volume I*. Burlington, MA: Elsevier Academic Press; 2008. p. 689-703.
22. Nieves JW, Formica C, Ruffing J, Zion M, Garrett P, Lindsay R, Cosman F. Males have larger skeletal size and bone mass than females, despite comparable body size. *J Bone Miner Res*. 2005; 20(3):529–535. [PubMed: 15746999]
23. Riggs BL, Melton LJ, Robb RA, et al. Population-based study of age and sex differences in bone volumetric density, size, geometry, and structure at different skeletal sites. *J Bone Miner Res*. 2004; 19:1945–1954. [PubMed: 15537436]
24. Roldan EJA, Capiglion R, Cointy GR, Capozza RF, Ferretti. Postmenopausal changes in the distribution of the volumetric BMD of cortical bone. A pQCT study of the human leg. *J Musculoskel Neuron Interact*. 2001; 2(2):157–162.
25. Bemben MG, Massey BH, Bemben DA, Boileau RA, Misner JE. Age-related variability in body composition methods for assessment of percent fat and fat-free mass in men aged 20–74 years. *Age Aging*. 1998; 27:147–153.
26. Kohrt WM, Malley MT, Dalsky GP, Holloszy JO. Body composition of healthy sedentary and trained, young and older men and women. *Med Sci Sports Exerc*. 1992; 24(7):832–837. [PubMed: 1501570]
27. Kyle UG, Genton L, Hans D, Karsegard L, Slosman DO, Pichard C. Age-related differences in fat-free mass, skeletal muscle, body cell mass and fat mass between 18 and 94 years. *Eur J Clin Nutr*. 2001; 55:663–672. [PubMed: 11477465]
28. Van Pelt RE, Davy KP, Stevenson ET, Wilson TM, Jones PP, Desouza CA, Seals DR. Smaller differences in total and regional adiposity with age in women who regularly perform endurance exercise. *Am J Physiol*. 1998; 275(4 pt 1):E626–E634. [PubMed: 9755081]
29. Hernandez ER, Revilla M, Seco-Durban C, Villa LF, Cortes J, Rico H. Heterogeneity of trabecular and cortical postmenopausal bone loss: a longitudinal study with pQCT. *Bone*. 1997; 20(3):283–287. [PubMed: 9071480]
30. Ito M, Nakamura T, Tsurusaki K, Uetani M, Hayashi K. Effects of menopause on age-dependent bone loss in the axial and appendicular skeletons in healthy Japanese women. *Osteoporos Int*. 1999; 10:377–383. [PubMed: 10591835]
31. Riggs BL, Melton LJ, Oberg AL, Atkinson EJ, Khosla S. Substantial trabecular bone loss occurs in young adult women and men: a population-based longitudinal study. *J Bone Miner Res*. 2005; 20(Suppl 1):S4.

32. Darling AL, Millward DJ, Torgerson DJ, Hewitt CE, Lanham-New SA. Dietary protein and bone health: a systematic review and meta-analysis. *Am J Clin Nutr.* 2009; 90(6):1674–1692. [PubMed: 19889822]
33. Sukumar D, Ambia-Sobhan H, Zurfluh R, Schlussek Y, Stahl TJ, Gordon CL, Shapses SA. Areal and volumetric bone mineral density and geometry at two levels of protein intake during caloric restriction: A randomized, controlled trial. *J Bone Miner Res.* 2011; 26(6):1339–1348. [PubMed: 21611972]
34. Ashe MC, Liu-Ambrose TYL, Cooper DML, Khan KM, McKay HA. Muscle power in related to tibial bone strength in older women. *Osteoporos Int.* 2008; 19:1725–1732. [PubMed: 18629571]
35. Kohrt WM, Bloomfield SA, Little KD, Nelson ME, Yingling VR. American College of Sports Medicine Position Stand: physical activity and bone health. *Med Sci Sports Exerc.* 2004; 36(11): 1985–1996. [PubMed: 15514517]
36. Nikander R, Sievanen H, Uusi-Rasi K, Heinonen A, Kannus P. Loading modalities and bone structures at nonweight-bearing upper extremity and weight-bearing lower extremity: a pQCT study of adult female athletes. *Bone.* 2006; 39:886–894. [PubMed: 16731064]
37. Wilks DC, Winwood K, Gilliver SF, et al. Bone mass and geometry of the tibia and the radius of master sprinters, middle and long distance runners, race-walkers and sedentary control participants: a pQCT study. *Bone.* 2009; 45:91–97. [PubMed: 19332164]
38. Barry DW, Kohrt WM. BMD decreases over the course of a year in competitive male cyclists. *J Bone Miner Res.* 2008; 23(4):484–491. [PubMed: 18072875]
39. Ferry B, Duclos M, Burt L, Therre P, Le Gall F, Jaffre C, Courteix D. Bone geometry and strength adaptations to physical constraints inherent in different sports: comparison between elite female soccer players and swimmers. *J Bone Miner Metab.* 2011; 29:342–351. [PubMed: 20963459]
40. Smathers AM, Bemben MG, Bemben DA. Bone density comparisons in male competitive road cyclists and untrained controls. *Med Sci Sports Exerc.* 2009; 41(2):290–296. [PubMed: 19127198]
41. Rittweger J, Simunic B, Bilancio G, et al. Bone loss in the lower leg during 35 days of bed rest is predominantly from the cortical compartment. *Bone.* 2009; 44:612–618. [PubMed: 19168165]

Figure 1. Strength Strain Index (SSI) at Each Tibia Site from 15% to 85% of the Limb Length. Mean $\pm$ SE. $p < 0.01$; * $p < 0.01$: Sex was significant at all sites.

Figure 2.

Polar Moment of Inertia (Ip) at Each Tibia Site from 15% to 85% of the Limb Length. Mean $\pm$ SE. $p < 0.01$; Site, sex and site*sex effects. * $p < 0.01$: Sex was significant at all sites.

Figure 3. Maximum Moment of Inertia (Imax) at Each Tibia Site from 15% to 85% of the Limb Length. Mean $\pm$ SE. $p < 0.01$ Significant site, site*age, site*sex, and sex effects. * $p < 0.01$: Sex significant at all sites.

Figure 4. Minimum Moment of Inertia (Imin) at Each Tibia Site from 15% to 85% of the Limb Length. Mean $\pm$ SE. $p < 0.01$; Significant site, site*sex, and sex effects. * $p < 0.01$: Sex significant at all sites.

Figure 5.

Strength Strain Index to Total BMC Ratio (SSI:Tot.BMC) at Each Tibia Site from 15% to 85% of the Limb Length. Mean $\pm$ SE. $p < 0.01$; Significant site, site*age, site*sex, age, and sex effects. All sites were significantly different from each other. * $p < 0.01$ Sex significant at all sites.

Figure 6.

Polar Moment of Inertia to Total BMC Ratio (Ip:Tot.BMC) at Each Tibia Site from 15% to 85% of the Limb Length. Mean $\pm$ SE. $p < 0.01$; Significant site, site*age, site*sex, age, and sex effects. All sites were significantly different from each other. * $p < 0.01$ Sex significant at all sites. † $p < 0.05$ Pairwise age difference ($p < 0.05$) at this site (20s < 30s, 50s).

Table 1

Age and Body Composition Variables for Each Group. (Mean $\pm$ SE)

Variable	Age & Sex Group	20-29 M = 15 W = 15	30-39 M = 15 W = 14	40-49 M = 10 W = 15	50-59 M = 15 W = 15
Age ^c	Men	24.3 $\pm$ 0.8	34.6 $\pm$ 0.8	46.1 $\pm$ 0.9	54.8 $\pm$ 0.8
(yrs)	Women	21.2 $\pm$ 0.3	35.3 $\pm$ 0.9	47.0 $\pm$ 0.5	55.2 $\pm$ 0.7
Ht ^a	Men	176.9 $\pm$ 1.6	180.4 $\pm$ 1.3	177.3 $\pm$ 1.9	178.9 $\pm$ 2.2
(cm)	Women	165.2 $\pm$ 1.3	163.6 $\pm$ 2.4	164.4 $\pm$ 1.4	165.3 $\pm$ 1.6
Wt ^d	Men	82.9 $\pm$ 4.1	91.7 $\pm$ 3.5	90.0 $\pm$ 5.9	88.1 $\pm$ 4.6
(kg)	Women	65.0 $\pm$ 3.1	69.2 $\pm$ 3.7	78.7 $\pm$ 5.7	73.1 $\pm$ 4.2
BFLBM ^a	Men	63.5 $\pm$ 2.4	61.0 $\pm$ 1.2	60.2 $\pm$ 2.6	59.9 $\pm$ 2.1
(kg)	Women	39.8 $\pm$ 1.1	40.9 $\pm$ 1.9	44.7 $\pm$ 2.0	37.5 $\pm$ 2.9
FM ^c	Men	16.2 $\pm$ 2.1	27.1 $\pm$ 3.0	26.3 $\pm$ 3.9	24.8 $\pm$ 2.9
(kg)	Women	21.9 $\pm$ 2.3	24.8 $\pm$ 2.5	31.7 $\pm$ 4.0	37.5 $\pm$ 2.9
Total body	Men	19.0 $\pm$ 2.2	28.5 $\pm$ 2.4	28.1 $\pm$ 2.6	27.3 $\pm$ 1.7
fat % ^{ac}	Women	33.1 $\pm$ 1.8	35.4 $\pm$ 2.3	38.1 $\pm$ 2.9	39.7 $\pm$ 2.2

Significant sex difference

^a p < 0.01,

^b p < 0.05.

Significant age effect

^c p<0.01

^d p<0.05.

Ht: Height; Wt: Weight; BFLBM: Bone-Free Lean Body Mass; FM: Fat Mass.

Table 2
Physical Activity and Selected Dietary Intake Variables for Each Group. (Mean $\pm$ SE)

Variable	Age & Sex Group	20-29 M = 15 W = 15	30-39 M = 15 W = 14	40-49 M = 10 W = 15	50-59 M = 15 W = 15
Current PA	Men	4.0 $\pm$ 0.8	4.5 $\pm$ 1.6	4.3 $\pm$ 1.4	3.1 $\pm$ 1.1
	Women	11.6 $\pm$ 6.2	5.2 $\pm$ 1.1	3.8 $\pm$ 1.8	2.0 $\pm$ 0.7
Past PA ^{bd}	Men	64.9 $\pm$ 10.3	69.1 $\pm$ 16.6	75.8 $\pm$ 19.8	57.5 $\pm$ 11.4
	Women	179.8 $\pm$ 33.7	125.1 $\pm$ 48.2	112.3 $\pm$ 33.9	36.0 $\pm$ 7.0
Total PA ^{bdf}	Men	34.4 $\pm$ 5.2	36.8 $\pm$ 8.2	40.0 $\pm$ 10.1	30.3 $\pm$ 5.6
	Women	95.7 $\pm$ 15.7	65.2 $\pm$ 24.1	58.1 $\pm$ 17.5	19.0 $\pm$ 3.5
Total Intake ^a	Men	2426 $\pm$ 302	1984 $\pm$ 158	1869 $\pm$ 191	1582 $\pm$ 127
(kcal)	Women	1680 $\pm$ 193	1433 $\pm$ 127	1699 $\pm$ 142	1579 $\pm$ 192
Protein ^{ad} (g)	Men	112 $\pm$ 16	80 $\pm$ 7	74 $\pm$ 9	64 $\pm$ 5
	Women	65 $\pm$ 8	55 $\pm$ 5	68 $\pm$ 6	59 $\pm$ 7
% Protein ^{df}	Men	19 $\pm$ 1	16 $\pm$ 1	16 $\pm$ 0	16 $\pm$ 1
	Women	16 $\pm$ 0	15 $\pm$ 1	16 $\pm$ 1	15 $\pm$ 1
Calcium ^f (mg)	Men	1432 $\pm$ 196	1021 $\pm$ 104	1137 $\pm$ 159	976 $\pm$ 122
	Women	870 $\pm$ 122	919 $\pm$ 103	1265 $\pm$ 150	1265 $\pm$ 150
Vitamin D (IU)	Men	649 $\pm$ 267	338 $\pm$ 63	306 $\pm$ 87	413 $\pm$ 66
	Women	236 $\pm$ 51	336 $\pm$ 64	377 $\pm$ 76	387 $\pm$ 65

Significant sex difference

^a p < 0.01,

^b p < 0.05.

Significant age effect

^c p < 0.01

^d p < 0.05.

Significant age*sex interaction

^e p < 0.01,

$f_p > 0.01$

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Table 3

Bone strength index ($\text{mg}^2/\text{mm}^4/1,000,000$) at the tibia 5% and 15% sites.

Site	Age Groups ^a	Men	Women
5%	20–29	146.8 ± 9.3	101.3 ± 6.8
	30–39	127.5 ± 9.3	103.0 ± 16.1
	40–49	143.1 ± 9.5	86.5 ± 3.6
	50–59	115.6 ± 7.2	77.8 ± 5.8
15%^b	20–29	197.6 ± 7.2	147.4 ± 7.4
	30–39	186.9 ± 10.1	137.2 ± 6.9
	40–49	200.8 ± 11.0	128.1 ± 8.0
	50–59	171.5 ± 6.7	123.6 ± 6.7

Significant site, sex, site*sex, and age effect, $p < 0.05$.

^a20–29 > 50–59 ($p < 0.05$);

^bSex difference greater at 15% site (M > W at both sites).