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Quantifying Leisure Physical Activity and Its Relation to Bone Density and Strength

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Abstract

Purpose—Compare three published methods of quantifying physical activity (total activity, peak strain, and bone-loading exposure (BLE) scores) and identify their associations with areal bone mineral density (aBMD), volumetric BMD (vBMD), and bone strength.

Methods—Postmenopausal women (N = 239; mean age: 53.8 yr) from Iowa (ISU) and California (UCD) completed the Paffenbarger Physical Activity Questionnaire, which was scored with each method. Dual energy x-ray absorptiometry assessed aBMD at the spine, hip, and femoral neck, and peripheral quantitative computed tomography (pQCT) measured vBMD and bone strength properties at the distal tibia and midshaft femur.

Results—UCD women had higher total activity scores and hours per week of leisure activity. All scoring methods were correlated with each other. No method was associated with aBMD. Peak strain score was negatively associated with polar moment of inertia and strength–strain index at the tibia, and total activity score was positively associated with cortical area and thickness at the femur. Separating by geographic site, the peak strain and hip BLE scores were negatively associated with pQCT measures at the tibia and femur among ISU subjects. Among UCD women, no method was significantly associated with any tibia measure, but total activity score was positively associated with measures at the femur ($P < 0.05$ for all associations).

Conclusion—Given the significantly greater hours per week of leisure activity done by UCD subjects, duration may be an important determinant of the effect physical activity has on bone. The positive association between leisure physical activity (assessed by the total activity score) and cortical bone measures in postmenopausal women may indicate a lifestyle factor that can help offset age-related bone loss.

Keywords

PQCT; DXA; BONE LOADING; MENOPAUSE

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Physical activity is a positive modulator of health status, aiding in the prevention and management of chronic diseases including cardiovascular disease, diabetes, obesity, and osteoporosis. Activities that seem to have the most substantial effect on skeletal mass are those that include 1) high-impact, rapid, forceful loading (e.g., jumping, running, gymnastics, volleyball); 2) changing, diverse, or novel loading angles and force magnitudes over time (e.g., ball sports, gymnastics); 3) weight-bearing, high forces (e.g., dancing, weight lifting); and 4) direct impact on the bone of interest (e.g., dominant arm of tennis players) (18). Nonimpact activities such as swimming and cycling (although the torso experiences some weight-bearing forces when using a traditional racing bicycle) typically do not a have an osteogenic effect on bone density (19), but they may be beneficial for bone strength (13).

Bone mineral density (BMD) and strength benefits of physical activities that introduce stress on the skeleton are well documented among various groups, including children (21), young adults (13), and postmenopausal women (1). However, the majority of these studies have either tested weight-bearing exercise interventions or used a sample of elite athletes. Very few studies have observed regularly active, nonelite individuals.

Despite the favorable effects that physical activity—specifically, weight-bearing physical activity—has on bone, there is no well-accepted standardized method for quantifying the loading component of weight-bearing physical activities in observational settings. Broadly, three methods have been employed in the literature to quantify bone loading in human studies. Groothausen et al. (8) have proposed using a "peak strain score" based on the ground reaction forces reported for various physical activities. This method strictly accounts for the magnitude of the load placed on the skeleton during an activity and does not consider duration, frequency, or aerobic intensity. On the other hand, Wang et al. (20) recently have proposed an equation to calculate a "total activity score" that accounts for the frequency, aerobic intensity, duration, and loading components of the three physical activities in which a subject participates most frequently over a specified time period. Finally, Dolan et al. (6) have developed a method to calculate a "bone-loading exposure (BLE) score" at both the hip and spine, based on all physical activities a subject reports during a given time period. This method also considers the frequency and duration of participation for all activities.

Capturing and evaluating the loading effects of physical activity is critical for understanding the positive, and potentially protective, adaptations bones make in response to weight-bearing physical activity. Likewise, having standardized methods to assess these activities is imperative. Therefore, the purpose of this study was to compare these three aforementioned methods of quantifying physical activity, and to identify which method(s), after controlling for current dietary calcium and vitamin D intake, had a stronger association with areal BMD (aBMD; $g \cdot cm^{-2}$) of the spine, hip, and femoral neck using dual-energy x-ray absorptiometry (DXA), as well as with volumetric density (vBMD; $g \cdot cm^{-3}$) and strength measures at the distal tibia and midshaft femur assessed by peripheral quantitative computed tomography (pQCT).

METHODS

Research Design

We enrolled 255 healthy, postmenopausal women (45–65 yr of age) as part of a randomized, double-blind, placebo-controlled, multicenter (Iowa State University (ISU), Ames, IA and University of California at Davis (UCD), Davis, CA) clinical trial. The parent study (*S*oy *I*soflavones for *R*educing *B*one *L*oss; SIRBL) was designed to examine the effect of two doses of isoflavones extracted from soybeans on bone loss during the course of 3 yr in at-risk, early postmenopausal (e.g., less than 10 yr since their last menses) women. As part of an ancillary project, this report examines the baseline cross-sectional relationship between physical activity quantification methods and cortical and trabecular vBMD and strength measures using pQCT and aBMD from DXA.

Subject Screening, Selection, and Characteristics

Subjects were recruited throughout the state of Iowa and the Sacramento region in California through direct mailing lists, stories in local newspapers, local/regional radio advertisements, a story on a local television channel, community announcements, cooperative extension nutrition and health field specialists, and mailings/flyers at local school systems, medical centers/clinics, grocery stores, university campus, public libraries, local women's groups, and local businesses. We screened women who responded ($N = 5255$) to outreach materials initially via a telephone questionnaire to identify healthy women who went through a natural menopause, were ≤ 65 yr of age, nonsmokers, and had a body mass index (BMI, $kg \cdot m^{-2}$) ranging from 18.5 to 29.9 (inclusive). We excluded women with currently diagnosed or previous history of bone disease, renal disease, urinary stones, cancer, malignancy or tumor of any kind, cardiovascular disease, diabetes mellitus, respiratory disease, parathyroid disease, thyroid or liver disease, and/or those women who had a first-degree relative with breast cancer. Additionally, we also excluded women currently using chronic medications, such as cholesterol-lowering or antihypertensive medications, or women who refused to cease taking herbal therapies and/or nutritional/dietary supplements. We also excluded vegans and high alcohol consumers (more than seven servings per week). Use of oral hormone or estrogen therapy, selective estrogen receptor modulators, or other hormones within the last 12 months; use of estrogen or progestogen creams or calcitonin within the last 6 months; use of antibiotics within the last 3 months; and/or any previous use of bisphosphonates were grounds for exclusion. We also excluded subjects with excessive vasomotor symptoms from the study.

Women who met the initial criteria via telephone ($N = 677$) attended a prebaseline appointment at the testing center to determine additional entry criteria. We measured height and weight to confirm BMI status. We used DXA to determine aBMD of the lumbar spine and left proximal femur. Women with evidence of osteopenia or osteoporosis according to lumbar spine and/or proximal femur aBMD (using > 1.5 SD below the young adult mean as cutoff), and women with evidence of previous or existing spinal fractures, were excluded. We also excluded women with spine and/or femur aBMD > 1.0 SD above the mean. If a woman qualified on the basis of her aBMD, blood was drawn for a clinical chemistry profile. We excluded women if their fasted blood values indicated diabetes mellitus (blood glucose > 126 $mg \cdot dL^{-1}$), abnormal renal, liver, and/or thyroid function, or abnormal lipid profile (low-density lipoprotein cholesterol > 160 $mg \cdot dL^{-1}$; triacylglycerol > 200 $mg \cdot dL^{-1}$). To be qualified for the parent study, each woman needed to undergo a transvaginal ultrasound at area clinics (ISU: McFarland Clinic, Ames IA; UCD: Mather VA Medical Center, Mather, CA). Each woman was required to have an endometrial thickness ≤ 5.0 mm to verify postmenopausal status and to rule out endometrial pathology before soy isoflavone exposure in the parent study. Women with a thickness between 5.0 and 6.0 mm were included if they underwent an endometrial biopsy and it proved normal. This paper examines 239 women at baseline who met entry criteria in the parent study.

The study protocol, consent form, and subject-related materials were approved by ISU human subjects review committee (institutional review board; IRB ID# 02-199) and the UCD IRB (ID# 200210884-2). Approvals for the DXA and pQCT procedures were obtained from each institution's IRB and appropriate radiation safety boards. Written informed consent was obtained from all women at the start of prebaseline screening.

Data Collection

Anthropometric measurements—We measured body mass of each subject, who wore minimal clothing, using an electronic scale at UCD and a balance beam scale at ISU (Abco

Health-o-meter; Health-o-meter Inc., Bridgeview, IL). Body mass was recorded to the nearest 0.1 kg. Height was measured using a wall-mounted stadiometer (Ayrton stadiometer, Model S100; Ayrton Corp., Prior Lake, MN) and recorded to the nearest 0.1 cm. Women were without shoes and instructed to stand erect, place hands on their hips, and inhale maximally. Sitting height, with women seated on a stool 44 cm high, was also measured at maximal inhalation using the same wall-mounted stadiometer and recorded to the nearest 0.1 cm. Leg length was calculated as standing height minus sitting height.

Physical activity assessment—Physical activity during the past 12 months was assessed using a modified Paffenbarger Physical Activity Questionnaire (15), which assesses frequency, duration, and aerobic intensity of usual physical activity. Questionnaires were interview-administered at ISU. At UCD, the questionnaires were self-administered; the data were subsequently reviewed and verified by a UCD staff member with each subject. Both leisure and nonleisure activities were reported by all subjects. However, in our analyses we are only reporting leisure physical activity. Activities of daily living that could be considered chores as a contribution to the household, such as household cleaning, gardening, yard work, and farm work, were excluded because two of the three physical activity scoring methods used for this study could not evaluate nonleisure activity (6,8). Therefore, all nonleisure activities were excluded from the analyses.

Physical activity scoring methods—Peak strain score for each woman was assigned, as previously described (8). Jumping activities (e.g., basketball) were assigned a strain score of 3; activities with turning and sprinting actions (e.g., soccer) were given a strain score of 2; all other types of weight-bearing physical activity were assigned a strain score of 1; and non–weight-bearing physical activity received a strain score of 0. The total peak strain score for each woman was calculated as the sum of all strain scores for each current leisure physical activity reported.

The total activity score for each woman was computed using an equation from Wang et al. (20) that accounted for the aerobic intensity, weight-bearing load, frequency, and total duration of participation for each leisure physical activity during the past 12 months. We modified this equation for the present study to include all leisure-time activities a subject reported and not just the three most frequently reported; "load" was assigned a broader range of values (0.5–3.0) rather than designated as a dichotomous variable for weight bearing (yes or no). Values for the load were based on peak strain scores as reported by Groothausen et al. (8). Low-impact activities that fell between categories (like aerobic dance) were given a load of 1.5. Non–weight-bearing physical activities, like swimming and cycling, were assigned a load value of 0.5. Although weight-bearing physical activity has a greater osteogenic effect on the skeleton, non–weight-bearing physical activity may also benefit bone strength (13). Had the load value for non–weight-bearing physical activities been designated as 0, then the additional benefits of frequency, aerobic intensity, and duration of a non–weight-bearing physical activity would have been ignored in the calculation. Thus, non–weight-bearing physical activities were assigned a load value of 0.5 to give these activities some weight in the total activity score. Activities for which ground reaction forces had not been reported in the literature were assigned a load value corresponding to the activity to which it is most similar. Because our objective was not to quantitate ground reaction forces but, rather, to account for the various loads that occur with different activities, the load values were used as a way to rank activities by their weight-bearing impact rather than to precisely depict the ground reaction forces. The following equation was used to calculate total activity score: total activity score = $\sum_{1-n}$ (frequency × aerobic intensity × load × duration), where *n* was the number of activities a subject reported during the past year. The frequency and duration, respectively, were the number of times per week per season and the number of minutes per session a subject participated in an activity during the past year. Aerobic intensity was scored as METs based on those reported in the compendium of physical activities (2).

Recent (during the past year) BLE scores at both the hip and the spine were calculated as previously described (6). For each activity, the product of the bone-loading unit at the hip (which considers both the load magnitude and load rate), the number of seasons of participation, and the frequency of participation was calculated to find the BLE score for each activity. The total BLE score at the hip was then defined as the sum of all hip BLE scores from each leisure physical activity reported during the previous year. The same procedure was performed to determine the total BLE score at the spine, but the bone-loading unit at the spine for each activity was used instead.

Calcium and vitamin D intake—At the baseline testing appointment, we assessed dietary intake using a semi-quantitative food frequency questionnaire from Block Dietary Data Systems (Berkeley, CA) and soy food intake using a soy food questionnaire (Kirk et al., 1999). Current dietary and supplemental calcium and vitamin D daily intakes were assessed using the Block Food Frequency Questionnaire (4).

Bone and body composition measurements—We assessed volumetric BMD (vBMD; $g\cdot cm^{-3}$) at the midshaft femur of the left leg for all subjects except 1 (surgical rod in her left leg because of traumatic fracture; right leg used instead) and in a subset of women at the distal tibia, using pQCT (XCT 3000; STRATEC Medizintechnik, Pforzheim, Germany, Division of Orthometrix; White Plains, NY). Because of improper alignment at the distal tibia site, 51 UCD subjects and 1 ISU subject were excluded, leaving 66 UCD and 121 ISU subjects available for tibial analyses. The midshaft femur was chosen to represent a skeletal site that is predominantly cortical bone, and the distal tibia to represent a site that is predominantly trabecular bone.

Each subject was seated on a nonmovable chair with her spine erect and feet flat on the floor, with the tibia at a 90° angle to the floor. The length of the fibula from the apex of the fibular head to the edge of the lateral malleolus was measured. A scout scan was then conducted to locate the distal end of the tibia, with the computer programmed to subsequently determine the 4% site proximal to the distal end. For the femur, the length of the femur from the apex of the lateral epicondyle to the inguinal crease was measured and then divided by three. The 33% site (moving proximally from the lateral condyle of the femur to the inguinal crease) was marked on the thigh so the mark could be superimposed by the laser once the subject was positioned in the gantry while seated on the pQCT chair. At the tibia, contour mode 3 at 169 $mg\cdot cm^{-3}$ was used to define the total bone. Peel mode 4 at 650 $mg\cdot cm^{-3}$ with a 10% peel was then used to define the marrow area. Cort mode 4 at 200 $mg\cdot cm^{-3}$ was used, with an additional threshold of –50 $mg\cdot cm^{-3}$ for cortical analysis. At the femur, contour mode 1 at 710 $mg\cdot cm^{-3}$ and cort mode 2 at 710 $mg\cdot cm^{-3}$ were used. Slice thickness was 2.2 mm, and the voxel size was set at 0.6 mm at the femur and 0.5 mm at the tibia. Total proximal femur (subregions: femoral neck, total proximal femur (hip)) and lumbar spine (L1–L4 in the anteroposterior projection) aBMD ($g\cdot cm^{-2}$) was assessed via a Delphi W DXA (Hologic, Inc; Bedford, MA) instrument.

Matching instruments at each geographic site and daily calibration ensured that the pQCT and DXA across the two testing locations instruments provided comparable results. One operator at each geographic site performed pQCT and DXA scans. Cross-training for pQCT and DXA scanning between sites has ensured comparable quality control. Laboratory personnel at each site were trained by the manufacturers' technicians and received further training on pQCT software analysis (Bone Diagnostic, Inc.; Fort Atkinson, WI). A research assistant at UCD performed all pQCT scan analyses following guidelines provided by Bone Diagnostic, Inc. The ISU DXA operator performed all DXA scan analyses following Hologic guidelines for BMD using software version 12.3:7. The procedures were approved by the state departments of public health in both Iowa and California. The within-subject *in vivo* precision error (coefficient of variation; CV) for trabecular vBMD and cortical vBMD using pQCT was 1.24% and 0.40% at the distal tibia and midshaft femur, respectively, at ISU (N = 10 per skeletal site) and 0.28% and 0.38%, respectively, at UCD (N = 7 per skeletal site). The ISU within-subject *in vivo* CV for aBMD using DXA was 1.13% at the spine and 0.66% at the hip. The UCD within-subject *in vivo* CV for aBMD using DXA was 0.94% at the spine and 0.77% at the hip.

Bone at the midshaft femur is predominantly cortical; thus, we assessed cortical density ($mg \cdot cm^{-3}$) at this site. Conversely, the 4% distal tibia is predominantly trabecular; thus, we assessed trabecular density ($mg \cdot cm^{-3}$) at this site. The polar moment of inertia (mm^4; field code: ip_cm_w), polar strength–strain index (mm^3; field code: rp_cm_w), and periosteal circumference (mm) were the strength indices measured at both skeletal sites. Additionally, cortical thickness (mm), cortical area (mm^2), and endosteal circumference (mm) were assessed at the femur, and trabecular area (mm^2) was measured at the tibia.

The resistance of bone to torsion, described as the polar moment of inertia, was found by taking the sum of the product of each voxel area (A) and the square of the voxel's respective distance (d_z) to the neutral axis: polar moment of inertia = $[\sum (A d_z^2)]$. The strength–strain index, which also represents the torsional resistance of bone, takes into account both the structural and material properties of bone, the latter of which are represented by the quotient of cortical density and normal physiological density (taken to be 1200 $mg \cdot cm^{-3}$). pQCT cannot directly measure the material properties of bone, but the quotient of cortical density and normal physiological density has a very strong relationship with bone elastic modulus (R^2 = 0.73–0.88) (15), which is a material property (9). Therefore, strength–strain index was determined using the following equation: strength– strain index = $\sum ((A d_z^2[\text{cortical density/normal density}])/d_{max})$, where d_{max} is the maximum distance of a voxel from the neutral axis.

Statistical Analyses

Descriptive statistics were used to characterize the subjects in the study. Pearson correlation analysis depicted the linear relationship among the three physical activity scoring methods. The relationship among physical activity and bone density and strength was first evaluated with Pearson correlation analysis, which examined the simple correlations among physical activity scores and bone density and strength statistics. The relationship between a single physical activity score from one method alone and each density and strength measure was then evaluated using separate multiple linear regression models. This was performed for all three methods. Because of the significant difference in hours per week of leisure physical activity between the women at ISU and UCD, all analyses were also run separately for each geographic site.

Because the load experienced at the distal tibia and midshaft femur is more likely to be similar to that experienced at the hip, hip BLE score was used, and spine BLE score was excluded, in models that entered all scoring methods simultaneously. For models predicting spinal aBMD, spine BLE score was used instead of hip BLE score. Covariates accounted for in all regression analyses were current dietary and supplemental calcium and vitamin D intake, age, body mass, and years since menopause. In addition, height was included in models explaining aBMD of the spine, hip, and femoral neck, whereas leg length was included in models explaining vBMD or strength of the tibia or femur to reflect the mechanical lever arm effect that the leg exhibits with movement. For each density and strength measure, the percentage of variation explained (R^2) by physical activity together with all covariates was also calculated. The level of significance was set at $P < 0.05$. All analyses were performed using SPSS (version 15.0, Chicago, IL).

RESULTS

Descriptive characteristics

Descriptive characteristics of the 239 subjects are presented in Table 1. At baseline, the mean age was 53.8 yr and the average number of years since menopause was 3.5. There was no significant difference between geographic sites for age, body mass, height, leg length, years since menopause, and hip or spine BLE scores. Significant differences between ISU and UCD were observed for total activity score and hours per week of physical activity, with UCD reporting higher values for both variables. There were no differences observed in DXA-related variables; however, many pQCT measures at the midshaft femur were significantly different between geographic sites.

Relationship among physical activity scoring methods

All scoring methods were significantly correlated with each other (Table 2). The BLE scores at the hip and spine had a nearly perfect association (r = 0.963), and a strong correlation was also observed between peak strain score and BLE score at the hip (r = 0.706) and at the spine (r = 0.712). The correlations between total activity score and BLE scores at the hip (r = 0.714) and spine (r = 0.729) were also significant. Although a significant association was observed between total activity score and peak strain score, the strength of the relationship was only moderate (r = 0.595) ($P < 0.01$ for all associations).

Associations among physical activity, aBMD, vBMD, and strength

Using Pearson correlation analysis, no physical activity score was significantly associated with aBMD or any bone parameter at the distal tibia or midshaft femur. After accounting for covariates in multiple linear regression models with total activity score, peak strain score, or BLE score as contributors to aBMD at the spine, hip, or femoral neck, no physical activity scoring method was significantly associated with aBMD at any of the three bone sites. Body mass was the only significant contributor ($P < 0.05$). At the tibia, the peak strain score was negatively associated with polar moment of inertia (β = –0.126, P = 0.048) and strength–strain index (β = –0.132, P = 0.045) (Table 3A), but there were no significant associations with either the total activity or hip BLE score and pQCT measures at the distal tibia. Body mass and leg length were the only other significant contributors to tibia vBMD and strength measures.

When the tibia analyses were run separately for each geographic site, there were still no significant associations between physical activity scores and aBMD (data not shown). However, among ISU women the peak strain score was negatively associated with strength–strain index (β = –0.194, P = 0.018), and the hip BLE score was negatively associated with polar moment of inertia and strength–strain index ($P < 0.05$ for both) (Table 3B). No physical activity score was significantly associated with any tibia measure among UCD women.

In contrast, when each physical activity method was entered individually, along with potential covariates, into multiple linear regression models to determine its contribution to pQCT vBMD and strength properties at the midshaft femur, only total activity score was a significant contributor to cortical area (β = 0.161, P = 0.011) and cortical thickness (β = 0.145, P = 0.027) (Table 4A). No other significant associations were observed among physical activity scoring methods and pQCT vBMD or strength variables at the midshaft femur when all subjects were analyzed together.

However, among ISU women, the peak strain score was negatively associated with femur periosteal circumference, endosteal circumference, and polar moment of inertia ($P < 0.02$ for all), and the hip BLE score was negatively associated with femur polar moment of inertia and strength–strain index ($P < 0.05$ for both) (Table 4B). On the other hand, among the UCD women, total activity score was positively associated with femur cortical area (β = 0.208, P = 0.017) and polar moment of inertia (β = 0.142, P = 0.046) (Table 4C). No other physical activity score was associated with any pQCT femur measure among UCD women.

DISCUSSION

In the present study, we sought to determine which leisure physical activity scoring method was most strongly associated with 1) aBMD at the spine, hip, and femoral neck; and 2) pQCT vBMD and strength measures at the distal tibia and midshaft femur. Our results show that the scores from all three methods were significantly correlated with one another, suggesting that the three methods similarly reflect the various aspects of physical activity (duration, aerobic intensity, and load). None of the physical activity scoring methods were associated with aBMD at the spine, hip, or femoral neck, which is similar to the results found by Bassey et al. (3) regarding physical activity and aBMD in their sample of postmenopausal women. Only total activity score was a significant contributor to femur cortical area, but after separating the subjects by geographic site, total activity score was consistently and positively associated with femur pQCT measures among UCD women, whereas peak strain and hip BLE scores were significant, yet negative, contributors to many femur and tibia parameters among ISU women. The contrasting results may be the result of some significantly different characteristics between the women at ISU and UCD.

Hours per week of leisure physical activity were significantly different between ISU and UCD, which most likely influenced the total activity score, whose calculation is dependent on specific leisure activity duration, unlike the other two scoring methods. Additionally, there were significant differences in the pQCT femur measures between ISU and UCD, particularly with respect to the greater variability in the measurements at UCD. After accounting for covariates, the total activity score was not significantly associated with any pQCT femur measure among the ISU women, although it was positively associated with cortical area and polar moment of inertia at the femur among the UCD women. This suggests that hours per week of leisure physical activity—as incorporated into the total activity score—may play a beneficial role in building or maintaining cortical bone properties at the midshaft femur.

On average, the ISU women reported 3.6 $h \cdot wk^{-1}$ of leisure activity, whereas the UCD women reported an average of 5.1 $h \cdot wk^{-1}$. Lorentzon et al. (13) have suggested that 4 $h \cdot wk^{-1}$ of physical activity is the threshold required to induce a positive bone response, below which no effect will be observed. On average, the ISU subjects were below this threshold, whereas the UCD subjects were above it. In fact, more than half of UCD subjects participated in leisure physical activities for four or more hours per week, whereas fewer than 40% of ISU subjects did the same. Furthermore, when we ran the analyses using only the subjects who participated in leisure physical activities for less than 4 $h \cdot wk^{-1}$, all the positive associations observed between total activity score and femur pQCT measures disappeared (not shown). This was particularly obvious among the UCD women whose total activity scores consistently had positive associations with femur pQCT measures when all UCD women were included in the analyses. This supports the theory that a threshold level of activity may need to be reached for leisure physical activity to exert a positive effect on bone.

The lack of many positive, significant associations between physical activity scores and femur or tibia measures using all ISU and UCD subjects combined was surprising. In terms of the total activity score, the fewer hours per week of leisure physical activity by ISU women may have countered the greater number of hours per week by UCD women, negating most relationships between leisure activity and bone. Only total activity score showed a positive relationship with cortical area and thickness at the femur with all 239 subjects included in the analyses. There was not a significant difference in peak strain or hip BLE scores between ISU

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and UCD, but the peak strain score had a negative relationship with both polar moment of inertia and strength–strain index at the distal tibia, using all ISU and UCD subjects. Likewise, among only ISU women, the peak strain and hip BLE scores had negative relationships with multiple parameters at the distal tibia. The negative relationships observed between tibial parameters and physical activity among ISU women, but not among UCD women, suggest that the larger sample size of ISU compared with UCD for the tibia analyses may have influenced the results observed among the peak strain score and polar moment of inertia and strength–strain index in the models using all subjects combined. Regardless, the reason for this inverse relationship is not clear, and because of the cross-sectional nature of this study, we cannot prove that physical activity caused a decrease in these bone measurements.

In addition to the negative associations observed between physical activity scores and tibial pQCT measures with all subjects, negative relationships were also seen between the peak strain and hip BLE scores and femur strength parameters among ISU subjects. These negative associations contradict the majority of the literature that indicates that exercise has a beneficial effect on bone (12). Other studies have found that physical activity was primarily associated with cortical bone size (14,20), yet the influence of physical activity on trabecular vBMD and size is less clear (1,20). The absence of estrogen that accompanies menopause has a profound, negative effect on the skeleton, particularly in the first 5–10 yr after menopause, with a preferential loss of trabecular compared with cortical bone (7). Therefore, any positive effects that physical activity may have on trabecular skeletal sites may be masked by the changes bone undergoes in response to estrogen deficiency, and this may partially explain the absence of positive relationships observed between physical activity and tibia strength measures. However, this does not explain the negative associations observed between physical activity scores and measures at the midshaft femur among the ISU women. On the basis of these data, our results suggest that either these women did not participate in enough weight-bearing activities to exert a positive effect on bone or that they did not participate in leisure activities for a sufficient duration to induce a positive effect. Indeed, more than 60% of the women at ISU did less than 4 $h \cdot wk^{-1}$ of leisure activity.

In other studies examining the relationship between physical activity and bone parameters among postmenopausal women, the subjects have been much older than our subjects (20), participating in an exercise intervention (1), or categorized into “high” or “low” physical activity groups (20). The women in our present study were all in their early postmenopausal years, did relatively low amounts of physical activity, and were analyzed using linear regression. However, because of the negative relationship we observed between physical activity (using the peak strain and hip BLE scoring methods) and some bone parameters among the ISU subjects, we went back and categorized the subjects into two groups (“high” and “low”) for both the peak strain and hip BLE scores (using the median score to divide the groups). Using these categorized variables, neither the peak strain nor hip BLE scores were significantly associated with any bone parameter, which opposes the results we found using linear regression and exemplifies the need for further examination of longitudinal data. Information regarding changes in bone (as measured with pQCT) in early postmenopausal women who are regularly active is very limited, and it is apparent that more information is needed to develop a clearer understanding of the geometrical changes that occur with aging and the role that physical activity plays in a nonintervention setting.

Physical activity is thought to increase bone strength through periosteal apposition because this surface is exposed to the greatest amount of mechanical stress (17). No physical activity score was positively associated with periosteal circumference in this study. However, the polar moment of inertia, whose calculation is dependent on the outer bone circumference, was positively associated with physical activity among UCD women. Regardless of activity level, though, both the periosteal circumference and endosteal circumference are reported to increase with age (10,20). Although higher activity levels may have contributed to the positive and significant association observed between physical activity and polar moment of inertia among UCD women, it is unclear why associations among physical activity scores and periosteal circumference and endosteal circumference were negative for the women at ISU. One possible explanation is that the lower leisure activity levels among ISU subjects may not be sufficient to counter age-related endosteal resorption. Unfortunately, the cross-sectional nature of this study makes it difficult to demonstrate a causal relationship.

Regardless of geographic site, no physical activity scoring method was significantly associated with aBMD at the spine, hip, or femoral neck. Given that the total activity and peak strain scoring methods were designed to capture the load experienced by the leg (as opposed to the hip or spine) during a specific activity, the lack of relationship between these methods and any of the aBMD measures suggests that these two methods do not accurately depict the weight-bearing load experienced by the axial skeleton. However, the BLE score was specifically designed to capture the load experienced at the spine and hip, and, therefore, the lack of relationship observed between this method and aBMD cannot be explained by a failure to assess loads at these bone sites. Using this BLE scoring method, Dolan et al. (6) also failed to detect a significant relationship between BLE score and spinal aBMD, but they did find a significant relationship between hip and spine BLE scores and aBMD at the femoral neck in women 18–45 yr. In our cohort of postmenopausal women, the hormonal impact on bone (i.e., the absence of estrogen) may outweigh any effect that physical activity has on the skeleton and, thus, may partially explain the conflicting results between findings of Dolan et al. (6) and our results. On the other hand, these women were recruited for the parent study whose inclusion criteria were a hip and spine DXA *T*-score within the range of –1.7 to +1.0. This relatively narrow range may have precluded us from observing a statistically significant association between physical activity and aBMD. Whether the relationship would be more significant between BLE score and aBMD at the spine, hip, or femoral neck among a group of early postmenopausal women with a greater range in *T*-scores remains to be determined.

Given the known positive effects of adequate calcium and vitamin D intake on bone in postmenopausal women (5), it is interesting that in models with density or strength measures as outcomes, only femoral neck aBMD and tibial trabecular area models revealed that calcium was a significant contributor. Surprisingly, these observed relationships—albeit modest—were negative, except for the positive association observed between calcium and femoral neck aBMD. Although the women at ISU had a significantly greater intake of both calcium (average intake 1314 $mg \cdot d^{-1}$) and vitamin D compared with the women at UCD, the average calcium intake at UCD was 1125 $mg \cdot d^{-1}$, which is close to the DRI of 1200 $mg \cdot d^{-1}$ for women older than 50 yr. Furthermore, more than 42% of the women at UCD reached this DRI, as did nearly 55% of the women at ISU. However, we assessed dietary intake on the basis of a food frequency questionnaire, which is not considered the gold standard in assessing dietary intake. Similar to our results, Uusi-Rasi et al. (19) likewise found no association between calcium intake and vBMD or strength measures at the distal tibia.

Our study was not without weaknesses. Because of its cross-sectional nature, we cannot determine whether the relationships we observed between physical activity and bone measures were causal. Additionally, each subject recalled and self-reported her physical activities from the previous year, which may have introduced recall bias, limiting the interpretation of our findings. It is also possible that activities beyond those that were captured under our definition of *leisure physical activity* contribute to the geometry and density of the skeleton. Nonleisure activities, including occupation- and household-related physical activities such as farm work, yard work, gardening, or cleaning, were not included in the primary analyses of the present study, because these activities do not lend themselves to analysis by the BLE or peak strain methods. However, we did examine nonleisure activities reported by the subjects using the total activity score, and we found no difference between ISU and UCD in hours per week of nonleisure activity (ISU = 4.4 h·wk^{-1}, UCD = 4.5 h·wk^{-1}; P = 0.904) or nonleisure physical activity score (P = 0.977), suggesting that the differences observed between ISU and UCD were not a result of different levels of nonleisure physical activity. Nevertheless, future studies should examine the impact of nonleisure physical activities—in addition to leisure physical activities—on measures of bone density and strength.

It is clear that bones cannot adapt to high mechanical forces purely by increasing their mass—structural adaptations that impart improvements in bone strength are necessary to maximally accommodate increasing loads. The present data indicate that weight-bearing physical activity, as assessed by a method that accounts for the duration and cardiovascular intensity of activities—such as the total activity score—has a beneficial effect on the geometry (and, therefore, strength) of cortical bone in postmenopausal women who are physically active an average of four or more hours a week. This may be especially important for this population of women whose top reported activities were walking and biking—both of which have very low ground-reaction forces that, alone, may not be great enough to induce a significant and positive effect on bone. An adequate duration of physical activity, in addition to the load-bearing nature and aerobic intensity of the activity, may be beneficial as a means to increase bone strength despite menopause-induced bone loss. Longitudinal studies are needed to determine whether exercise-stimulated bone strength improvements are an effective preventive adaptation against osteoporosis-related fractures.

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TABLE 1

A. Descriptive characteristics of subjects at each geographic site.

	ISU Mean (SD)	UCD Mean (SD)	Total Mean (SD)
	(*N* = 122)	**(*N* = 117)**	**(*N* = 239)**
Age (yr)	53.4 (3.0)	54.2 (3.5)	53.8 (3.3)
Body mass (kg)	67.9 (8.7)	67.7 (10.0)	67.8 (9.3)
Height (cm)	165.3 (6.0)	164.3 (6.6)	164.8 (6.3)
Leg length (cm)	32.0 (4.4)	32.2 (4.5)	32.1 (4.4)
Years since menopause	3.3 (1.9)	3.6 (2.1)	3.5 (2.0)
Physical activity			
Peak strain score	2.1 (1.4)	2.1 (1.6)	2.1 (1.5)
Total activity score	100,532 (105,915)	167,572 (188,483)*	133,350 (155,390)
Hip bone–loading exposure score	33.7 (21.0)	32.7 (23.6)	33.2 (22.3)
Spine bone–loading exposure score	27.5 (20.3)	27.1 (21.5)	27.3 (20.8)
Hours per week	3.6 (2.6)	5.1 (4.2)*	4.3 (3.6)

B. Dual-energy x-ray absorptiometry (DXA) areal bone mineral density (aBMD) and peripheral quantitative computed tomography (pQCT) volumetric bone mineral density (vBMD) and strength measures of subjects at each geographic site.

	ISU Mean (SD)	UCD Mean (SD)	Total Mean (SD)
DXA	(*N* = 122)	(*N* = 117)	(*N* = 239)
Spine aBMD ($g{\cdot}cm^{-2}$)	1.003 (0.075)	0.987 (0.079)	0.994 (0.078)
Hip aBMD ($g{\cdot}cm^{-2}$)	0.907 (0.076)	0.916 (0.073)	0.910 (0.074)
Femoral neck aBMD ($g{\cdot}cm^{-2}$)	0.753 (0.065)	0.746 (0.072)	0.748 (0.069)
pQCT†	(*N* = 121)	(*N* = 66)	(*N* = 187)
Tibia			
Trabecular density ($mg{\cdot}cm^{-3}$)	234.6 (30.3)	234.4 (31.6)	234.6 (30.7)
Trabecular area (mm^2)	790.9 (96.7)	770.2 (92.3)	783.6 (95.5)
Periosteal circumference (mm)	110.7 (6.2)	109.3 (5.9)	110.2 (6.1)
Polar moment of inertia (mm^4)	47,194.0 (8043.2)	45,808.6 (8834.5)	46,705.0 (8333.9)
Strength–strain index (mm^3)	2206.5 (295.2)	2160.9 (345.5)	2190.4 (313.7)
Femur	(*N* = 122)	(*N* = 117)	(*N* = 239)
Cortical density ($mg{\cdot}cm^{-3}$)	1110.9 (22.1)	1124.0 (24.8)*	1117.3 (24.3)
Cortical area (mm^2)	288.4 (26.4)	301.8 (31.2)*	294.9 (29.5)
Cortical thickness (mm)	3.8 (0.5)	4.3 (0.6)*	4.1 (0.6)
Periosteal circumference (mm)	88.2 (5.8)	84.5 (6.6)*	86.4 (6.5)
Endosteal circumference (mm)	64.2 (8.4)	57.5 (9.0)*	60.9 (9.4)
Polar moment of inertia (mm^4)	40,992.5 (7188.7)	38,385.3 (8883.3)*	39,716.2 (8151.1)
Strength–strain index (mm^3)	2547.8 (313.0)	2483.4 (419.0)	2516.3 (369.4)

*Significantly different from Iowa State University subjects, $P < 0.05$.

†At the tibia, contour mode 3 at 169 mg·cm^{-3} was used to define the total bone. Peel mode 4 at 650 mg·cm^{-3} with a 10% peel was then used to define the trabecular area. Cort mode 4 at 200 mg·cm^{-3} was used with an additional threshold of –50 mg·cm^{-3} for cortical analysis. At the femur, contour mode 1 at 710 mg·cm^{-3} and cort mode 2 at 710 mg·cm^{-3} were used.

TABLE 2

Pearson correlation coefficients among physical activity scoring methods (N = 239).

	Peak Strain Score[a]	**Hip BLE Score**[b]	**Spine BLE Score**[c]
Total activity score[d]	0.595*	0.714*	0.729*
Peak strain score		0.706*	0.712*
Hip BLE score			0.963*

BLE, bone-loading exposure.

[a]Total peak strain score = Σ (strain scores for all leisure physical activities).

[b]Hip BLE score = Σ_{1-n} (hip loading unit × number of seasons × frequency × years).

[c]Spine BLE score = Σ_{1-n} (spine loading unit × number of seasons × frequency × years).

[d]Total activity score = Σ_{1-n} (frequency × intensity × load × duration).

*$P < 0.01$.

TABLE 3

A. Contribution of peak strain score and other factors to selected peripheral quantitative computed tomography strength measures at the distal tibia (*N* = 239).†

Contributors	Polar Moment of Inertia	Strength–Strain Index
Model R^2	0.346**	0.301**
Peak strain score	–0.126*	–0.132*
Body mass	0.287**	0.258**
Leg length	0.382**	0.354**

B. Contribution of physical activity scores and other factors to selected peripheral quantitative computed tomography strength measures at the distal tibia among the subjects at Iowa State University only (*N* = 122).†‡

Contributors	Polar Moment of Inertia	Strength–Strain Index
Using peak strain score		
Model R^2		0.335**
Peak strain score	NS	–0.194*
Body mass		0.175*
Leg length		0.426**
Using hip BLE score		
Model R^2	0.385**	0.339**
Hip BLE score	–0.181*	–0.208*
Body mass	0.231**	0.175*
Leg length	0.417**	0.393**

NS, not significant.

BLE, bone-loading exposure.

* $P < 0.05$

** $P < 0.01$.

† Values are standardized regression coefficients. Models were generated using multiple linear regression analysis and accounted for calcium and vitamin D intake, body mass, leg length, age, and years since menopause. Only outcome variables for which a physical activity scoring method was a significant contributor are shown.

‡ Total activity score was not a significant contributor to any measure at the distal tibia.

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TABLE 4

A. Contribution of total activity score and other factors to cortical area at the midshaft femur (*N* = 239).†

Contributors	Cortical Area	Cortical Thickness
Model R^2	0.132**	0.052
Total activity score	0.161*	0.145*
Body mass	0.189**	NS
Leg length	0.215**	NS

B. Contribution of physical scores and other factors to peripheral quantitative computed tomography measures at the midshaft femur using Iowa State University subjects only (*N* = 122).†‡

Contributors	Periosteal Circumference	Endosteal Circumference	Polar Moment of Inertia	Strength–Strain Index
Using peak strain score				
Model R^2	0.306**	0.233**	0.336**	
Peak strain score	–0.206*	–0.210*	–0.189*	NS
Body mass	0.216*	0.140	0.280**	
Leg length	0.356**	0.333**	0.329**	
Using hip BLE score				
Model R^2			0.335**	0.320**
Hip BLE score	NS	NS	–0.190*	–0.222**
Body mass			0.281**	0.259**
Leg length			0.299**	0.262**
YSM			–0.162	–0.179*

C. Contribution of total activity score and other factors to peripheral quantitative computed tomography measures at the midshaft femur using University of California–Davis subjects only (*N* = 117).†

Contributors	Cortical Area	Polar Moment of Inertia
Model R^2	0.241**	0.493**
Total activity score	0.208*	0.142*
Body mass	0.164	0.266**
Leg length	0.350**	0.550**

* $P < 0.05$

** $P < 0.01$.

† Values are standardized regression coefficients. Models were generated using stepwise regression analysis and accounted for calcium and vitamin D intake, body mass, leg length, age, and years since menopause. Only outcome variables for which a physical activity scoring method was a significant contributor are shown.

‡Total activity score was not a significant contributor to any peripheral quantitative computed tomography femur measure among Iowa State University subjects.