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Skeletal loading score is associated with bone microarchitecture in young adults

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ABSTRACT

Physical activity that involves high strain magnitudes and high rates of loading is reported to be most effective in eliciting an osteogenic bone response. Whether a history of participation in osteogenic activities during youth, as well as current participation in osteogenic activities, contributes to young adult bone microarchitecture and strength is unknown. PURPOSE: We determined the association between a new skeletal loading (SkL) score reflecting physical activity from age 11 to adulthood, the bone specific physical activity questionnaire (BPAQ) and bone microarchitecture in young Black and White men and women.

Methods: We conducted a cross-sectional study of young ([mean ± SD] 23.7 ± 3.3 years) Black ($n = 51$ women, $n = 31$ men) and White ($n = 50$ women, $n = 49$ men) adults. Microarchitecture and estimated bone strength (by micro-finite element analysis) were assessed at the ultradistal tibia using high-resolution peripheral quantitative computed tomography (HR-pQCT). Physical activity questionnaires were administered and a SkL score was derived based on ground reaction force, rate of loading, frequency, duration, and life period of participation per activity from age 11 onwards. BPAQ score was also calculated. We used multiple linear regression to determine associations between both SkL score and BPAQ score and bone outcomes, adjusting for age, height, weight, sex, and race.

Results: We found that SkL score, which accounts for current and historical physical activity, was significantly associated with most cortical bone parameters at the tibia including area, area fraction, porosity, thickness, and tissue mineral density ($R^2 = 0.27$–0.55, all $p < 0.01$). Further, trabecular thickness, separation, number, and bone mineral density ($R^2 = 0.22$–0.32, all $p < 0.01$), as well as stiffness and failure load ($R^2 = 0.63$–0.65, all $p < 0.01$), were associated with the SkL score. The BPAQ was also significantly associated with most bone parameters, but to a lesser degree than SkL score.

Conclusion: These findings suggest that among young adults, greater amounts of osteogenic physical activity, as assessed by the SkL score and BPAQ are associated with improved bone microarchitecture and strength. With the potential to predict bone parameters in young adults, these scores may ultimately serve to identify those most vulnerable to fracture.

Abbreviations: BPAQ, bone specific physical activity questionnaire; pBPAQ, past bone specific physical activity questionnaire; cBPAQ, current bone specific physical activity questionnaire; tBPAQ, total bone specific physical activity questionnaire; SkL, Skeletal Loading; C, loading coefficient; vGRF, vertical ground reaction force; PA, posterior-anterior; FN, femoral neck; TH, total hip; HR-pQCT, high-resolution peripheral quantitative computed tomography; FEA, finite element analysis; Tt.Ar, total cross-sectional area; Tt.vBMD, total vBMD; Tb.vBMD, trabecular vBMD; Tb.N, trabecular number; Tb.Sp, trabecular separation; Tb.Th, trabecular thickness; Ct.Ar, cortical area; Ct.Th, cortical thickness; Ct.vBMD, cortical vBMD; Ct.TMD, cortical tissue mineral density; Ct.Po, cortical porosity; Tb.Ar, trabecular area; Ct.Ar/Tt.Ar, cortical area fraction; μFEA, micro-finite-element-analysis; BLHQ, bone loading history questionnaire; PYPAQ, past year physical activity questionnaire

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1. Introduction

It is well established that mechanical loading through physical activity has a positive effect on bone density, strength, and microarchitecture during growth [1–5]. In particular, activities that involve high-strain magnitudes and high rates of loading are most effective in eliciting an osteogenic response [6–10]. Several attempts have been made to assess physical activity patterns during certain life periods to estimate mechanical loading and ultimately determine the influence of physical activity on bone properties such as bone density and strength [11–15]. Most methods utilize questionnaires that rely on assumptions regarding which activities may be osteogenic to assess physical activity [4,14,15]. These studies have also focused on homogeneous study populations, usually White men and women [11–15]. The bone specific physical activity questionnaire (BPAQ) is one of the more commonly used bone relevant physical activity assessment tools [12]. This questionnaire is designed to capture past and current physical activity patterns. The BPAQ utilizes ground reaction forces and rates of loading as a basis for creating a loading coefficient, which is then used in an age-weighted algorithm to generate a score [12]. The BPAQ includes three possible measures, past BPAQ (pBPAQ), current BPAQ (cBPAQ), and total BPAQ (tBPAQ). Current physical activity as captured by the cBPAQ has been shown to predict areal bone mineral density (aBMD) by dual-energy X-ray absorptiometry (DXA) in men, but not women, while the pBPAQ (based historical physical activity, excluding the most recent year) is predictive of calcaneal broadband ultrasound attenuation (BUA) in women, but not men [12]. Another study reported that among girls, the cBPAQ is associated with cortical bone microarchitecture measured by magnetic resonance imaging (MRI) [11]. The tBPAQ is the most comprehensive assessment of lifelong loading, but findings to date have been inconsistent regarding its association with bone outcomes. Reports suggest the tBPAQ is associated with bone geometry variables and total hip and femoral neck aBMD in young women [16,17], but not middle-aged women [17]. Conversely, another study reports no association between the tBPAQ and aBMD at any site in young women or young men [12], whereas in older men tBPAQ is associated with aBMD at the femoral neck, total hip, and total body [18]. While possibly due to inconsistent use of the BPAQ (current vs. past vs. total), small sample sizes, and different bone assessment technologies, current literature using the BPAQ to predict bone parameters is inconclusive. Moreover, there is a gap in the literature in that no study has used historical and current physical activity to predict bone strength and microarchitecture in a young adult men and women of different racial/ethnic backgrounds.

Thus, in this study we determined the associations between bone microarchitecture and estimated strength and a novel skeletal loading (SkL) score that characterizes historical and current physical activity among young adult Black and White men and women, and compared this association to that provided by the tBPAQ score in the same cohort. The SkL score differs from the BPAQ in that there is only one score, there is no age weighting factor, and it captures a more comprehensive estimate of past physical activity (i.e. the historical portion of the SkL score estimates hours per year as well as number of years of participation per physical activity whereas the historical portion of the BPAQ captures only number of years of participation per physical activity).

2. Materials and methods

2.1. Study subjects

We previously reported differences in bone microarchitecture and estimated bone strength according to race/ethnicity and sex in a cohort of young adults [19]. We used this same cohort to determine the association between our novel SkL score that reflects the osteogenic nature of historical and current physical activity and areal bone mineral density (aBMD), bone microarchitecture and estimated bone strength. Briefly, we enrolled Black and White, young (ages 18–30) men and women. Inclusion criteria included self-identified race/ethnicity as either Black or White, and a body mass index (BMI) between 18.5 and 30 kg/m^2. Those with self-reported history of endocrine disorders, metabolic bone diseases, or medications known to influence bone health (e.g., corticosteroids, hormone therapy other than birth control, bisphosphonates, etc.) were excluded. Additionally, those reporting injuries or events that prevented normal weight bearing activity within the past 6 months, bilateral tibial fractures, and/or recent history of bilateral tibial stress fractures were excluded. Women enrolled in this study were required to be currently eumenorrheic (≥9 menses in the prior 12 months, including 1 menses in last 60 days). This study was approved by the Institutional Review Board of Partners Health Care and the Human Research Protection Office at the US Army Medical Research and Materiel Command. Informed written consent was obtained from each subject prior to participation in the study.

2.2. Questionnaires and clinical data

We assessed clinical history and covariates as previously described [19]. In brief, questionnaires were administered to assess health history, basic medical history, and lifestyle factors. Each participant was queried regarding their physical activity history from age 11 to present day. Height (to the nearest millimeter) was obtained using a wall-mounted stadiometer. Body mass (to the nearest 0.1 kg) was measured on a calibrated electronic scale. BMI was calculated as mass (kg) divided by height squared (m^2). We measured tibia length from the medial tibial plateau to the distal edge of the medial malleolus to the nearest mm using an anthropometric tape.

2.3. Skeletal loading (SkL) score

We developed the SkL score by first creating a loading coefficient (C) for each activity by log transforming the approximate loading coefficient (i.e., estimated vertical ground reaction force (vGRF) × rate of force application) for common sports/activities used in the BPAQ [12]. In order to make this a positive number we added 1 to the loading coefficient prior to each log transformation ($\log_{10}$(loading coefficient + 1)). For each activity reported in this data set that was not previously reported, the loading coefficients were estimated based on similar activities.

We recorded self-reported physical activity during four distinct life periods (ages 11–13, 14–17, 18–23, 24–present) for each subject. These data were then used in an algorithm that includes two summations. In the first summation (Eq. (1)), the skeletal load (L) within a given life period (j) for each activity (i) was calculated by summing the product of the loading coefficient (C) associated with each activity, hours per week (H) of participation, weeks per month (W) of participation, months per year (M) of participation, and years per life period (Y) of participation in the given activity over the number of years that make up that life period (R). In Eq. (1), n represents the number of activities participated in during the given life period. Eq. (2) provides a total SkL score and is the summation of Skeletal loads (L) for each life period (j) as calculated in Eq. (1). In Eq. (2), p represents the number of life periods lived.

2.3.1. SkL scoring algorithm

$$L_j = \sum_{i=1}^{n} C_i \times H_i \times W_i \times M_i \times \frac{Y_i}{R_i} \tag{1}$$

$$SkL\ Score = \sum_{j=1}^{p} L_j \tag{2}$$

where:

L = Load within a given life period

C = Loading coefficient (body weight^2/s) for a specified physical activity
H = Hours/week (hrs/wk) of participation for a specified physical activity
W = Weeks (wks/month) of activity participation per month
M = Months (months/yr) of activity participation per year
Y = Years (yrs) of activity participation per life period
R = Number of years (yrs) lived in a given life period
i = specified physical activity
j = specified loading period
n = number of activities performed in a given life period
p = number of life periods lived

2.4. BPAQ

We calculated BPAQ scores using physical activity data from ages 11 years and beyond. The BPAQ questionnaire has been described in detail previously [12]. Briefly, the BPAQ relies on self-reported current (sessions per week during the past 12 months), and historical (years of participation) physical activity patterns. All BPAQ scores were calculated using the online BPAQ calculator developed by Weeks and Beck [20]. The cBPAQ algorithm weighs weekly frequency of physical activity participation and a loading coefficient based on estimated vGRF × rate of force application for a given activity performed by adult men and women. The pBPAQ score uses an age weighted algorithm, years of participation and loading coefficient of each activity. The tBPAQ is the most comprehensive of the BPAQ scores and is an average of the past and current BPAQ scores. Further, among our cohort the tBPAQ and pBPAQ were highly correlated ($r = 0.92$). Thus, we chose to report tBPAQ results.

2.4.1. Bone mineral density

Dual-energy X-ray absorptiometry (DXA: QDR4500A; Hologic Inc., Bedford, MA, USA) was used to assess the posterior-anterior (PA) spine, femoral neck (FN), and total hip (TH) aBMD (g/cm^2). To maintain quality control, we performed daily measurements of a Hologic anthropomorphic spine phantom and an investigator experienced in bone densitometry visually reviewed every scan image.

2.5. Volumetric bone density, microarchitecture and strength

We measured cortical and trabecular vBMD and microarchitecture at the distal tibia using high-resolution peripheral quantitative computed tomography (HR-pQCT, XtremeCT, Scanco Medical AG, Bassersdorf, Switzerland; isotropic voxel size of 82 μm). The scan region started at 4% of tibial length (distal) and extended proximally for 110 slices (9.02 mm) as previously described [19]. The non-dominant leg (dominant leg was determined as the leg used to kick a ball) was scanned unless there was a history of lower limb fracture, in which case the contralateral side was scanned. Quality control was maintained with daily scanning of the manufacturer's phantom. Scans were reviewed by investigators for motion artifact and were repeated if significant motion artifact was noted [21].

Scanco analysis software version 5.11 was used to obtain total cross-sectional area (Tt.Ar, mm^2), total and trabecular vBMD (Tt.vBMD, Tb.vBMD, mg HA/cm^3), trabecular number (Tb.N, 1/mm), trabecular separation (Tb.Sp, mm), trabecular thickness (Tb.Th, mm). We used a semiautomated technique [22,23] to measure cortical area (Ct.Ar, mm^2), cortical thickness (Ct.Th, mm), cortical vBMD (Ct.vBMD, mg HA/cm^3), cortical tissue mineral density (Ct.TMD, mg HA/cm^3), cortical porosity (Ct.Po, %), and trabecular area (Tb.Ar, mm^2). Cortical area fraction (Ct.Ar/Tt.Ar,%) was then calculated. We also used three-dimensional (3D) HR-pQCT images to perform linear micro-finite-element-analysis (μFEA) to estimate tibia metaphyseal stiffness and failure load under uniaxial compression, as previously described [19].

2.6. Statistical analysis

Data are reported as mean ± standard deviation (SD) unless otherwise noted. We used *t*-tests (equal variances not assumed) and Chi-Square tests to compare demographic characteristics of the cohort by race and sex. We used a Pearson's correlation to determine the relationships between SkL score and tBPAQ, and between tBPAQ and pBPAQ.

We used multiple linear regression to assess the relationship of SkL score and bone parameters after adjusting for age, height, weight, sex, and race. Similarly, we used multiple linear regression to assess the relationship of tBPAQ and bone parameters after adjusting for age, height, weight, sex, and race. Adjusted R^2 values of the regression models with and without the inclusion of SkL score or tBPAQ score were compared to assess the amount of variability in bone parameters that was accounted for by the physical activity score. We also performed a sensitivity analysis by looking at the load within each given life period (SkL Eq. (1) only) as a covariate in the regression model already containing age, height, weight, sex, and race.

Using the total SkL score, “Low”, “Moderate”, and “High” SkL loading tertiles were determined from the overall cohort and then applied to each race and sex stratum. To compare mean estimated bone stiffness and failure load by μFEA within each sex and race stratum we used a non-parametric test for trend.

In exploratory analyses we tested whether the association between SkL score and bone parameters varied by race or sex. To do so we used linear regression models within each group after adjusting for age, height, and weight. A comparison of the *p*-values and standardized regression coefficient (ß (95%CI)) associated with adding SkL score to the models were then compared for each race and sex stratum to detect differences in the prediction capacity of the regression model on bone parameters. All analyses for this research were completed utilizing Stata version 14.2. An alpha level of 0.05 was used to conclude significance for all statistical tests.

2.7. Key resources table

Resource	Source	Identifier
Chemical bisphosphonates		

3. Results

3.1. Subject characteristics

We previously reported differences in estimated bone strength and microarchitecture in this cohort of 181 Black ($n = 51$ women, $n = 31$ men) and White ($n = 50$ women, $n = 49$ men) individuals (Table 1) [19]. Women were shorter, lighter, and had lower BMI than men. Black subjects were younger, and experienced fewer fractures compared to their White counterparts. As reported previously [19], 85% of fractures among this cohort were due to sports related injuries, falls, and motor vehicle accidents. The remaining 15% of fractures were due to other accidents (i.e. blunt force trauma, accidents during child's play, etc.). Here we found that White men and women had higher SkL scores compared to Black men and women (Table 1, Fig. 1). When comparing loading tertiles, Black subjects and women were overrepresented in the lower loading tertiles compared to White subjects and men, though 48% of White women in our cohort were in the highest loading tertile (Table 1, Fig. 2). The SkL score was moderately associated ($r = 0.55$) with the tBPAQ score.

Table 1
Demographic characteristics of study subjects [mean (SD) for quantitative variables and n (%) for categorical variables].

	White women n = 50	Black women n = 51	White men n = 49	Black men n = 31	p race	p sex
Age (yrs)	24.5 (2.9)	22.2 (3.2)	24.6 (3.1)	23.6 (3.6)	< 0.001	0.060
Height (cm)	164.9(10.8)	166.1 (7.9)	180.0 (8.1)	177.5 (7.6)	0.202	< 0.001
Weight (kg)	63.4 (9.6)	64.4 (10.2)	78.5 (11.5)	78.1 (11.7)	0.508	< 0.001
BMI (kg/m^2)	23.3 (3.2)	23.3 (2.5)	24.2 (2.9)	24.9 (3.4)	0.705	0.012
Tibia length (mm)	368 (24)	378 (29)	408 (29)	413 (31)	0.538	< 0.001
Fracture history (total)	18 (36%)	4 (8%)	24 (48%)	6 (18%)	< 0.001	0.062
SkL score	1610 (1148)	953 (1016)	1603 (1056)	1110 (1042)	< 0.001	0.339
Loading tertiles					0.001	0.048
Low	15 (30%)	26 (51%)	8 (16%)	12 (39%)		
Moderate	11 (22%)	16 (31%)	21 (43%)	12 (39%)		
High	24 (48%)	9 (18%)	20 (41%)	7 (22%)		

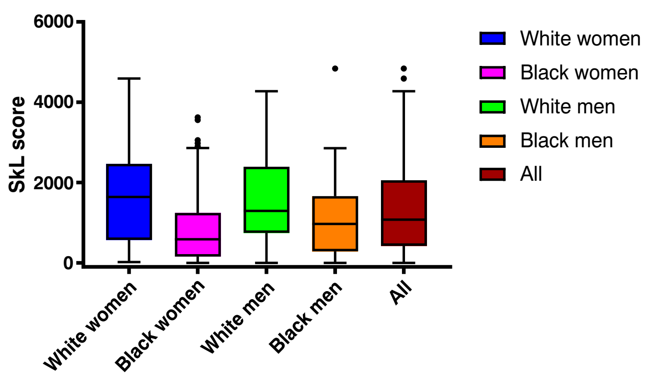

Fig. 1. SkL score distribution per race/sex strata and among the entire cohort.

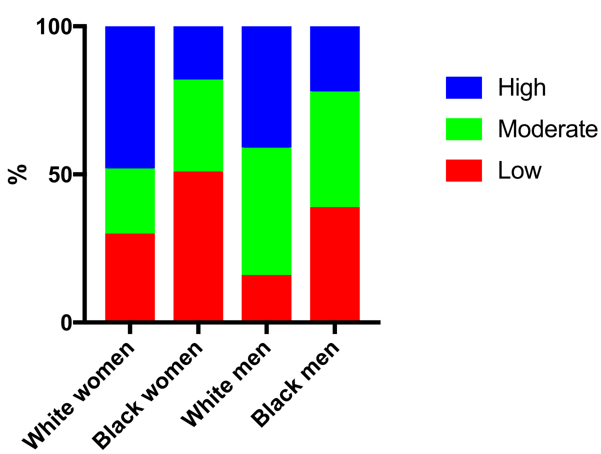

Fig. 2. Percentage of individuals in each Skeletal loading (SkL) score tertile (low, moderate or high), as determined among the entire cohort, by race and sex strata.

3.2. SkL score and bone parameters

Comparing R^2 values of linear regression models including age, height, weight, sex, and race with and without the inclusion of SkL revealed that the addition of SkL significantly improved the fit of the model for all DXA-BMD and most HR-pQCT measurements except Tt.Ar and Ct.vBMD (Table 2). All other models with cortical bone outcomes were significantly improved with the addition of SkL score. For cortical parameters, the adjusted R^2 values in models including SkL score ranged from 0.27 to 0.55 with a median increase in R^2 of 0.06 (range 0.03–0.15) after the addition of SkL score. While the addition of the SkL score also significantly improved the models for trabecular parameters, the adjusted R^2 values were lower, on average (0.22–0.32) compared to those assessing cortical parameters. However, in models assessing trabecular parameters the median increase in R^2 with the addition of SkL was similar (0.07, range 0.06–0.18) to the increases seen in cortical models. Sixty-four percent of stiffness and 65% failure load, estimated by μFEA, were predicted by the regression model including SkL score and increased significantly according to SkL tertile in all sex and race strata (Fig. 3). We performed a sensitivity analysis to determine whether certain life periods were better associated with bone parameters than others or than the combination of all life periods. Based on numerically higher R^2 values, our analysis suggests that the cumulative SkL score (SkL Eqs. (1) and (2)) reflective of both historical and current loading was more strongly associated with bone parameters than the loading score within any given life period alone (ages 11–13, 14–17, 18–23, 24–present (SkL Eq. (1) only): Supplemental Table 1).

Finally, in an exploratory analysis assessing differences in the impact of SkL on bone parameters according to race and sex, SkL score improved the fit of the linear regression model already containing age, height, and weight for most bone parameters for each race and sex stratum. The standardized regression coefficients for SkL in the linear regression model were generally similar between White men and White women, but were higher among Black.

men than Black women, though we were not adequately powered to detect significant differences between groups (Supplemental Table 2).

3.3. BPAQ and bone parameters

We compared R^2 values of linear regression models including age, height, weight, sex, and race with and without the inclusion of tBPAQ. The addition tBPAQ improved the fit of the model for all DXA and most HR-pQCT measurements except Ct.TMD, Tt.Ar and Ct.vBMD. Similar to the SkL score findings, statistically significant R^2 values for the BPAQ models assessing cortical parameters were higher overall than models assessing trabecular parameters. Specifically, the R^2 for the models including cortical parameters ranged from 0.24 to 0.48 whereas those including trabecular parameters ranged from 0.17 to 0.25. Though the median change in R^2 with the addition of tBPAQ to the models was similar for cortical (0.06, range 0.02–0.07) and trabecular (0.04, range 0.03–0.09) models. The regression model including tBPAQ predicted 59% of stiffness and 56% of failure load, estimated by μFEA.

4. Discussion

Using previously established loading coefficients [12] for different types of physical activity, we created a SkL score designed to account for both current and historical physical activity. Our study revealed that, among young Black and White men and women, SkL score was significantly associated with most bone microarchitecture parameters and indices of bone strength at the distal tibia as assessed by HR-pQCT. We also evaluated the association between previously described tBPAQ score and bone microarchitecture and strength and found similar, but

Table 2
Associations of bone parameters and Skeletal Loading (SkL) score or total BPAQ (tBPAQ) among the cohort (*n* = 181). The *p*-value represents the significance associated with adding the SkL score or tBPAQ to a model already containing age, weight, height, sex, and race.

	R^2 adjusted for age, height, weight, sex and race	R^2 adjusted for age, height weight, sex and race + SkL score	β SkL score	R^2 adjusted for age, height weight, sex and race + tBPAQ	β tBPAQ
Size/morphology					
Tt.Ar (mm^2)	0.70	0.70	0.03	0.70	0.06
Ct.Ar (mm^2)	0.41	0.55***	0.38	0.47***	0.26
Ct.Ar/Tt.Ar (%)	0.20	0.29***	0.33	0.22*	0.18
Microarchitecture					
Ct.Th (mm)	0.25	0.40***	0.40	0.30***	0.24
Ct.Po (%)	0.31	0.37***	0.27	0.38***	0.28
Tb.Th (mm)	0.22	0.28***	0.26	0.25**	0.20
Tb.Sp (mm)	0.13	0.22***	−0.32	0.17**	−0.22
Tb.N (1/mm)	0.15	0.22***	0.29	0.18**	0.20
Density					
Tt.vBMD ($mgHA/cm^3$)	0.17	0.35***	0.44	0.24***	0.28
Tb.vBMD ($mgHA/cm^3$)	0.14	0.32***	0.44	0.23***	0.31
Ct.vBMD ($mmHA/cm^3$)	0.30	0.30	0.05	0.30	−0.09
Ct.TMD ($mgHA/cm^3$)	0.24	0.27**	0.20	0.24	0.06
μFEA					
Stiffness (kN/mm)	0.51	0.64***	0.38	0.59***	0.30
Failure Load (kN)	0.53	0.65***	0.37	0.56***	0.19
DXA					
Femoral Neck BMD (g/cm^2)	0.28	0.42***	0.39	0.35***	0.27
Total Hip BMD (g/cm^2)	0.24	0.40***	0.43	0.31***	0.29
PA Spine BMD (g/cm^2)	0.25	0.31***	0.26	0.27*	0.17

* $p < 0.05$.
** $p < 0.01$.
*** $p < 0.001$ vs r^2 for age, height, weight, sex, and race adjusted model.

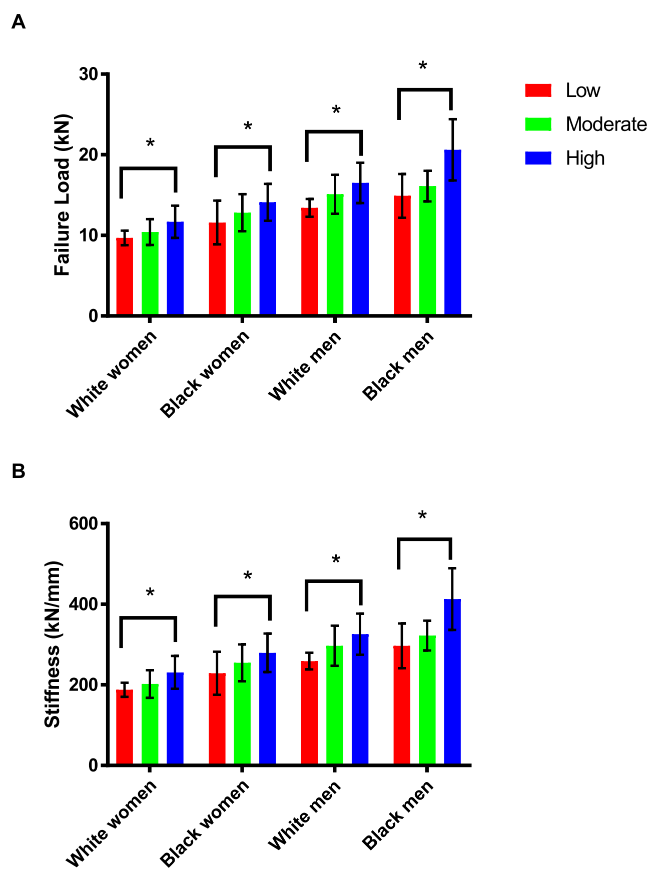

Fig. 3. Failure Load (A) and Stiffness (B) per Skeletal loading (SkL) score tertile and race/sex strata. *Indicates test for trend $p < 0.05$.

weaker, associations than SkL and bone microarchitecture.

There are few studies that have examined the relationship between bone relevant physical activity and bone microarchitecture. Our findings are largely in alignment with the lone study aimed at predicting bone microarchitecture in adults through a physical activity questionnaire [11]. This earlier study utilized magnetic resonance imaging (MRI), the bone loading history questionnaire (BLHQ) and cBPAQ, and reported significant associations between both the BLHQ and the cBPAQ and all mid-tibia cortical measures as well as aBMD in young women (18–19 years). In our study, SkL score was significantly associated with all DXA and cortical parameters except Ct.vBMD and tBPAQ was significantly associated with all DXA and cortical parameters except Ct.BMD and Ct.TMD.

Most studies using physical activity history to predict bone parameters have, so far, been limited to bone density and geometry and ultrasound properties (DXA, pQCT and BUA) [12,14,16–18,24]. Our overall findings that skeletal loading score is a significant predictor of estimated bone strength and stiffness are consistent with these prior reports, and expand upon several previous studies [3–5,14,17,25–28]. Intervention studies in children and adolescents [3,5], adult women [25], and postmenopausal women [26] report that exercise leads to improved measures of bone strength and geometry as assessed by DXA and pQCT. Further, among male and female racquet sport athletes, the humerus and radius of the dominant arm show improved strength compared to the non-dominant arm [27,28]. Studies assessing self-reported historical and current physical activity patterns suggest similar findings. Outcomes from the past year physical activity questionnaire (PYPAQ), which accounts for the duration, frequency, and load of physical activity, are correlated with the strength-strain index of the femoral midshaft and bone strength index at the distal tibia and femur in girls [14]. Results from the BPAQ are varied, with one study showing no association between cBPAQ scores and indices of bone strength [14] and one study showing a significant positive association between SSI measured by pQCT and tBPAQ in young women [17]. These discrepant findings may be explained by one or more differences in study populations, physical activity assessment tools, and bone imaging technologies.

Our analysis revealed that SkL score and tBPAQ score significantly improved the fit of the regression model for both trabecular and cortical parameters at the distal tibia, suggesting that physical activity impacts both bone compartments. These findings align with several human and animal studies that suggest both trabecular and cortical bone respond to historical, current, and novel mechanical loading [29–36]. Using HR-pQCT, it has been reported that female athletes have greater μFEA estimated stiffness and failure load in addition to larger cortical perimeter, greater trabecular vBMD, and more platelike and axially aligned trabeculae than non-athletes [35,36], suggesting that chronic historical and current physical activity contributes to advantageous cortical and trabecular microstructure. Similarly, among female Soldiers, 8 weeks of Basic Combat Training elicited an increase in trabecular thickness, number and vBMD as well as cortical thickness and total vBMD, suggesting novel physical activity among adults also impacts both trabecular and cortical bone [33]. In contrast, a study assessing HR-pQCT bone measurements and high impact physical activity performed over the previous week, reported that among adolescent boys and girls high impact physical activity explains 4% of the variance in total vBMD, 5% of the variance in trabecular vBMD and 8% of the variance in trabecular thickness at the distal tibia, but was not a significant predictor of cortical parameters in girls [4]. This same study reported no relationship among boys between high impact physical activity and bone microarchitecture. Of note, this study assessed only current physical activity and only high impact physical activity, whereas our study assessed both current and historical physical activity as well as all forms of physical activity (both high and low impact), which may explain the differences in findings.

There is some debate in the literature regarding the life period during which bone is optimally responsive to mechanical loading, with some studies reporting the years prior to puberty are the most responsive to osteogenic loading [37–41] and some reporting that the years during puberty, particularly the years of peak height velocity, are most conducive to adding new bone in response to loading [2,42–47]. Because we did not have data regarding the timing of puberty or years of peak height velocity in our cross-sectional study, when creating our algorithm we chose to weight loading scores from all ages/periods of life equally. However, we did a sensitivity analysis in which we calculated SkL separately for each life period (ages 11–13, 14–17, 18–23, and 24–present) and found that the adjusted R^2 values were highest using our total SkL algorithm that accounts for all periods of life beyond 11 years old. This suggests that the cumulative physical activity history is more strongly associated with adult bone strength and microarchitecture than physical activity during the years of growth alone. While this neither supports, nor refutes the literature as we did not capture the timing of puberty, it does suggest our choice to avoid weighting a specific time period in our overall skeletal loading score was appropriate.

We were unable to test whether the influence of SkL on bone parameters varied by race and sex due to insufficient power. However, we note that the standardized beta coefficients were numerically higher among Black men compared to Black women, but similar between White men and women. When we divided the cohort into SkL tertiles, Black individuals were over-represented in the lowest loading tertile, despite their higher bone stiffness and failure load and more favorable bone microarchitecture compared to White individuals. Thus, although Black individuals in our cohort have significantly stronger bones than White individuals, they participate in significantly less “osteogenic” physical activity. To the best of our knowledge there are no studies that have assessed the impact of physical activity on bone strength and microarchitecture according to race and ethnic origin in adults. Studies in pre-pubertal South African children demonstrate that bone loading history differentially effect bone properties in Black and White children [48,49], with White children exhibiting improved bone properties with greater levels of physical activity as opposed to no difference among Black children based on physical activity. The authors concluded that physical activity levels offer little additional benefit above the genetic protection already evident among Black children compared to White children [49]. Further, animal models also support the notion that bone mechanosensitivity has a significant genetic component [50,51]. Of note, the self-reported fracture history was higher among White men and women compared to their Black counterparts. It is unclear whether the higher incidence of fracture among White individuals is due to their impaired bone strength and microarchitecture [19], greater exposure to sports and physical activity, and/or other factors. The current observations indicate that larger prospective studies are needed to better understand the possible contribution of race and ethnic origin, or other genetic and environmental variation, to the osteogenic response to mechanical loading.

Limitations of this study include the cross-sectional design and reliance on self-reported racial background and physical activity patterns. Further, we examined only the tibia, and thus cannot say whether SkL score or tBPAQ score are associated with bone microarchitecture and strength at other skeletal sites. Because this is the first study using the SkL score and we only included young adults, we do not know if our findings can be translated to younger and older populations. Additionally, though the tBPAQ was significantly associated with most bone parameters, we only recorded physical activity patterns from 11 years of age and older, whereas the original BPAQ utilizes physical activity patterns starting at birth. Finally, although we included a more diverse population than the existing literature, we were not adequately powered to detect between group differences based on race and sex. Though our findings suggest SkL score is more strongly associated with improved bone parameters than tBPAQ, the simplistic nature of the BPAQ may render it a more practical tool among large cohorts, or when time is limited. Nevertheless, larger, prospective studies are needed to confirm and extend our findings, determine differences in skeletal response to loading based on race and sex, and determine whether this association exists in among more diverse populations.

5. Conclusion

Our results confirm and extend prior observations of enhanced skeletal parameters among those who participate in physical activity that elicits high ground reaction forces and rates of loading. Based on the skeletal loading (SkL) score, higher levels of self-reported current and historical physical activity are associated with improved bone microarchitecture, geometry, and strength in young Black and White adults. We found similar, but weaker associations, between the BPAQ and bone parameters. Thus, this novel skeletal loading (SkL) score may be useful to identify those at risk for poor bone mass acquisition, low bone strength and fracture.

Declaration of Competing Interest

The authors have no conflicts of interest to disclose. The results of this study do not constitute endorsement by Bone.

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Appendix A. Supplementary data

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