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Sex differences in physical activity dose-response effects on site-specific bone mineral density during childhood and adolescence

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Physical activity (PA) serves as a modifiable determinant of bone mineral density (BMD). However, sex- and site-specific dose–response relationships remain poorly defined. Leveraging data from the National Health and Nutrition Examination Survey (NHANES 2011–2014), this cross-sectional study investigated sex-specific associations between accelerometer-derived PA (volume and intensity) and site-specific BMD in 2,659 children and adolescents aged 8–19 years. BMD assessment was conducted via dual-energy X-ray absorptiometry, and PA was quantified using monitor-independent movement summary units (MIMS). Linear and nonlinear analyses revealed distinct patterns: boys exhibited stronger linear associations between PA volume and BMD at weight-bearing sites (e.g., pelvis, arms, and legs; β = 0.003–0.004, $P < 0.05$), and girls demonstrated nonlinear thresholds (e.g., volume threshold: 15.0×10^3 MIMS/day). Both sexes had intensity-driven thresholds (~ 45–49 MIMS/min), with diminishing returns above these values (β = 0.010 in boys; stagnation in girls). Directional trends suggest the greater BMD gains per standard deviation (SD) increase in PA for boys compared with that for girls across most skeletal regions (e.g., total body less head: 0.131 SD vs. 0.106 SD for intensity). However, statistical significance ($P < 0.05$) was observed only for arm BMD responses. Mechanistic analyses highlighted the corresponding biomechanical principles, with weight-bearing regions showing stronger PA-BMD links than nonweight-bearing sites (e.g., spine). These findings underscore the importance of prioritizing high-intensity, weight-bearing activities, particularly for girls, to optimize skeletal health during growth. Public health strategies should focus on achieving, rather than exceeding, the identified daily 60 min intensity thresholds (~ 45–49 MIMS/min) through school- and community-based interventions.

Keywords Bone mineral density, Physical activity, Dose-response, Pediatric, Sex differences.

Abbreviations

NHANES	National Health and Nutrition Examination Survey
PA	Physical activity
BMD	Bone mineral density
TBLH	Total body less head
PIR	Poverty income ratio
MIMS	Monitor-independent movement summary units
MET	Metabolic equivalent
MVPA	Moderate to vigorous physical activity
GAM	General additive model
CI	Confidence interval
SD	Standard deviations

Skeletal health during childhood and adolescence lays the foundation for lifelong bone integrity, with approximately 80% of peak bone mass accruing prior to adulthood[1–3]. Bone mineral density (BMD) must be

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maximized during this critical window to prevent osteoporosis and reduce fracture risk later in life[4–6]. Physical activity (PA), particularly during growth spurts when the capacity for mechanoadaptation is highest, represents a key modifiable determinant of bone health[2,4,7,8].

BMD is influenced by nonmodifiable (e.g., genetics) and modifiable factors (e.g., nutrition, PA), with the latter providing actionable targets for public health interventions[9–13]. According to meta-analyses, weight-bearing and high-impact PA, such as jumping and resistance training, are the most effective in enhancing BMD[5,14–16]; however, the optimal dose–response relationships across skeletal sites and between sexes remain poorly defined[9,17–19].

Historically, PA assessment relied on subjective questionnaires, which are susceptible to recall bias and misclassification of intensity[20]. By contrast, accelerometers objectively capture movement patterns at a sampling rate of 80 Hz and convert raw acceleration data into monitor-independent movement summary units (MIMS)[21,22]. This advancement permits the precise quantification of PA volume (i.e., cumulative daily activity) and intensity (i.e., activity magnitude), which facilitates cross-study comparisons and mechanistic investigations of the PA–BMD relationship[23,24].

To date, most pediatric research categorizes movement into sedentary behavior, moderate-intensity PA (e.g., brisk walking or cycling for transportation), and vigorous-intensity PA (e.g., running or jump-rope during leisure or structured sports).This broad classification may obscure dose-dependent relationships between PA and incremental BMD benefits per unit of PA[14,25,26]. Moreover, in the pediatric literature, sex- and site-specific variations in the osteogenic response to PA remain understudied, although emerging evidence suggests possibly different response of boys and girls[13,27]. Addressing these gaps can pave the way for tailored exercise guidelines to maximize skeletal benefits during growth.

Leveraging data from the National Health and Nutrition Examination Survey (NHANES 2011–2014), this study explored potential sex-associated differences in the dose–response relationships between accelerometer-derived PA (volume and intensity) and site-specific BMD in children and adolescents. NHANES combines gold-standard dual-energy X-ray absorptiometry (DXA) scans with accelerometry data and relevant covariates (e.g., demographics and nutrition), which ensures a rigorous analytical precision[28]. Our findings are expected to deepen our understanding of PA's osteogenic potential across developmental stages and offer precision exercise prescriptions for the optimization of pediatric bone health.

Materials and methods

Study population

This study analyzed data from the NHANES, a nationally representative survey that employs stratified multistage probability sampling to assess the health and nutritional status of the U.S. population. Data from two consecutive NHANES cycles (2011–2014) were utilized. The study population comprised participants aged 8–19 years with valid BMD and PA data. BMD measurements were available only for the participants aged 8 years and older. The study protocol received approval from the National Center for Health Statistics Research Ethics Review Board (https://www.cdc.gov/nchs/nhanes/about/erb.html).

PA (exposure)

PA data were subjected to objective measurement using the ActiGraph GT3X + accelerometer (Pensacola, FL, USA) during the 2011–2014 NHANES cycles. The participants wore the accelerometer on their non-dominant wrist for 7 consecutive days (including weekdays and weekend days). Data were collected in triaxial form and downloaded as minute-by-minute counts representing the sum of acceleration on the x, y, and z axes. Only valid "wear" minutes (≥ 10 h/day for at least 3 days) were included in the analysis[28,29].

For this study, the MIMS metrics comprised PA volume, which were measured as average MIMS units per day, and PA intensity, which was calculated as the peak 60 min MIMS. The average number of MIMS per day served as an indicator for quantifying the daily total PA, which was defined as the average number of daily MIMS (calculated by summing all MIMS within a day and dividing the sum by the number of valid days)[23]. The peak 60 min MIMS value was based on the highest 60 MIMS/min (not necessarily consecutive) across all valid days. This value was obtained through the initial sorting of individual data by the MIMS/min for every valid observation day. The average of the top 60 values for each day was then calculated, and the mean of the averages across all valid wear days was obtained[28,30]. The peak 60 min MIMS values aligned closely with the recommendations for daily aerobic exercise (moderate to vigorous) for children and adolescents[31] and partially with the 60 min peak step frequency employed in previous research[28].

BMD (outcome)

The area BMD (g/cm^2) was measured at multiple anatomical sites using DXA (Hologic Inc., Bedford, MA) in participants aged ≥ 8 years. Scans were obtained using Apex 4.0 software under a standardized protocol (https://wwwn.cdc.gov/nchs/data/nhanes/public/2011/manuals/Body_Composition_Procedures_Manual.pdf). Total body less head (TBLH) BMD was used as a comprehensive indicator of systemic bone mass dynamics, given that the head is minimally responsive to environmental stimuli such as PA[32]. By contrast, regional BMD measurements at the thoracic spine, lumbar spine, pelvis, and limbs skeleton are sensitive to PA-induced changes[17,33]. Accordingly, TBLH and site-specific BMD assessments from the 2011–2014 cycles were selected as primary outcomes. This dual evaluation strategy enabled the comprehensive characterization of systemic bone metabolism and site-specific structural adaptations.

Covariates

Covariates included demographic variables (age, sex, and race/ethnicity) and socioeconomic status, with the latter defined as the poverty income ratio (PIR) and calculated as the family income-to-poverty threshold ratio

adjusted for household size, in accordance with the U.S. Department of Health and Human Services guidelines. In pediatric populations, auxological parameters (height [cm] and weight [kg]) were prioritized over body mass index because they show a stronger association to bone mineral accrual during growth phases[34]. Given the sole availability of serum calcium measurements for participants aged ≥ 12 years, nutritional covariates, namely, dietary intake and supplementation records of vitamin D and calcium, collected via 24 h dietary recalls, were also incorporated. The final adjusted model therefore included age, sex, race/ethnicity, PIR, anthropometric measures (height and weight), and micronutrient intake (vitamin D and calcium).

Statistical analysis

This study adhered to the guidelines of Strengthening the Reporting of Observational Studies in Epidemiology for cross-sectional studies[35]. To account for the complex multistage probability sampling design of NHANES, we incorporated all analyses sampling weights, stratification variables, and cluster adjustments using the R survey package (version 4.4-2) to yield nationally representative estimates (https://wwwn.cdc.gov/nchs/nhanes/tutorials/default.aspx).

Baseline characteristics were stratified by sex and age group, with participants categorized into 8–14 years and 15–19 years to align with pubertal growth phases and their influence on BMD dynamics. Categorical variables were compared using weighted Rao–Scott corrected chi-square tests, and continuous variables were analyzed using survey-weighted Wilcoxon rank-sum tests. Based on prior evidence suggesting sex differences in associations between PA and BMD[13,36], sex-stratified analyses were subsequently performed to evaluate potential heterogeneity in the PA–BMD relationships.

Linear associations between PA metrics (volume and intensity) and site-specific BMD (TBLH, thoracic and lumbar spine, pelvis, arms, legs) were assessed using weighted multivariable linear regression. Nonlinear relationships were examined via generalized additive models (GAMs; mgcv package version 1.9-0), with threshold effects evaluated using the log-likelihood ratio test. Associations demonstrating a log-likelihood ratio test P-value < 0.05 were classified as exhibiting significant nonlinear correlations, indicating threshold inflection points. For these nonlinear associations, weighted two-piecewise linear regression models quantified relationships below and above the identified inflection points.

For standardized effect size interpretation, BMD measurements and PA variables were converted to z-scores, which allowed the beta coefficients to represent changes in the BMD (in standard deviations [SD]) per SD increment in PA exposure. Z-test was employed to compare standardized β values between sexes.

All models were adjusted for age, sex, race/ethnicity, PIR, height, weight, and dietary intake of calcium and vitamin D. Model fit was assessed using the adjusted R^2 values. For improved interpretability of regression coefficients, PA metrics were scaled as follows: volume to 10^3 MIMS/day and intensity to 10 MIMS/min.

Analyses were conducted under R 4.3.0 (The R Foundation, http://www.R-project.org), with statistical significance defined as a two-tailed P-value < 0.05 and effect estimates reported with 95% confidence intervals (CIs).

Results

Basic characteristics of the study population

Figure 1 shows the selection flow chart. From the original cohort of 19,931 participants, 4,450 individuals aged 8–19 years with complete BMD and PA data were identified. After the exclusion of 347 participants with missing covariate information, 2,659 eligible participants (1,339 boys and 1,320 girls) were included in the analysis. Table 1 presents the baseline characteristics stratified by sex and age group.

Demographic, anthropometric, and nutritional characteristics

The cohort exhibited comparable age distributions between sexes (mean: 13.3 ± 3.4 vs. 13.3 ± 3.3 years), balanced racial/ethnic representation (56% non-Hispanic White in both groups), and equivalent PIR ($P > 0.05$). Boys demonstrated significantly greater stature than girls, with higher height (160.3 ± 16.9 vs. 154.4 ± 11.6 cm, $P < 0.05$) and weight (59.1 ± 23.3 vs. 54.6 ± 19.3 kg, $P < 0.05$). Nutritional analyses revealed higher daily micronutrient intake in boys, including calcium (1,172.9 ± 529.5 vs. 955.1 ± 444.3 mg, $P < 0.05$) and vitamin D (8.5 ± 9.8 vs. 7.0 ± 8.0 μg, $P < 0.05$). Age-stratified comparisons showed significant differences in vitamin D intake ($P < 0.05$) but not in calcium consumption ($P > 0.05$).

PA and BMD

PA volume did not differ significantly between sexes (boys: 15,809 ± 4,062 vs. girls: 15,919 ± 3,686 MIMS/day, $P > 0.05$), whereas PA intensity was higher in boys (54.5 ± 13.9 vs. 50.7 ± 10.5 MIMS/min, $P < 0.05$).

Sex-specific disparities in BMD were evident across anatomical sites. Boys had higher BMD at TBLH (0.86 ± 0.16 vs. 0.83 ± 0.13 g/cm², $P < 0.05$), arms (0.68 ± 0.13 vs. 0.64 ± 0.09 g/cm², $P < 0.05$), and legs (1.03 ± 0.20 vs. 0.99 ± 0.16 g/cm², $P < 0.05$). Girls exhibited a higher lumbar spine BMD (0.90 ± 0.18 vs. 0.85 ± 0.18 g/cm², $P < 0.05$) and minor but significant differences at the thoracic spine and pelvis ($P < 0.05$).

Age-stratified analyses revealed higher BMD in the 15–19-year group compared to the 8–14-year group across all sites (e.g., TBLH: 0.97 ± 0.10 vs. 0.77 ± 0.12 g/cm², $P < 0.05$). Figure 2 illustrates age-related BMD trends: girls showed higher BMD at the thoracic, spine lumbar spine, and pelvis during ages 8–14 ($P < 0.05$), with diminishing sex differences after age 15 ($P > 0.05$). Conversely, boys exhibited greater appendicular BMD (arms and legs) throughout adolescence ($P < 0.05$).

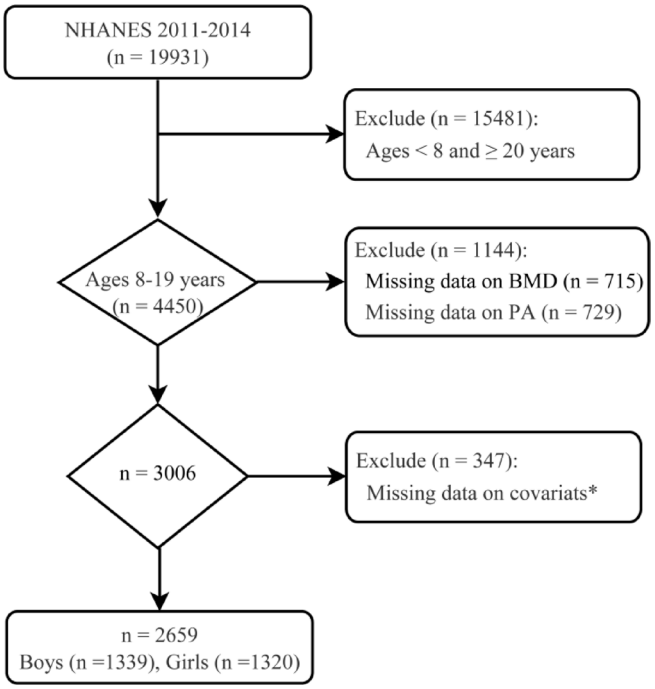

Fig. 1. Participant selection flowchart. *Covariates analyzed: age, sex, race/ethnicity, height, weight, poverty income ratio, dietary calcium, and vitamin D. PA, physical activity; BMD, bone mineral density; NHANES, National Health and Nutrition Examination Survey.

Characteristic	Sex			Age group (year)		
	Boys[a]	Girls[a]	*P*[b]	8-14[a]	15-19[a]	*P*[b]
N (%)	1339 (50%)	1320 (50%)		1731 (61%)	928 (39%)	
Age (years)	13.3 ± 3.4	13.3 ± 3.3	0.7	11.1 ± 2.0	16.8 ± 1.4	**< 0.001**
Race/ethnicity (%)			> 0.9			0.8
Mexican American	274 (15%)	281 (15%)		367 (16%)	188 (14%)	
Other Hispanic	135 (7.0%)	134 (6.8%)		170 (6.8%)	99 (7.0%)	
Non-Hispanic White	364 (56%)	335 (56%)		459 (56%)	240 (56%)	
Non-Hispanic Black	374 (14%)	358 (14%)		489 (14%)	243 (14%)	
Other/multiracial	192 (7.9%)	212 (8.0%)		246 (7.6%)	158 (8.4%)	
Height (cm)	160.3 ± 16.9	154.4 ± 11.6	**< 0.001**	150.3 ± 13.2	168.5 ± 9.4	**< 0.001**
Weight (kg)	59.1 ± 23.3	54.6 ± 19.3	**0.001**	48.2 ± 17.6	70.6 ± 19.9	**< 0.001**
PIR	2.46 ± 1.63	2.36 ± 1.62	0.3	2.43 ± 1.63	2.38 ± 1.62	0.6
Vitamin D intake (μg)	8.5 ± 9.8	7.0 ± 8.0	**< 0.001**	7.8 ± 7.0	7.8 ± 11.5	**< 0.001**
Calcium intake (mg)	1,172.9 ± 529.5	955.1 ± 444.3	**< 0.001**	1,059.5 ± 476.2	1,073.5 ± 538.2	> 0.9
PA volume (MIMS/day)	15,809 ± 4,062	15,919 ± 3,686	0.4	17,150 ± 3,664	13,826 ± 3,298	**< 0.001**
PA intensity (MIMS/min)	54.5 ± 13.9	50.7 ± 10.5	**< 0.001**	57.3 ± 12.1	45.3 ± 9.1	**< 0.001**
BMD (g/cm^2)						
TBLH	0.86 ± 0.16	0.83 ± 0.13	**< 0.001**	0.77 ± 0.12	0.97 ± 0.10	**< 0.001**
Thoracic spine	0.67 ± 0.13	0.68 ± 0.12	**0.002**	0.61 ± 0.10	0.78 ± 0.09	**< 0.001**
Lumbar spine	0.85 ± 0.18	0.90 ± 0.18	**< 0.001**	0.77 ± 0.15	1.03 ± 0.13	**< 0.001**
Pelvis	1.06 ± 0.24	1.08 ± 0.21	**0.009**	0.96 ± 0.19	1.25 ± 0.16	**< 0.001**
Arms	0.68 ± 0.13	0.64 ± 0.09	**< 0.001**	0.60 ± 0.09	0.76 ± 0.08	**< 0.001**
Legs	1.03 ± 0.20	0.99 ± 0.16	**< 0.001**	0.92 ± 0.15	1.15 ± 0.12	**< 0.001**

Table 1. Descriptive statistics of the variables stratified by sex and age group. [a]Mean ± SD; n (unweighted) (%). [b]Wilcoxon rank-sum test for complex survey samples; chi-squared test with Rao & Scott's second-order correction. PIR poverty income ratio; PA, physical activity; MIMS, monitor-independent movement summary units; BMD, bone mineral density; TBLH, total body less head.

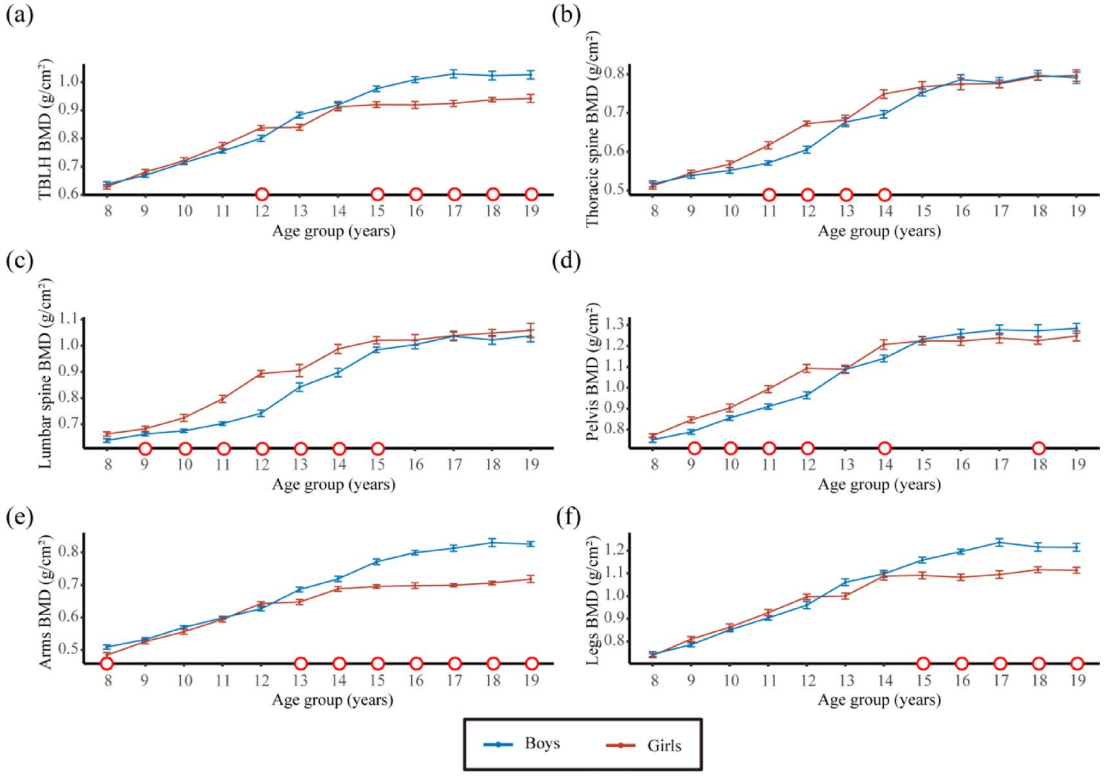

Fig. 2. Age-related BMD distribution across skeletal sites (8–19 years). Weighted mean BMD values with standard errors are represented by data points. Significant sex differences (Benjamini-Hochberg adjusted $P < 0.05$) are annotated with red circles along the x-axis. Regions: (**a**) TBLH, (**b**) thoracic spine, (**c**) lumbar spine, (**d**) pelvis, (**e**) arms, (**f**) legs. BMD, bone mineral density; TBLH, total body less head.

Sex-stratified associations between PA and site-specific BMD

Linear associations by sex

In boys, significant linear correlations were observed between PA volume and BMD at multiple sites, including the TBLH ($\beta = 0.003$, $P < 0.05$), pelvis ($\beta = 0.004$, $P < 0.05$), arms ($\beta = 0.003$, $P < 0.05$), and legs ($\beta = 0.003$, $P < 0.05$), with the exception of the thoracic spine ($P > 0.05$). PA intensity exhibited linear effects at all these sites. By contrast, for girls, no significant correlations were found between BMD and either PA volume or intensity at the lumbar spine ($P > 0.05$). However, positive correlations were observed at other sites, similar to the findings revealed in the boys (Table 2).

Nonlinear threshold effects

Associations with a log-likelihood ratio test p-value less than 0.05 featured significant nonlinear correlations, which are indicative of the presence of threshold inflection points. Nonlinear analyses identified critical thresholds at sites featuring the divergence of the effects of PA on BMD. The results are presented in Table 3, and Fig. 3. In boys, intensity-driven thresholds clustered around 45 MIMS/min for TBLH, pelvis, arms, and legs ($P < 0.05$). Below these thresholds, PA intensity resulted in stronger BMD gains (e.g., TBLH: $\beta = 0.047$ vs. $\beta = 0.010$, $P < 0.05$), whereas effects above the thresholds remained significant but diminished ($P < 0.05$). For volume-dependent thresholds, only lumbar spine BMD displayed a threshold at 22.2×10^3 MIMS/min ($P < 0.05$), beyond which BMD gains became significant ($\beta = 0.012$, $P < 0.05$).

In girls, volume-dependent thresholds clustered near 15.0×10^3 MIMS/min for TBLH, pelvis, and legs, and intensity-dependent thresholds (approximately 49 MIMS/min) were observed across TBLH, pelvis, arms, and legs. Below these thresholds, significant BMD gains were observed (e.g., TBLH volume: $\beta = 0.006$, $P < 0.05$; intensity: $\beta = 0.034$, $P < 0.05$), whereas effects plateaued above the thresholds ($P > 0.05$).

Sex- and site-specific trends

Following Z-score normalization of PA and BMD variables, standardized effect sizes demonstrated comparability across skeletal sites and sexes (Table 2; Fig. 4). Overall, boys exhibited greater PA-associated BMD gains than girls in most regions. A 1-SD increase in PA volume corresponded to TBLH BMD increments of 0.078 SD (95% CI: 0.039–0.117) in boys versus 0.067 SD (95% CI: 0.031–0.103) in girls, and PA intensity yielded increments of 0.131 (boys) and 0.106 SD (girls). Sex-related differences in PA-BMD associations were statistically non-significant at all skeletal sites ($P > 0.05$), except for arm BMD responses to PA intensity (boys: $\beta = 0.112$ vs. girls: $\beta = 0.056$; $P < 0.05$).

Outcome	Variables	Raw data[a]				Z-scored data[b]		
		β (95% CI)[c], boys	p[d]	β (95% CI)[c], girls	p[d]	β (95% CI)[e], boys	β (95% CI)[e], girls	p[f]
TBLH	Volume	0.003 (0.001, 0.004)	**< 0.001**	0.003 (0.001, 0.004)	**0.001**	0.078 (0.039, 0.117)	0.067 (0.031, 0.103)	0.651
	Intensity	0.016 (0.011, 0.02)	**< 0.001**	0.013 (0.008, 0.017)	**< 0.001**	0.131 (0.095, 0.166)	0.106 (0.066, 0.146)	0.333
Thoracic Spine	Volume	0.001 (-0.002, 0.003)	0.605	0.001 (0, 0.003)	0.063	0.017 (-0.049, 0.082)	0.039 (-0.002, 0.079)	0.557
	Intensity	0.008 (0.004, 0.012)	**0.001**	0.007 (0.002, 0.013)	**0.015**	0.076 (0.035, 0.117)	0.072 (0.016, 0.128)	0.899
Lumbar Spine	Volume	0.002 (0.001, 0.004)	**0.006**	0.002 (-0.001, 0.005)	0.134	0.051 (0.017, 0.086)	0.045 (-0.015, 0.105)	0.852
	Intensity	0.013 (0.008, 0.017)	**< 0.001**	0.008 (-0.004, 0.02)	0.158	0.085 (0.052, 0.118)	0.057 (-0.024, 0.138)	0.497
Pelvis	Volume	0.004 (0.002, 0.006)	**0.001**	0.004 (0, 0.007)	**0.032**	0.067 (0.031, 0.104)	0.062 (0.006, 0.118)	0.866
	Intensity	0.02 (0.014, 0.026)	**< 0.001**	0.019 (0.008, 0.029)	**0.001**	0.109 (0.077, 0.142)	0.104 (0.047, 0.161)	0.86
Arms	Volume	0.003 (0.001, 0.004)	**< 0.001**	0.001 (0, 0.002)	**0.018**	0.092 (0.05, 0.134)	0.045 (0.009, 0.081)	0.079
	Intensity	0.01 (0.007, 0.013)	**< 0.001**	0.005 (0.002, 0.009)	**0.008**	0.112 (0.076, 0.148)	0.056 (0.017, 0.096)	**0.03**
Legs	Volume	0.003 (0.001, 0.005)	**0.001**	0.003 (0.002, 0.005)	**< 0.001**	0.068 (0.03, 0.106)	0.07 (0.036, 0.104)	0.919
	Intensity	0.017 (0.012, 0.022)	**< 0.001**	0.016 (0.01, 0.023)	**< 0.001**	0.118 (0.084, 0.152)	0.11 (0.065, 0.154)	0.768

Table 2. Sex-stratified linear associations between PA and site-specific BMD based on Raw data and z-scored data. [a]Raw data, unstandardized. [b]Z-scored data, standardized variables for comparable effect sizes. [c]β (95% CI), Regression coefficients from weighted linear models (volume scaled to 10^3 MIMS/day; intensity to 10 MIMS/min). [d]p-value from weighted linear models. [e]β (95% CI), BMD changes per SD increment in PA. [f]p-value obtained from Z-test comparing standardized β between sexes. Model adjustments: age, race/ethnicity, height, weight, poverty-income ratio, dietary calcium, and vitamin D. PA, physical activity; BMD, bone mineral density; TBLH, total body less head; MIMS, monitor-independent movement summary units.

Characteristics	Inflection point[a]	< Inflection point[a]		≥ Inflection point[a]		
		β (95% CI)[b]	p[c]	β (95% CI)[b]	p[c]	p[d]
Volume						
Boys						
Lumbar spine	22.2	0.002 (0, 0.003)	0.064	0.012 (0.004, 0.02)	**0.006**	**0.022**
Girls						
TBLH	14.6	0.006 (0.003, 0.009)	**0.001**	0.001 (-0.001, 0.003)	0.418	**0.019**
Pelvis	14.4	0.011 (0.002, 0.02)	**0.02**	0 (-0.003, 0.002)	0.778	**0.025**
Legs	15.1	0.007 (0.003, 0.01)	**< 0.001**	0.001 (-0.002, 0.003)	0.584	**0.026**
Intensity						
Boys						
TBLH	4.5	0.047 (0.03, 0.063)	**< 0.001**	0.01 (0.005, 0.015)	**0.001**	**0.001**
Girls						
TBLH	4.9	0.034 (0.021, 0.046)	**< 0.001**	0.002 (-0.006, 0.011)	0.585	**0.002**
Pelvis	4.6	0.077 (0.035, 0.119)	**0.001**	0.002 (-0.009, 0.013)	0.72	**0.004**
Arms	4.9	0.014 (0.005, 0.023)	**0.004**	0.001 (-0.005, 0.006)	0.78	**0.036**
Legs	4.9	0.044 (0.028, 0.06)	**< 0.001**	0.002 (-0.007, 0.012)	0.604	**0.001**

Table 3. Nonlinear threshold effects of PA volume and intensity on BMD at select skeletal sites. Only skeletal sites with significant nonlinear threshold effects (log-likelihood ratio test, $P < 0.05$) are illustrated. [a]Inflection points (units: 10^3 MIMS/day for volume; 10 MIMS/min for intensity). [b]β (95% CI), Regression coefficients from weighted linear models. [c]p-value from weighted linear models. [d]p-value from log-likelihood ratio test for nonlinear threshold effects. Model adjustments: age, race/ethnicity, height, weight, poverty income ratio, dietary calcium, and vitamin D. PA, physical activity; BMD, bone mineral density; TBLH, total body less head; MIMS, monitor-independent movement summary units.

Boys showed maximal benefits in the limbs (arms: β = 0.092–0.112; legs: β = 0.068–0.118), whereas girls exhibited peak effects in the legs (β = 0.070–0.110) and pelvis (β = 0.062–0.104). By contrast, thoracic and lumbar spine regions exerted the smallest effects on both sexes. Notably, PA intensity consistently conferred larger BMD benefits than volume across sexes. The effect size ratios at the TBLH indicated a 1.68-fold greater benefit for intensity over volume in boys (0.131 vs. 0.078) and a 1.58-fold difference in girls (0.106 vs. 0.067).

Discussion

This study delineated distinct linear and nonlinear associations between PA metrics (volume and intensity) and site-specific BMD across skeletal regions in children and adolescents and revealed trends of differential BMD

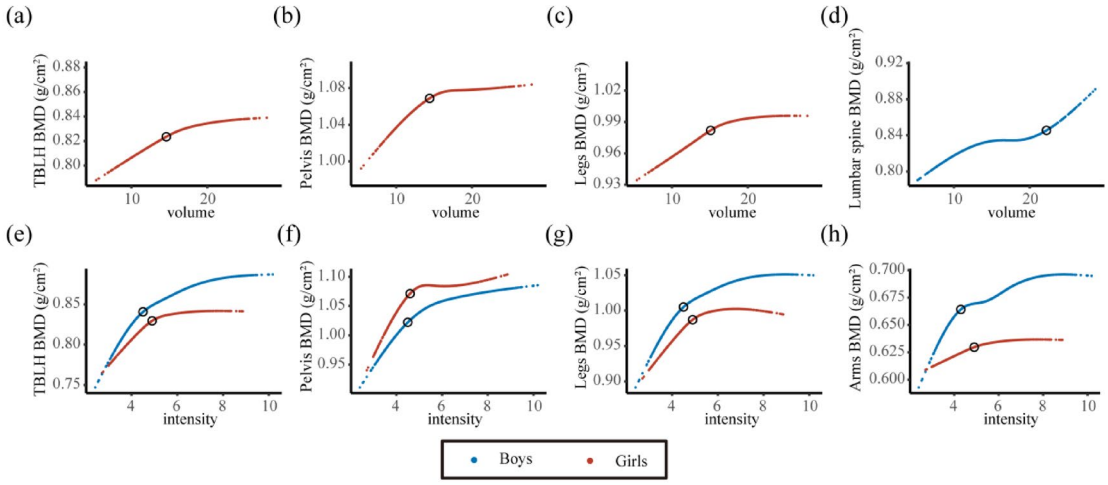

Fig. 3. Nonlinear threshold effects of PA volume and intensity on BMD at select skeletal sites. Panels display regions with statistically significant nonlinear associations ($P < 0.05$): Volume effects (per 10^3 MIMS/day): (**a**) TBLH, (**b**) pelvis, (**c**) legs, (**d**) lumbar spine; Intensity effects (per 10 MIMS/min): (**e**) TBLH, (**f**) pelvis, (**g**) legs, (**h**) arms. PA, physical activity; BMD, bone mineral density; MIMS, monitor-independent movement summary units; TBLH, total body less head.

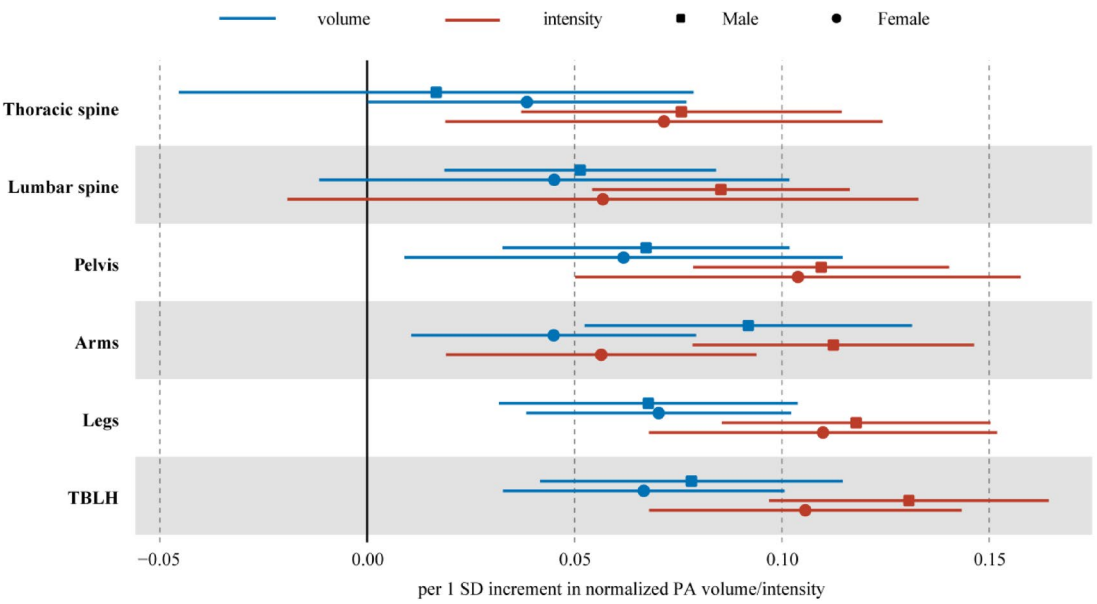

Fig. 4. Sex- and site-specific associations between PA and BMD. Associations are presented as standardized β-values (95% CIs) based on weighted linear regression comparing z-score normalized PA and BMD measurements. PA, physical activity; BMD, bone mineral density; SD, standard deviation; TBLH, total body less head.

responses between sexes and potential threshold effects. The findings refine our understanding of PA's osteogenic potential and emphasize the necessity of tailored exercise prescriptions to optimize skeletal health during critical developmental stages.

We observed significant positive associations between TBLH BMD and PA in boys and girls, irrespective of PA metrics (volume or intensity), consistent with previous evidence[33,37]. However, site-specific analyses uncovered divergent patterns. At the lumbar spine, PA showed a correlation with BMD in boys but not girls, whereas thoracic spine BMD displayed intensity-dependent associations in both sexes, independent of PA volume. These findings are in contrast to those of earlier studies reporting inconsistent PA–BMD relationships at the lumbar and thoracic spine[38,39]. Methodological variations, such as pooling lumbar and thoracic spine data, may explain discrepancies in earlier reports on spine BMD responses[11,18,40].

For weight-bearing regions (pelvis, arms, and legs), PA exhibited consistent positive correlations with BMD across sexes. Pelvic BMD associations diverged from studies reporting the absence of PA effects in general populations[36,41] but aligned with those on athlete cohorts demonstrating sport-specific adaptations[18]. Female handball athletes, for example, exhibited elevated pelvic BMD compared with nonathletes, and this outcome was likely due to sport-specific mechanical loading patterns[18]. Similarly, appendicular BMD (arms and legs) showed robust PA-BMD links in both sexes, which corroborated mechanistic studies emphasizing weight-bearing strain[12,27,33,42]. Nonetheless, conflicting reports exist; some studies found no associations for boys' arms[36,41,42] or girls' legs[36]. These discrepancies may reflect variations in PA assessment methods (e.g., self-report versus accelerometry) or population characteristics (e.g., activity type and baseline BMD). Self-reported PA often underestimates high-intensity activities critical for osteogenesis[20], whereas accelerometry captures mechanical loading more objectively[23].

Site-specific responses further highlight the related biomechanical principles. Weight-bearing regions (limbs and pelvis) exhibited strong PA–BMD associations (e.g., boys' legs: $\beta = 0.118$; girls' pelvis: $\beta = 0.104$), consistent with bone's adaptive capacity to dynamic strain[7,43]. Conversely, nonweight-bearing sites (thoracic/lumbar spine) showed minimal associations, which was likely due to load dispersion during upright activities. The lumbar spine, while weight bearing, experiences compressive forces distributed across vertebrae and intervertebral discs, which potentially attenuates strain magnitudes compared with appendicular regions[44]. This condition underscores the need for nuanced interpretations of site-specific BMD responses given that skeletal adaptation is governed not only by PA dose but also by biomechanical context[45].

Notably, PA intensity outperformed volume as a BMD determinant, with effect size ratios of 1.58–1.68 (TBLH: 1.68 for boys and 1.58 for girls). This outcome aligns with the mechanostat theory, where short-duration, high-magnitude loading preferentially stimulates osteogenesis[7,43]. Activities, such as jumping, generate peak strains that exceed bone's adaptive threshold, which triggers osteoblast recruitment and mineralization[43]. Such findings reinforce the importance of prioritizing intensity in exercise prescriptions, particularly for girls, who may require targeted high-intensity interventions to overcome lower baseline gains ($\beta = 0.106$ vs. 0.131 in boys).

Our study is the first to identify PA intensity and volume thresholds governing BMD responses in a general pediatric population. Boys demonstrated intensity thresholds of approximately 45 MIMS/min across weight-bearing sites, with BMD gains plateauing above these thresholds (e.g., TBLH: $\beta = 0.047$ below vs. $\beta = 0.010$ above threshold). Girls exhibited comparable intensity thresholds (approximately 49 MIMS/min) but distinct volume thresholds (approximately 14.6×10^3 MIMS/day), beyond which PA benefits stagnated. The intensity threshold was determined using the peak 60 min MIMS value, calculated as the average of the highest 60 MIMS/min (not necessarily consecutive) recorded on each valid observation day and with an overall threshold representing the mean of daily averages. These peak values closely aligned with the World Health Organization guidelines, which recommend at least 60 min of moderate-to-vigorous PA (MVPA) per day for children and adolescents[31], and are consistent with those of previous research employing a 60 min peak step frequency[28]. Public health strategies should thus prioritize achieving these intensity thresholds to maximize BMD gains, especially important for girls, who showed a lower baseline responsiveness ($\beta = 0.106$ vs. 0.131 in boys). Beyond these thresholds, incremental PA yielded diminishing returns ($\beta = 0.010$ in boys; stagnation in girls), which emphasizes the need to optimize the activity within these threshold ranges. Interventions may include school-based programs incorporating high-impact exercises (e.g., plyometrics) or community initiatives promoting sports that involve intermittent bursts of intensity (e.g., basketball, dance) while avoiding training exceeding the identified thresholds.

Beyond general weight-bearing and impact activities, recent evidence supports the use of structured high-intensity interval training (HIIT) protocols—characterized by brief, vigorous 'all-out' efforts interspersed with rest—to stimulate osteogenic loading and improve multisite BMD in adolescents, particularly those with obesity (e.g., HIIT vs. moderate continuous training showed greater gains in bone geometry and strength)[46] Likewise, supervised resistance training in children and adolescents safely increases muscle strength and bone mass, with randomized trials demonstrating significant improvements in lumbar spine and femoral neck BMD following the 8–12-week progressive resistance programs[47]. Incorporating these modalities—either within school-based physical education or community leisure programs—may optimize BMD accrual by combining high mechanical loads with safe, scalable exercise prescriptions.

Although most sex-related differences lacked statistical significance ($P > 0.05$), directional trends suggest greater BMD benefits for boys, particularly in appendicular regions (arms: $\beta = 0.112$ vs. 0.056; legs: $\beta = 0.118$ vs. 0.110). These trends may reflect sex-divergent biomechanical loading patterns mediated by hormonal and behavioral factors[48,49]. Testosterone-driven increases in muscle mass during puberty may amplify skeletal strain in boys given that muscle force during contraction directly loads attached bones[50]. By contrast, estrogen's role in the modulation of bone turnover[51,52], that is, to promote endocortical apposition while suppressing resorption, can attenuate PA responsiveness in girls by reducing net bone formation rates. Behavioral factors further amplify these differences: boys report higher engagement in resistance training and high-intensity sports, whereas girls favor moderate-intensity activities that may fall below osteogenic thresholds[53].

Methodologically, unlike traditional metrics, such as metabolic equivalents (METs) or categorical intensity classifications (e.g., MVPA), that rely on indirect energy cost estimations or broad activity categories, MIMS quantifies triaxial acceleration patterns to capture the magnitude and duration of movements[23]. However, the relationship between MIMS and energy expenditure (e.g., METs) remains underexplored, and validated thresholds for the translation of MIMS values into time spent in health-relevant intensity categories (e.g., MVPA) are currently lacking. This gap limits direct comparisons with studies using traditional PA metrics and underscores the need to establish MIMS-based intensity cut-points in future research.

However, this study has several limitations. First, its cross-sectional design precludes causal inference, as bidirectional relationships between PA and BMD cannot be ruled out. Second, although emerging evidence highlights that specific nutrients (e.g., calcium, vitamin D) modulate the osteogenic response to PA, our reliance on dietary-recall–derived proxies for calcium and vitamin D—and lack of detailed macronutrient profiling—may have inadequately controlled for these nutritional confounders[54,55]. Third, we did not assess sedentary behavior, despite evidence that prolonged sitting adversely affects bone health in youth—partly through reductions in lean mass and mechanical loading[56–58]. Fourth, while socioeconomic status (SES; e.g., PIR) was included as a covariate, we did not explore its substantive impact on skeletal outcomes; SES influences access to nutrition and organized exercise opportunities, all of which can shape bone health trajectories[59,60]. Fifth, the absence of Tanner staging further obscured puberty-mediated effects on PA–BMD relationships despite controlling for age, height, and weight. Puberty timing influences hormonal surges (e.g., testosterone, estrogen) and growth velocity, both of which modulate bone's responsiveness to mechanical loading[48]. Finally, the generalizability of our findings may be constrained by the lack of fracture history data and incomplete exclusion of samples with underlying metabolic conditions.

Our findings advocate exercise prescriptions emphasizing high-intensity, weight-bearing activities to maximize the accrual of BMD, particularly in girls. Clinicians and public health initiatives should prioritize interventions that aid adolescents in achieving the identified intensity thresholds (~45–49 MIMS/min) rather than exceeding them. Practical strategies include the incorporation of high-impact exercises into physical education curricula that reward intensity-based goals. Future longitudinal studies should validate these thresholds by integrating SES, sedentary-behavior assessment, hormonal assays, and genetic profiling to clarify how PA and nutrition interact across pubertal stages.

Conclusion

This study advances the understanding of PA's dose–response effects on pediatric bone health and identified site-specific thresholds and trends favoring greater BMD gains in boys. Leveraging accelerometry and multisite BMD assessments, we demonstrated that PA intensity surpassed volume in driving osteogenic responses, particularly in weight-bearing regions. These findings promote precision exercise guidelines tailored to anatomical sites and activity profiles and provide strategies to reduce lifelong osteoporosis risk. By prioritizing high-intensity, biomechanically relevant activities, especially for girls, public health initiatives can capitalize on the transient "window of opportunity" during growth to maximize peak bone mass and fracture resilience in later life.

Data availability

The datasets generated and analyzed in the current study are available at NHANES website: https://wwwn.cdc.gov/nchs/nhanes.

Received: 13 December 2024; Accepted: 8 May 2025
Published online: 16 May 2025

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Acknowledgements
The authors thank the participants and staff involved in data collection and management in the NHANES.

Author contributions
S.O. conceptualisation, data curation, formal analysis, visualisation, original draft; D.C. formal analysis, review and editing; Y.Y. methodology, review and editing; F.M. conceptualisation, review and editing; G.R. conceptualisation, review and editing.

Declarations

Ethics approval and consent to participate
Ethical approval was obtained from the National Center for Health Statistics (NCHS) Ethics Review Board (ERB) (Protocol #2011-17, https://www.cdc.gov/nchs/nhanes/about/erb.html). NHANES has obtained written informed consent from all participants.

Competing interests
The authors declare no competing interests.

Additional information
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