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Moderate to vigorous physical activity and impact loading independently predict variance in bone strength at the tibia but not at the radius in children

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23 Abstract

24 **Objectives:** To assess if daily minutes of moderate-to-vigorous physical activity (MVPA) or
25 vigorous physical activity (VPA) and impact counts (acceleration peaks $\geq 3.9g$) would
26 independently predict variance in bone strength in children and youth. Second, to estimate bone
27 strength gain associated with increases in daily MVPA, VPA or impact counts.

28 **Methods:** We recorded 7-day activity of 49 participants, mean age 11.0; SD 1.7 years, using
29 accelerometers and estimated radius and tibia bone strength using peripheral quantitative
30 computed tomography. We used linear regression models adjusted for sex, body mass and
31 muscle area to address objectives.

32 **Results:** Daily MVPA (mean 50, SD 23 min) and VPA (17, 11) or impacts (71, 59 counts) did
33 not predict variance in radius strength. Daily VPA ($\beta=0.24$), predicted variance in tibia strength
34 at the distal and shaft sites, shaft strength was also predicted by MVPA ($\beta=0.20$) and impact
35 counts ($\beta=0.21$). Our models estimated a 3-6%, 4%, and 4-11% gain in tibia strength after
36 increasing daily MVPA by 10-20 min, VPA by 5 min, or impacts by 30-100 counts, respectively.

37 **Conclusions:** Daily minutes MVPA, VPA and impact counts were independent predictors of
38 tibia but not radius strength. Objective recording of activities associated with forearm bone
39 strength and trials testing efficacy of increasing daily MVPA, VPA and related impacts on bone
40 strength development in children and youth are warranted.

41 **Key Words:** child, accelerometer, skeleton, peripheral quantitative computed tomography,
42 exercise, physical activity, bone strength

Introduction

The World Health Organization, alongside the Canadian 24-Hour Movement Guidelines for Children and Youth, recommend at least 60 minutes, per day, of moderate-to-vigorous physical activity (MVPA), and vigorous physical activity (VPA) along with muscle and bone strengthening activities at least 3 times per week (Tremblay et al. 2016; World Health Organization 2010). However, there is limited evidence of the relationships between objectively recorded MVPA or VPA and bone strength at the upper and lower extremities, particularly from children approaching accelerated pubertal growth – a time period considered a window of opportunity for bone strength adaptation to loading (Kontulainen et al. 2003; Macdonald et al. 2007). Daily minutes of MVPA or VPA have been positively associated with estimated bone strength at the weight-bearing tibia in children, adolescents and young adults (Gabel et al. 2017a; Gabel et al. 2017b; Janz et al. 2014; Meiring and McVeigh 2014). Less evidence pertains to the associations at the non-weight bearing upper extremity bones, and findings seem to indicate weaker relationships at the distal radius (Gabel et al. 2017b; Meiring and McVeigh 2014).

Experimental studies with animal models have identified dynamic activities with impact-type of loading osteogenic (Turner and Robling 2003). Accelerometers have been validated against ground reaction forces to estimate bone impacts in children (Meyer et al. 2015). While accelerometer-recorded impact counts have been positively associated with bone geometry or strength in older adolescents, young adults and pre-menopausal women (Deere et al. 2012a; Vainionpää et al. 2007), evidence linking impact counts with bone strength in children is not yet available. This information is warranted to guide new physical activity interventions aiming to optimize bone strength development in children.

Our first objective was to assess if daily minutes of MVPA, VPA and daily impact counts would independently predict variance in bone strength at distal and shaft sites of the radius and tibia in children. Our second objective was to estimate increases in bone strength associated with greater objectively measured MVPA, VPA, and daily impact counts and explore associations across PA outcomes, and between radius bone strength and subjectively recorded physical activities using hands or arms. We hypothesized that daily minutes of MVPA, VPA, and impact counts would independently predict variance in bone strength at the radius and tibia in children and youth.

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Methods

Study Design and Participants

Using a cross-sectional study design, we assessed data from 49 children and youth between the ages of 8 and 14 years (mean age 11.0, SD 1.7y) from a participant pool of two cohort studies assessing seasonal physical activity (PA) and bone strength development in children, recruited from local schools and community programs in Saskatoon (Bunyamin et al. 2018; Muhajarine et al. 2015). To be included in the present study, participants had to have pQCT scans of the forearm and lower leg as well as valid tri-axial accelerometer recording of PA (Deere et al. 2012a; Sioen et al. 2015). From the bone health study cohort of 165 children (Bunyamin et al. 2018), 49 participants met the inclusion criteria. Twenty-two of these 49 participants had a recent tri-axial accelerometer PA recording as they also participated in the seasonal PA study (Muhajarine et al. 2015). We obtained informed assent from participants and consent from their parents or guardians. Study was approved by the University of Saskatchewan Biomedical Research Ethics Board and was conducted in accordance with the World Medical Association Declaration of Helsinki – Ethical Principles for Medical Research Involving Human Subjects.

Measurements

Anthropometrics

We completed anthropometric measurements on the same day as bone measurements. We recorded height, sitting height, body mass, ulna and tibia lengths using previously described methods (Duff et al. 2017). We measured height, sitting height, and limb lengths three times and the median values were used in analyses. We estimated maturation by calculating years from age

at peak height velocity (PHV) for each participant using sex-specific equations (Moore et al. 2015).

Physical activity

We asked all participant to wear a triaxial accelerometer (model wGT3X-BT, ActiGraph) for seven consecutive days. The accelerometer is a small, lightweight device that is capable of measuring ± 8 g of acceleration along three axes. We chose a sampling rate of 30 Hz for the duration of the wear period (Evenson et al. 2008; Trost et al. 2011). We instructed the participants to wear the accelerometer on an elastic belt above their right hip bone (mid-axillary line) during waking hours. They were asked to remove the accelerometer before taking part in activities where there was a high risk of the accelerometer getting wet, such as showering, bathing and swimming. We analyzed the data was analyzed using software provided by the manufacturer (ActiLife, v6.13.2). We defined non-wear times as 20 consecutive minutes of zero accelerometer counts (Borghese et al. 2017; Stevens et al. 2007; Treuth et al. 2003). We included days with a wear time minimum of 8 hours per day (Deere et al. 2012a; Sioen et al. 2015). We included data from participants with a minimum of 2 days of valid wear time, including a minimum of one day on the weekend in our analyses (Deere et al. 2012a).

Activity counts were stored in intervals of 10 seconds. Validated cut-points were used to define moderate (2296-4011 counts per minute, cpm) and vigorous physical activity (≥ 4012 cpm) in children (Evenson et al. 2008). We calculated daily MVPA and VPA as the total minutes of MVPA and VPA divided by the number of days of valid wear. As raw accelerometer data is considered a valid measurement of bone loading during physical activity (Jamsa et al. 2011), we acquired accelerometer data using the feature extraction tool from the manufacturer's software.

We used a custom algorithm (Matlab 2016a, MathWorks) to count the daily average number of impacts equal to, or greater than, a resultant acceleration peak of 3.9 g after controlling for the effects of gravity by subtracting 1 g from each impact count (i.e., standing is equal to 0 g of impact). We based our 3.9 g threshold on previous work in pre-menopausal women (Vainionpää et al. 2007; Vainionpää et al. 2006). We calculated daily impact counts as the total number of impacts divided by the number of days of valid wear.

We measured self-reported physical activity using the Physical Activity Questionnaire for Older Children (PAQ-C) (Kowalski et al. 1997). This questionnaire calculates an average physical activity score from 12 questions with a score of 1 indicating the lowest level of activity and a score of 5, the highest level of activity. We also asked participants if they regularly participated in activities including upper body loading and to report the number of sessions per week they participated in physical activities involving their hands or arms in the past 12 months.

pQCT Data Acquisition and Analysis

We estimated bone strength and cross-sectional muscle area of the dominant radius and tibia using peripheral quantitative computed tomography (pQCT) (XCT 2000, Stratec Medizintechnik GmbH). We analyzed the data using software provided by the manufacturer (version 6.00B). Reference line placement, scan acquisition and analysis protocols were conducted following previously described methods (Duff et al. 2017). Briefly, two trained pQCT technicians obtained scans at distal (4% ulna and tibia) and shaft sites (65% ulna and 66% tibia) of the dominant radius and tibia. We excluded 2 distal radius, 2 radius shaft, 2 tibia shaft and 6 distal tibia scans from the analyses based on our pQCT scan quality inclusion criteria (Duff et al. 2017). We analyzed distal bone sites with contour model 1 with an outer bone threshold of 200 mg/cm³ and

shaft sites with separation mode 4 and outer and inner thresholds of 280 and 480 mg/cm³, respectively (Duff et al. 2017). We estimated bone strength at the distal sites as the product of total bone area and total bone density squared, which estimates the bone's resistance to compressive loading (BSIc, mg²/mm⁴) and at the shaft sites, using the density weight polar section modulus, which estimates the bone's resistance to torsion (SSI_p, mm³) (Ashe et al. 2006; Kontulainen et al. 2008). We analyzed cross-sectional muscle area (mm²) from the forearm and lower leg scans using contour mode 1 with a threshold of 40 mg/cm³ to separate muscle from the subcutaneous fat. The short-term precision of pQCT outcomes was calculated using root-mean-squared coefficient of variation (CV%_{RMS}) in 31 children. CV%_{RMS} values of distal and shaft bone strength at the radius and tibia were between 6.2% and 8.0% (Duff et al. 2017). Forearm and lower leg muscle area short-term precision CV%_{RMS} values were 2.8% and 3.6%, respectively (Björkman et al. 2017).

Statistical Analyses

All variables met our assumptions for our linear regression models, including normally distributed variables based on visual inspection of P-P plots, a linear relationship between physical activity and bone strength outcomes, no outliers outside ± 3 SD, independence of residuals, homoscedasticity of residuals, and no multicollinearity between covariates. To address our first objective, we used two step hierarchical linear regression models. In the first step, we created a base model including determinants of bone strength (sex, body mass, and site-specific cross-sectional muscle area) based on preliminary models of our data and previous literature (Macdonald et al. 2006). In the second step, we included daily minutes of MVPA, VPA, and daily impact counts in each base model to estimate their independent role in predicting variance

164 in bone strength at the distal and shaft sites of the radius and tibia. We report coefficient of
165 determination (R^2) of our base models, R^2 changes after including PA outcomes in the base
166 model, and standardized β -coefficients for daily minutes of MVPA, VPA, and daily impact
167 counts. We also report Pearson correlation coefficients (r) to explore associations across MVPA,
168 VPA and bone impacts, and between radius bone strength and subjectively recorded physical
169 activities using hands or arms. Significance was set at $p < 0.05$. We performed statistical analyses
170 using SPSS Statistics for Windows, Version 24.0 (IBM Corp.).

171 To address our second objective, we applied standardized beta coefficients of our models
172 and means and standard deviations of daily MVPA, VPA, and impact counts to predict increases
173 in tibia bone strength. We built our models to estimate increases in bone strength based on
174 reported PA in pediatric exercise interventions (Fuchs et al. 2001; Gortmaker et al. 2012; Hollis
175 et al. 2016; Kontulainen et al. 2017; Macdonald et al. 2007). We chose to model a 10-minute
176 increase in MVPA since the mean daily MVPA was 50 minutes in our sample, and the current
177 Canadian guidelines recommend children and youth to participate in at least 60 minutes of
178 MVPA per day (Tremblay et al. 2016). Our rationale for modeling a 20-minute increase in
179 MVPA reflected a 20-minute average MVPA reported in a systematic review of physical
180 education classes (Hollis et al. 2016). We modeled a 5-minute increase in VPA, based on 5-
181 minute increases in daily VPA from an after-school PA intervention (Gortmaker et al. 2012). We
182 modeled increases of 36, 60 and 100 impact counts based on school-based exercise intervention
183 with up to 36 jumps/day (Macdonald et al. 2007), our pediatric physical activity intervention
184 showing an average number of 64 impacts/session (Kontulainen et al. 2017), and a pediatric
185 exercise intervention with 100 two-foot drop jumps/session (Fuchs et al. 2001), respectively. We
186 estimated increases in bone strength using the following formula.

187

$$\text{Pred. \% bone strength increase} = \left(\frac{(\text{Std.}\beta * SD_{\text{bone strength}})}{SD_{\text{physical activity}}} * (10\text{min physical activity}) \right) \frac{1}{Mean_{\text{bone strength}}} * 100\%$$

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189 **Results**

190 We provide background characteristics, and descriptive data of physical activity outcomes and
191 bone strength estimates for all participants and for each sex in Table 1. Daily average minutes of
192 MVPA, VPA, and daily impact counts ≥ 3.9 g did not independently predict (all standardized β -
193 coefficients non-significant) variance in bone strength at distal or shaft sites at the radius (Table
194 2). Daily minutes of VPA was an independent predictor ($\beta=0.24$, $p=0.029$) and improved the
195 prediction of variance ($\Delta R^2=0.55$, $p<0.001$) in distal tibia strength (Table 2). Daily minutes of
196 MVPA ($\beta=0.20$, $p=0.020$), VPA ($\beta=0.24$, $p=0.005$), and daily impact counts ($\beta=0.21$, $p=0.013$)
197 were independent predictors and improved the prediction of variance ($\Delta R^2=0.037$, $p<0.001$;
198 $\Delta R^2=0.053$, $p<0.001$; $\Delta R^2=0.042$, $p<0.001$) in tibia shaft strength, respectively (Table 2).

199 Based on our models, a 10 and 20-minute increase in daily MVPA would result in
200 respective gains of 3% and 6% in tibia bone strength, and a 5-minute increase in VPA would
201 result in a 4% increase in tibia bone strength (Figure 1). We also estimated that a 36, 60, and
202 100-count increase in daily impact counts would result in a 4%, 7%, and 11% increase in tibia
203 bone strength, respectively (Figure 2). Finally, mean minutes of MVPA (0.68 , $p<0.001$) and
204 VPA ($r=0.81$, $p<0.001$) were associated with number of bone impacts. Weekly number of
205 activities using hands or arms (mean 4.9, SD 3.4) correlated positively with bone strength at the
206 radius shaft ($r=0.44$, $p=0.027$).

Discussion

Our findings suggested that children and youth who participate in more daily minutes of MVPA and VPA, and attain a greater number of daily impact counts have greater tibia, but not radius bone strength. Based on our models, we also estimate a 3-6%, 4%, and 4-11% gain in tibia strength after increasing daily MVPA by 10-20min, VPA by 5min, or impacts by 30-100 counts, respectively.

These findings support the evidence of positive relationships between MVPA and VPA and tibia bone strength in children and adolescents (Gabel et al. 2017b; Janz et al. 2014; Sayers et al. 2011). Our findings provide further evidence of daily impact counts predicting variance in bone strength at the tibia shaft in children and youth. These findings add to the literature indicating positive relationships between impact counts and bone size or strength at the weight-bearing lower extremity bones (tibia and femur) in adolescent boys and girls and premenopausal women (Deere et al. 2012a; Deere et al. 2012b; Vainionpää et al. 2007).

We observed no associations between bone strength estimates at the distal radius and MVPA, VPA or bone impacts. This may relate to the site-specificity in bone adaptation to loading stimulus (Kontulainen et al. 2003). Waist-worn accelerometers monitor accelerations within the center of body mass, which is ideal when recording weight-bearing activities and loadings stimulus for the lower extremity but appear less effective to capture activities providing loading stimulus for the upper extremity. With this note, the lack of a relationship between radius bone strength and MVPA, VPA or bone impacts could have been anticipated. However, previous studies have reported positive associations between distal radius bone strength and MPA, MVPA or VPA (Gabel et al. 2017b; Meiring and McVeigh 2014). Differences in study design and methodology (e.g., cohort size, skeletal maturity, used accelerometers and bone imaging tools)

challenge comparisons between these studies. Meiring and McVeigh (2014) reported a positive association between daily minutes of MPA and bone strength at the distal radius but not at the radius shaft in a comparable sample (N=38) of prepubertal children (Meiring and McVeigh 2014). Gabel et al. (2017b) followed a wider age range (9-20 years) of participants (N=309 at baseline) and reported positive associations between distal radius failure load and daily minutes of MVPA in this mixed longitudinal cohort (Gabel et al. 2017b). These studies recorded PA using uniaxial accelerometers (Actical or Actigraph GT1M), Meiring and McVeigh (2014) used different cut points to define physical activity intensity, and neither study estimated impact counts from the accelerometer data (Gabel et al. 2017b; Meiring and McVeigh 2014). Potential differences in the types of physical activities and related loading stimulus to lower and upper extremities may also contribute to observed differences in these associations. We asked our participants to report number and weekly frequency of physical activities or sports involving hands or arms. These findings indicated positive correlations between weekly sessions of physical activities involving both upper and lower extremities and bone strength at the radius shaft which suggest that estimation of impacts using waist-worn accelerometers may need to be complemented with additional measures to estimate loading stimulus in the upper extremity bones. Until we find a way to objectively measure bone loading, such as impacts on the upper body, future research could identify types and frequencies of physical activities associated with bone strength in the upper extremities of children and youth.

Our bone strength modeling approach was based on reported increases in MVPA, VPA, or number of impacts in physical activity sessions in children (Fuchs et al. 2001; Gortmaker et al. 2012; Hollis et al. 2016; Kontulainen et al. 2017; Macdonald et al. 2007). Our results linking estimated increases in MVPA, VPA and particularly in bone impacts with tibia bone strength

may benefit design of interventions aiming to optimize bone strength development in late childhood and early puberty. Future research to validate waist-worn accelerometers or another tool able to monitor bone impact/loading characteristics associated with bone strength at the upper extremity is warranted. These studies will guide future exercise interventions aiming to optimize bone strength development in children and youth. Such interventions may be useful in reforming physical activity guidelines by specifying the types, duration and intensity of activities that strengthen the lower extremity, as well as the fracture-prone upper extremity skeleton in children and youth.

It is important to note that the estimation of physical activity intensity (e.g. MVPA, VPA) using accelerometer measurements is based on the estimated energy expenditure. Physical activity intensity is defined based on specific cut-points for acceleration counts and these cut-points have been validated against indirect calorimetry measures of oxygen consumption (Evenson et al. 2008). Energy expenditure, however, is considered less relevant for bone adaptation than exposure to dynamic, impact-type loading exceeding (strain) threshold and stimulating bone from unusual directions (Al Nazer et al. 2012). Experimental findings suggest estimating intensity of osteogenic physical activity by multiplying peak load (strain) by the loading frequency (Turner and Robling 2003). It is a challenge to translate this estimation in clinical studies or practise. It appears possible to capture impact-type loading using tri-axial accelerometers. Accelerations have been associated with ground reaction forces in adults (Rowlands and Stiles 2012) and children while performing activities such as jumps on a force platform (Meyer et al. 2015). Our models suggested that daily increases of 60 to 100 impacts may be more beneficial to tibia bone strength than 10 and 20-minute increases in MVPA and a 5-minute increase in VPA. It is plausible that impacts during MVPA and VPA may explain, at least

part of these associations since impact counts were associated with daily minutes of MVPA and VPA. Altogether, these findings suggest that impact counts may provide an objective tool to quantify intensity and frequency of bone loading stimulus, particularly at the weight-bearing skeleton of children and youth (Meyer et al. 2015).

Our study had some strengths and limitations that warrant discussion. Strengths included the use of objective and previously validated methods to estimate bone strength and physical activity intensities. First, we used pQCT-estimates of bone strength which have been experimentally validated against mechanical testing (Kontulainen et al. 2008). Second, the estimated effect sizes in bone strength gain in our models appeared to exceed precision errors inherent to pediatric pQCT image acquisition (Duff et al. 2017). Third, we used accelerometers with validated methods to objectively quantify MVPA, VPA in children (Evenson et al. 2008; Trost et al. 2011) and developed new estimate for impact counts using acceleration peak resultants. Fourth, we estimated attainable increases in PA outcomes based on previously recorded times spent in MVPA, VPA, and number of impacts during a single physical activity session (Fuchs et al. 2001; Gortmaker et al. 2012; Hollis et al. 2016; Kontulainen et al. 2017; Macdonald et al. 2007).

Study limitations pertain to the cross-sectional design, inherent challenges with accelerometers to quantify impacts, and a small sample size. First, we employed a cross-sectional study design which only yielded predictive models and did not allow us to draw a causative link between physical activity, impacts and bone strength. Our cross-sectional findings may also be attributed to the effects of reverse causality. Second, while accelerometers allowed us to objectively measure physical activity and impact counts, accelerometer impact data must be interpreted with caution. Specifically, due to the low sampling rate of this accelerometer, we may

299 have error in our estimations of impact magnitude from raw accelerometer data (Brond and
300 Arvidsson 2016). This may lead to an underestimation of the number and magnitude of daily
301 impact counts. Unfilterable noise in the form of “accelerometer jiggle”, may also be introduced
302 into our data by following previously described methods of attaching accelerometers to the hip
303 using an elastic waistband (Evenson et al. 2008; Trost et al. 2011). Third, due to our small
304 sample size, we combined data from both sexes and included only three determinants of bone
305 strength in our base models. Future studies with larger samples are needed to assess potential
306 sex-specificity in bone strength and impact count relationships.

307 To summarize, our findings suggested that MVPA, VPA, and high-impact counts were
308 independent predictors of tibia, but not radius bone strength in children and youth. Daily minutes
309 of VPA predicted tibia bone strength at distal and shaft sites. Daily minutes of MVPA and
310 impact counts were predictors of tibia shaft strength. Our models estimated a 3-6%, 4%, and 4-
311 11% gain in tibia strength after increasing daily MVPA by 10-20 min, VPA by 5 min, or impacts
312 by 30-100 counts, respectively. These findings can aid in design of physical activity
313 interventions aiming to optimize bone strength development in late childhood and early puberty.

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322

323 **Conflict of Interest:** The authors declare that they have no conflict of interest.

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453 **Table 1.** Background characteristics, physical activity outcomes and bone strength estimates for study participants.

	All (n=49)	Boys (n=26)		Girls (n=23)	
	Mean (SD)	Mean (SD)	Median (IQR)	Mean (SD)	Median (IQR)
Age (y)	11.0 (1.7)	11.4 (1.7)	11.9 (3.4)	10.7 (1.6)	11.1 (2.6)
Years from Age at PHV (y)	-1.4 (1.4)	-1.8 (1.4)	-1.6 (2.8)	-1.1 (1.4)	-0.8 (2.3)
Height (cm)	148.2 (12.8)	151.7 (12.5)	150.6 (21.0)	144.3 (12.3)	146.7 (19.5)
Body Mass (kg)	42.3 (16.0)	47.8 (18.4)	46.0 (20.5)	36.0 (9.6)	33.0 (10.5)
PAQ-C Score	2.9 (0.5)	3.1 (0.4)	3.1 (0.7)	2.8 (0.6)	2.7 (0.8)
Activities Using Hands or Arms (sessions/week)	4.9 (3.4)	6.3 (4.0)	6.0 (7.8)	3.7 (2.1)	3.8 (3.3)
BMI (kg/m ²)	18.8 (4.7)	20.4 (5.5)	18.6 (4.8)	17.1 (2.8)	16.1 (2.3)
Days of Valid Wear	5.5 (1.7)	5.4 (2.0)	6.0 (3.0)	5.6 (1.5)	6.0 (3.0)
Total Wear Time (min)	5147 (2502)	5324 (2896)	5216 (4890)	4948 (2014)	5133 (3075)
Daily MVPA (min/day)	50.2 (22.6)	54.7 (25.8)	56.2 (41.3)	45.0 (17.4)	46.2 (24.5)
Daily VPA (min/day)	18.6 (10.6)	20.3 (12.2)	18.9 (18.7)	16.8 (8.2)	14.6 (12.2)
Daily Impacts (counts/day)	70.9 (59.4)	78.5 (65.0)	61.0 (122.4)	62.3 (52.5)	48.0 (55.0)
Radius BSIC (mg ² /mm ⁴)	20.9 (6.7)	23.7 (6.7)	22.0 (7.1)	17.7 (5.0)	17.4 (4.5)
Radius SSIP (mm ³)	199.3 (71.2)	218.6 (74.1)	211.2 (114.5)	175.3 (60.9)	160.1 (92.9)
Tibia BSIC (mg ² /mm ⁴)	62.0 (18.6)	68.1 (20.5)	61.4 (32.3)	56.2 (14.9)	56.2 (25.8)
Tibia SSIP (mm ³)	1533 (488.0)	1729 (503.3)	1695 (867.7)	1329 (384.2)	1271 (672.3)
Forearm Muscle Area (mm ²)	2334 (691.2)	2572 (762.9)	2361 (1079)	2040 (454.5)	2044 (735.6)

Lower Leg Muscle Area (mm ²)	6068 (1743)	6588 (1934)	6603 (2167)	5526 (1356)	5350 (1560)
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454 Abbreviations: BMI=body mass index, BSIC= bone strength index estimating bone's resistance against compression (distal sites)

455 MVPA=moderate-to-vigorous physical activity, PAQ-C=physical activity questionnaire for older children, PHV=peak height velocity,

456 SSIP= bone strength index estimating bone's resistance against torsion (shaft sites), VPA=vigorous physical activity.

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Table 2. Adjusted R² of base models (including sex, body mass and site-specific cross-sectional muscle area) and R² change and standardized β -coefficients of linear regression models predicting radius and tibia bone strength.

		Adj. R ²	R ² change	Std. β	p-value
Distal Radius BSIc (N=47)	Base model	0.32			<0.001
	Daily MVPA		0.000	0.002	0.990
	Daily VPA		0.001	0.027	0.833
	Daily Impacts		0.005	-0.073	0.560
Radius Shaft SSIp (N=47)	Base model	0.72			<0.001
	Daily MVPA		0.005	0.070	0.395
	Daily VPA		0.009	0.097	0.232
	Daily Impacts		0.006	0.079	0.327
Distal Tibia BSIc (N=43)	Base model	0.51			<0.001
	Daily MVPA		0.043	0.213	0.056
	Daily VPA		0.055	0.239	0.029
	Daily Impacts		0.038	0.198	0.071
Tibia Shaft SSIp (N=47)	Base model	0.67			<0.001
	Daily MVPA		0.037	0.200	0.020
	Daily VPA		0.053	0.236	0.005
	Daily Impacts		0.042	0.209	0.013

Abbreviations: BSIc=bone strength index estimating bone’s resistance against compression, MVPA=moderate-to-vigorous physical activity, SSIp=bone strength index estimating bone’s resistance against torsion, VPA=vigorous physical activity.

Figure 1. Predicted percent gain in tibia bone shaft strength per increase in daily MVPA and VPA.

Bar graph illustrating the predicted percent gain in tibia shaft bone strength per 10 and 20-minute increase in daily moderate-to-vigorous physical activity (MVPA) and 5-minute increase in daily vigorous physical activity (VPA) based on the standardized β -coefficients of our linear regression models.

Figure 2. Predicted percent gain in tibia bone shaft strength per increase in daily impact counts.

Bar graph illustrating the predicted percent gain in tibia shaft bone strength per 36, 60, and 100 count increase in daily impact counts $\geq 3.9g$ based on the standardized β -coefficients of our linear regression model.