©Journal of Sports Science and Medicine (2023) **22**, 117-132
http://www.jssm.org DOI: https://doi.org/10.52082/jssm.2023.117

Research article

The Influence of Accelerometer Epoch Length on Associations of Physical Activity Intensity and Volume with Bone Outcomes

Annie M. Skinner [1]✉, Alex V. Rowlands [2,3,4], Dimitris Vlachopoulos [1], Alan R. Barker [1], Kathleen F. Janz [5,6] and Sarah A. Moore [7]

[1] Children's Health and Exercise Research Centre, University of Exeter, Exeter, UK; [2] Assessment of Movement Behaviours Group (AMBer), Leicester Lifestyle and Health Research Group, Diabetes Research Centre, University of Leicester, Leicester, UK; [3] NIHR Leicester Biomedical Research Centre, UK; [4] Alliance for Research in Exercise, Nutrition and Activity (ARENA), Sansom Institute for Health Research, Division of Health Sciences, University of South Australia, Adelaide, Australia; [5] Department of Health and Human Physiology, The University of Iowa, Iowa City, IA; [6] Department of Epidemiology, The University of Iowa, Iowa City, IA; [7] School of Health and Human Performance, Dalhousie University, Halifax, Canada

Abstract

Two accelerometer metrics (intensity-gradient and average-acceleration) can be used to determine the relative contributions of physical activity (PA) volume and intensity for health, but it is unknown whether epoch length influences the associations detected. This is important when considering bone health, as bone is particularly responsive to high intensity PA, which may be underestimated by longer epochs. This study aimed to assess the associations between average-acceleration, a proxy measure of PA volume, and intensity-gradient, reflective of PA intensity distribution, from PA data from 1-s to 60-s epochs at age 17 to 23 years with bone outcomes at age 23 years. This is a secondary analysis of 220 participants (124 females) from the Iowa Bone Development Study, a longitudinal study of bone health from childhood to early adulthood. Accelerometer-assessed PA data, captured at age 17 to 23 years, were summarised over 1-s, 5-s, 15-s, 30-s, and 60-s epochs, to generate average-acceleration and intensity-gradient from each epoch length, averaged across ages. Regression analysed associations between mutually adjusted average-acceleration and intensity-gradient with dual-energy X-ray absorptiometry assessed total-body-less-head (TBLH) bone mineral content (BMC), spine areal bone mineral density (aBMD), hip aBMD, and femoral neck cross-sectional area and section modulus at age 23 years. Intensity-gradient was positively associated with TBLH BMC in females, with spine aBMD in males, and with hip aBMD and geometry in both sexes, when a 1 to 5-s epoch was used. Average-acceleration was positively associated with TBLH BMC, spine aBMD and hip aBMD in males, generally when the adjustment for intensity-gradient was from > 1-s epochs. Intensity and volume were important for bone outcomes in both sexes and males, respectively. A 1 to 5-s epoch length was most appropriate to assess the mutually adjusted associations of intensity-gradient and average-acceleration with bone outcomes in young adults.

Key words: Intensity gradient; average acceleration; volume; accelerometer; adolescents; young adults.

Introduction

Accelerometers are now widely used to assess physical activity (PA) for research purposes (Troiano et al., 2014). Traditionally, outcomes from accelerometer-assessed PA have been defined based on cut-points applied to accelerometer counts to classify time spent in different intensities (i.e. light, moderate and vigorous), typically based on the metabolic equivalents of task (METs) framework (Troiano et al., 2014). Validation studies have related the energy expenditure of various tasks to accelerometer counts in order to classify PA intensity based on accelerometer counts (Trost et al., 2011). The application of cut-points to categorize PA intensity condenses the PA intensity continuum into three or four broad categories validated against METs (Colley and Tremblay, 2011; Janz et al., 2014; Rowlands et al., 2020; Trost et al., 2011; Zymbal et al., 2019). However, as movement is accumulated across an intensity continuum, rather than focusing on specific intensities of activity, it has been proposed that the whole intensity spectrum should be considered when examining the relationships between PA with health outcomes (Rowlands et al., 2020). Further, various cut-points have been proposed to define PA intensities, and as such the amount of time spent in different intensities is highly dependent on the applied cut-points (Migueles et al., 2019a).

To overcome some of the limitations with the cut-point based approach to summarising PA data, Rowlands and colleagues have previously proposed using metrics which capture both the volume and intensity of the PA profile (Rowlands et al., 2018). The total volume of PA is reflected in the average-acceleration over the waking day or 24-hour period, providing a proxy measure of PA volume that is not dependent on cut-points (Rowlands et al., 2018). The intensity distribution of PA can be characterised with the intensity-gradient; the slope of a log-log regression between intensity and time accumulated in each intensity bin (Rowlands et al., 2018). Together, these metrics can be used to provide a description of the PA profile (Rowlands et al., 2018).

These metrics have been applied in children and adults, to assess the associations between PA with a range of health outcomes, including body mass index, metabolic health, physical function, bone density and well-being (Fairclough et al., 2019; Rowlands et al., 2018; Rowlands et al., 2020; Skinner at al., 2023). However, most studies to date have calculated the intensity-gradient from high-resolution data, averaged over 5-s epochs (Fairclough et

Received: 17 November 2022 / Accepted: 09 February 2023 / Published (online): 01 March 2023

al., 2019; Rowlands et al., 2018; Rowlands et al., 2020). It is widely acknowledged that accelerometer data should be collected over the shortest epoch possible, to reflect the transient and intermittent nature of PA (Baquet et al., 2007; Heil et al., 2012). However, as some longitudinal cohort studies have been collecting accelerometry data for many years, there is a wealth of longitudinal accelerometry data captured in 60-s epochs (Haapala et al., 2017; Heil et al., 2012; Janz et al., 2010; Loprinzi et al., 2012; Ness et al., 2007). Furthermore, the harmonisation of datasets, as with the International Children's Accelerometry Database which includes data collected from 1997 to 2007, necessitates the application of 60-s epochs in order for PA data from different studies and protocols to be combined for analysis (Sherar et al., 2011). Therefore, it is important to test whether the associations between intensity-gradient with health outcomes are influenced by epoch length to inform whether these metrics have utility when applied to PA data with varying epoch lengths, and to understand whether the observed associations when using shorter epochs are reflected when using longer epochs, thereby informing the use of intensity-gradient in PA data averaged over longer epochs.

Longer epochs underestimate the time spent in high intensity PA, and therefore epoch length may have a greater influence on the associations between intensity and health when considering health outcomes which are particularly responsive to high intensity PA, such as bone (Brailey et al., 2022; Nilsson et al., 2001). Understanding the relationships between PA with bone outcomes is important, as osteoporosis risk in later life is influenced by both peak bone mass achieved in young adulthood, and subsequent age-related bone loss (Bonjour et al., 2009). PA, through impact loading forces, stimulates bone formation by exposing the skeleton to mechanical strains (Gunter et al., 2012; Tobias, 2014). Accelerometer-assessed high intensity PA has been positively associated with measures of bone health in children and adolescents (Brailey et al., 2022), pre- and post-menopausal women (Stiles et al., 2017), and older adults (Parsons et al., 2022). However, there is limited research considering the influence of epoch length on the associations between PA and bone outcomes during the years around peak bone mass, though in post-menopausal women the relationship between moderate-to-vigorous PA with bone outcomes did not differ between 10-s and 60-s epoch (Gabriel et al., 2010).

Previous research has found contradictory associations between intensity-gradient with bone outcomes (Rowlands et al., 2020; Rowlands et al., 2019b). Rowlands and colleagues found both intensity-gradient and average-acceleration were important for total-body-less-head bone mineral content (TBLH BMC) in adolescents and adults in the Iowa Bone Development Study (IBDS) cohort (Rowlands et al., 2020). However, in an analysis of UK Biobank data, both intensity-gradient and average-acceleration were positively associated with bone density T-score in premenopausal women, but neither were independent of the other, and only intensity-gradient was positively associated with bone density T-score in post-menopausal women (Rowlands et al., 2019b). Aside from differences in the study populations, although both used data from raw acceleration sensors, the PA data from the IBDS were averaged over 5-s epochs, and the data from UK Biobank were averaged over 1-s epochs (Rowlands et al., 2020; Rowlands et al., 2019b). However, as the associations between intensity-gradient from varying epoch lengths with bone outcomes have yet to be assessed within the same sample, the influence of epoch length on the associations between intensity-gradient with bone is not yet understood.

The IBDS study analysed by Rowlands and colleagues captured PA using raw acceleration accelerometers (Rowlands et al., 2020). Therefore, extending the previous analyses by Rowlands and colleagues by averaging the accelerometer data over various epoch lengths would facilitate examination of whether the relationship between intensity-gradient and average-acceleration with bone outcomes is dependent on the epoch used, thus informing the application of these novel accelerometer metrics in historical datasets.

The primary aim of this study was to assess the mutually adjusted associations between average-acceleration and intensity-gradient from PA data averaged over 1-s, 5-s, 15-s, 30-s, and 60-s epochs at age 17 to 23 years with bone outcomes (TBLH BMC, spine areal bone mineral density (aBMD), total hip aBMD, femoral neck cross-sectional area, femoral neck section modulus) at age 23 years. We hypothesised that the associations between intensity-gradient with bone outcomes would decrease as epoch length increased, and that the associations between average-acceleration with bone outcomes would decrease when adjusting for intensity-gradient from shorter epoch lengths. The secondary aim of this study was to apply translational metrics, in order to describe the PA profile as assessed by the 1-s, 5-s, 15-s, 30-s, and 60-s epoch PA data.

Methods

Study Design and Participants

This study is a secondary analysis of data from IBDS, an ongoing longitudinal study, tracking bone development, PA, and lifestyle measures from childhood into adulthood (Janz et al., 2001; Metcalf et al., 2020). Beginning in 1998 (wave 1), participants aged 5 years were invited to participate. Follow-up measurements occurred when participants were aged 8 (wave 2), 11 (wave 3), 13 (wave 4), 15 (wave 5), 17 (wave 6), 19 (wave 7), 21 (wave 8) and 23 (wave 9) years, with approximately 400 to 500 participants in each wave. Further details of the IBDS and participant demographics have been previously published (Janz et al., 2001).

The present analyses used data from wave 6 (at age 17 years), to wave 9 (at age 23 years), when PA was captured using raw acceleration accelerometers. Data for raw acceleration accelerometers were available for approximately 60% of participants at wave 6, and for waves 7 to 9 (Rowlands et al., 2020). PA exposures were averaged from available data from waves 6 to 9, and anthropometric measures and bone outcomes were taken wave 9 at age 23 years.

The IBDS received ethical approval from the University of Iowa Institutional Review Board (IRB ID

#:199112665). Legal caregivers and participants aged 18 or over provided written informed consent, and participants provided written informed assent when they were younger than 18 years.

Anthropometrics and maturation

Stature was measured using a Harpenden stadiometer (Holtain Ltd., Crosswell, UK), and body weight was measured using a Healthometer physician's scale (Continental, Bridgeview, IL). Biological age, as the estimated number of years since peak height velocity, was estimated from height, sitting height, leg length, and age, using the Mirwald equation (Mirwald et al., 2002). As the equation is most precise when the measures used in the prediction equation are taken close to the actual age of peak height velocity, for each participant the predicted peak height velocity age that was closest to chronological age of assessment was used (e.g., in wave 2 or 3) (Mirwald et al., 2002).

Bone measures

TBLH BMC (g), lumbar spine (L1 to L4) aBMD (g/cm^2) and left total hip aBMD (g/cm^2) were measured using the Hologic QDR 4500A dual-energy X-ray absorptiometry (DXA) (Delphi upgrade) device, with software V.12.3 in the fan beam mode, as described elsewhere (Janz et al., 2014; Saint-Maurice et al., 2018; Ward et al., 2019). The boundaries of the hip and spine images were specified using software-specific Global Regions of Interest (ROI). After review and editing of the bone within the ROI box, aBMD was determined. Hip structural geometry was estimated from the hip DXA scans, as described by Ward and colleagues (2019), with the Hip Structure Analysis program (Hologic Apex 3.0 software). The Hip Structure Analysis program locates cross-sections traversing the femoral neck at its narrowest point (Ward et al., 2019). Femoral neck cross-sectional area (cm^2) and cross-sectional moment of inertia (cm^4) for bending in the image plane were calculated, and from this section modulus (cm^3) was derived (Ward et al., 2019). The scans were carried out by one of three technicians, certified by the International Society of Clinical Densitometry. Daily quality control scans were performed using the Hologic spine phantom. The precision error for BMC measurements was low in the laboratory, with a coefficient of variation <1% for quality control scans using the phantom (Janz et al., 2004; Janz et al., 2014).

Physical Activity

PA was measured using hip worn ActiGraph GT3X+ (ActiGraph, Pensacola, FL) accelerometers. Participants were requested to wear the monitors for five consecutive days, including both weekend days to account for differences in weekday and weekend activity patterns (Scheers et al., 2012). For waves 6 and 7, the protocol was waking day only, and for waves 8 and 9 24-hour wear was optional. Data were captured with 30 Hz sampling frequency, apart from approximately one third of files in wave 7 where data were captured with 100 Hz sampling frequency. There is a high correlation between PA outcomes from data collected at 30 Hz and 100 Hz (correlation coefficient for vector magnitude acceleration = 0.999, bias = -0.06), suggesting the data were comparable despite differences in sampling rate (Clevenger et al., 2019).

Accelerometer data were processed as described previously (Rowlands et al., 2020). Data were initialised and downloaded from the ActiGraphs using the most recent release of ActiLife available at the time of data collection (versions 6.0.0-6.13.3; ActiGraph, Pensacola, FL). Data were converted from raw format GT3X files to raw csv files for signal processing and were processed and analysed with R-package GGIR version 2.4 - 0 (http:// cran.r-project.org) (Migueles et al., 2019b). In GGIR, signal processing includes autocalibration using local gravity as a reference (van Hees et al., 2014), detection of sutained abnormally high values, detection of nonwear, and calculation of the average magnitude of dynamic acceleration corrected for gravity (Euclidean Norm minus 1*g*, ENMO) (Rowlands et al., 2020). Data were averaged over 1-s, 5-s, 15-s, 30-s, and 60-s epochs, and expressed in milligravitational units (m*g*). Non-wear was imputed by the average at similar time-points on different days of the week, and for the waking day only data non-wear during the night was imputed as zeros, as 24-hour data are required for the calculation of the intensity-gradient (Rowlands et al., 2020). Following exclusion criteria outlined previously, participants were excluded if their accelerometer file showed post-calibration error greater than 0.01 *g* (Rowlands et al., 2020). For data to be considered valid, participants had to have at least 3 days with > 16 hour per day (after imputing non-wear during the night) and wear data had to be present for each 15-min period of the 24 - h cycle (after imputation for non-wear during the night) (Rowlands et al., 2020). Previous analyses on this dataset have shown that the included participations did not differ from those excluded for the majority of wave 9 outcomes (Rowlands et al., 2020). For more details see Rowlands *et al.* (Rowlands et al., 2020).

Average-acceleration was calculated as the mean acceleration across the 24-hour day and is a proxy for the daily volume of PA and is therefore consistent across epoch lengths (Rowlands et al., 2018). Intensity-gradient reflects the distribution of intensity across the 24 hour day, characterising the negative curvilinear relationship between PA intensity and time accumulated at that intensity (Rowlands et al., 2020). The process for calculating the intensity-gradient has been described in detail elsewhere, and this approach was followed in the present study, with the intensity-gradient generated in GGIR (Migueles et al., 2019b; Rowlands et al., 2018). Briefly, the time accumulated in each intensity bin was regressed on intensity, with both variables log-transformed to linearise the curvilinear relationship. An R^2, a constant and a slope were calculated for each participant. The slope is always negative, with a more negative coefficient reflecting less time in higher intensities, and a less negative coefficient reflecting more time in higher intensities (Rowlands et al., 2020). Intensity-gradient was calculated for the accelerometer data averaged over each of the different epoch lengths to provide an intensity-gradient from 1-s (intensity-gradient$^{1\text{-S}}$), 5-s (intensity-gradient$^{5\text{-S}}$), 15-s (intensity-gradient$^{15\text{-S}}$), 30-s (intensity-gradient$^{30\text{-S}}$), and 60-s (intensity-gradient$^{60\text{-S}}$) data. Translational metrics were calculated in GGIR as the intensity above which a participant's most active 2, 5, 10, 15, 30, 60, 120, 240 and 480 minutes (MX minutes, whereby X = time in minutes) were accumulated (Migueles et al., 2019b; Rowlands et al., 2019c). The MX metrics (M2, M5, M10, M15, M30, M60, M120, M240 and M480) were generated from 1-s, 5-s, 15-s, 30-s, and 60-s epoch PA data.

All PA outcome variables were averaged over waves 6 to 9, to yield a mean intensity-gradient and average-acceleration for each participant, providing an estimate of PA patterns in late adolescence and early adulthood (Rowlands et al., 2020). Participants were included if at least one measurement was available from the four waves, under the assumption that data were missing at random (Rowlands et al., 2020). The mean age of the included PA outcomes was calculated to include as a covariate in analyses.

Statistical Analysis

Analyses were performed with Stata (v17.0) (StataCorp LLC, College Station, TX) and radar plots created in RStudio, using an openly available code that can be accessed on GitHub (Maylor et al., 2021; R Core Team, 2021).

Descriptive statistics (mean and standard deviation) were calculated for the total study sample, and for females and males separately, with independent samples t-tests used to test for sex differences. Further analyses were split by sex, due to the sex-specific patterns of bone accrual during adolescence (Baxter-Jones and Jackowski, 2021). Pearson's correlation coefficients were used to investigate the association between average-acceleration with intensity-gradient for each epoch length, to assess whether the correlation between the metrics varied by epoch.

Multiple linear regression analyses were used to assess the associations between average-acceleration and intensity-gradient for each epoch length with TBLH BMC, spine aBMD, total hip aBMD, hip femoral neck cross-sectional area, and hip femoral neck section modulus, all taken from wave 9. Analyses were adjusted for age at scan in wave 9, stature, body mass, years from peak height velocity (all from wave 9), the proportion of the 24-hour cycle that the accelerometer was worn, and the mean age of the included PA waves. Model 1 included either average-acceleration or intensity-gradient, adjusted for covariates, and Model 2 included both average-acceleration and intensity-gradient. The analysis was repeated with intensity-gradient$^{1\text{-S}}$, intensity-gradient$^{5\text{-S}}$, intensity-gradient$^{15\text{-S}}$, intensity-gradient$^{30\text{-S}}$, and intensity-gradient$^{60\text{-S}}$ as the intensity-gradient variables. Activity metrics were standardised prior to entry into the regression analysis, so the regression coefficients show the change in the dependent variable per SD (standard deviation) change in metric. The variance inflation factor remained less than 2 in all models, and less than 1.5 in most cases, indicating multicollinearity was not a problem. Regression coefficients (ß) and their 95% confidence intervals (CI) are presented. The alpha level for significance was set at 0.05.

For the presentation of descriptive MX metrics, mean MX values were calculated from each epoch length. Both raw MX values and MX values standardised based on the 1-s epoch length data were used. The mean and standard error of the MX metrics from each epoch length were visualised on radar plots (Maylor et al., 2021; Rowlands et al., 2019a).

Results

Descriptive characteristics

Descriptive statistics are presented in Table 1 for the total sample and for females and males separately. Anthropometric, maturation and bone measures are from wave 9 at age 23 years, and PA data are an average of waves 6 to 9. As the epoch length increased from 1-s to 60-s, the intensity-gradient increased from -2.92 to -2.28 for females and from -2.90 to -2.24 for males. The R^2 for the linear fit of the intensity-gradient remained similar across epoch lengths (~ 0.9). The correlations between the average-acceleration and the intensity-gradient increased as epoch length increased from 0.48 to 0.70 in females and from 0.29 to 0.45 in males (Table 2).

Females

Average-acceleration was not associated with TBLH BMC (g) when entered separately into the regression (see Table, Supplementary Content 1), or when adjusted for intensity-gradient across all epoch lengths (Table 3). Intensity-gradient from all epoch lengths were positively associated with TBLH BMC (see Table, Supplementary Content 1), but this association only persisted for intensity-gradient$^{1\text{-S}}$ and intensity-gradient$^{5\text{-S}}$ after adjustment for average-acceleration (Table 3).

There were no associations between average-acceleration or intensity-gradient of any epoch length with spine aBMD (g/cm^2), when the activity variables were entered separately (see Table, Supplementary Content 1), or together (Table 3). The results for spine BMC (g) were similar to those for aBMD in the fully-adjusted models in terms of significance and direction (see Table, Supplementary Digital Content 1).

Average-acceleration was not associated with total hip aBMD (g/cm^2) when entered separately into the regression, (see Table, Supplementary Content 1), and after additional adjustment for intensity-gradient (Table 3). Intensity-gradient calculated from all epochs was positively associated with total hip aBMD (see Table, Supplementary Content 1), but only the association between intensity-gradient$^{1\text{-S}}$ with total hip aBMD remained significant when adjusting for average-acceleration (Table 3). The results for total hip BMC (g) were similar to those for aBMD in the fully-adjusted models in terms of significance and direction (see Table, Supplementary Content 1).

Average-acceleration was not associated with femoral neck cross-sectional area (cm^2) when entered separately into the regression (see Table, Supplementary Content 1) or when adjusted for intensity-gradient (Table 3). Intensity-gradient$^{1\text{-S}}$, intensity-gradient$^{5\text{-S}}$ and intensity-gradient$^{15\text{-S}}$ were positively associated with femoral neck cross-sectional area (see Table, Supplementary Content 1). The association remained significant for intensity-gradient$^{1\text{-S}}$ only after adjustment for average-acceleration (Table 3). There were no associations between average-acceleration or intensity-gradient with femoral neck section modulus (cm^3) (Table 3).

Table 1. Descriptive characteristics of participants

	Total sample[a]		Females[a]		Males[a]	
	Mean	SD	Mean	SD	Mean	SD
Age at DXA scan at wave 9 (years)	23.4	0.5	23.4	0.5	23.4	0.6
Years from peak height velocity at wave 9	10.7	1.3	11.5*	0.8	9.7*	1.0
Body weight at wave 9 (kg)	81.5	22.6	74.0*	20.0	91.3*	22.2
Stature at wave 9 (cm)	171.9	9.8	166.0*	7.0	179.5*	7.5
Bone measures at wave 9						
TBLH BMC (g)	2100	481	1826*	311	2454*	428
Spine aBMD (g/cm2)	1.085	0.120	1.069*	0.127	1.105*	0.108
Total hip aBMD (g/cm2)	1.080	0.151	1.031*	0.128	1.143*	0.157
Femoral neck cross-sectional area (cm2)	3.63	0.77	3.26*	0.58	4.11*	0.72
Femoral neck section modulus (cm3)	1.80	0.53	1.49*	0.35	2.20*	0.46
Physical Activity from mean of available waves						
Mean age of physical activity measurements (years)	21.3	1.5	21.2	1.5	21.3	1.5
Proportion of 24-hour wear	0.87	0.08	0.87	0.08	0.86	0.07
Average-acceleration	15.30	3.95	14.96	3.92	15.74	3.96
1-s epoch Intensity-gradient[1-S]	-2.91	0.20	-2.92	0.21	-2.90	0.19
R^2 for linear fit	0.90	0.04	0.89*	0.04	0.91*	0.03
5-s epoch Intensity-gradient[5-S]	-2.62	0.21	-2.62	0.22	-2.62	0.19
R^2 for linear fit	0.89	0.04	0.89	0.05	0.90	0.04
15-s epoch Intensity-gradient[15-S]	-2.41	0.22	-2.42	0.23	-2.40	0.20
R^2 for linear fit	0.90	0.04	0.90	0.05	0.90	0.04
30-s epoch Intensity-gradient[30-S]	-2.33	0.24	-2.35	0.25	-2.32	0.22
R^2 for linear fit	0.91	0.04	0.91	0.05	0.91	0.03
60-s epoch Intensity-gradient[60-S]	-2.27	0.25	-2.28	0.27	-2.24	0.23
R^2 for linear fit	0.91	0.04	0.92	0.04	0.91	0.04

[a] For anthropometric variables, maturation, and bone measures, n = 220 (females = 124, males =96). For physical activity data, n = 217 (females = 121, males = 96). * indicates sex difference with $p < 0.05$ from independent samples t-tests. Intensity-gradient was calculated from accelerometer data averaged over a 1-s epoch (intensity-gradient[1-S]), a 5-s epoch (intensity-gradient[5-S]), a 15-s epoch (intensity-gradient[15-S]), a 30-s epoch (intensity-gradient[30-S]), and a 60-s epoch (intensity-gradient[60-S]). *SD,* standard deviation; *DXA,* dual-energy X-ray absorptiometry; TBLH, total body less head; *BMC,* bone mineral content; *aBMD,* areal bone mineral density.

Table 2. Correlations between average-acceleration and intensity-gradient.

	Total sample (n = 217) Average-acceleration	Females (n = 121) Average-acceleration	Males (n = 96) Average-acceleration
Intensity-gradient[1-S]	0.40	0.48	0.29
Intensity-gradient[5-S]	0.43	0.51	0.33
Intensity-gradient[15-S]	0.47	0.54	0.38
Intensity-gradient[30-S]	0.52	0.62	0.38
Intensity-gradient[60-S]	0.60	0.70	0.45

Values are Pearson's correlation coefficient. Intensity-gradient was calculated from accelerometer data averaged over a 1-s epoch (intensity-gradient[1-S]), a 5-s epoch (intensity-gradient[5-S]), a 15-s epoch (intensity-gradient[15-S]), a 30-s epoch (intensity-gradient[30-S]), and a 60-s epoch (intensity-gradient[60-S]).

Males

Average-acceleration was positively associated with TBLH BMC (g) when entered separately into the regression (see Table, Supplementary Content 2), and when adjusted for intensity-gradient across all epoch lengths (Table 4). Intensity-gradient from all epoch lengths were positively associated with TBLH BMC (see Table, Supplementary Content 2), but this association did not persist after adjustment for average-acceleration (Table 4).

Average-acceleration was positively associated with spine aBMD (g/cm^2) when entered separately into the regression (see Table, Supplementary Content 2), and when adjusted for intensity-gradient across all epoch lengths (Table 4). Intensity-gradient from all epoch lengths were positively associated with spine aBMD (see Table, Supplementary Content 2). Only the association with intensity-gradient[1-S] and intensity-gradient[5-S] remained significant after adjustment for average-acceleration (Table 4). The results for spine BMC (g) were similar to those for aBMD in the fully-adjusted models in terms of significance and direction, though intensity-gradient across all epoch lengths remained significantly associated with spine BMC (see Table, Supplementary Content 2).

Average-acceleration was positively associated with total hip aBMD (g/cm^2) when entered separately into the regression (see Table, Supplementary Content 2), and the association remained significant after adjustment for intensity-gradient (Table 4), with the exception of intensity-gradient[1-S]. Intensity-gradient[1-S] and intensity-gradient[5-S] were positively associated with total hip aBMD (see Table, Supplementary Content 2). Only the association between intensity-gradient[1-S] with total hip aBMD remained significant when adjusting for average-acceleration (Table 4). The results for total hip BMC (g) were also similar to those for aBMD in the fully-adjusted models in terms of significance and direction, though intensity-gradient[1-S] was not associated with total hip BMC, and average-acceleration was associated with total hip BMC in all models (see Table, Supplementary Content 2).

Table 3. **The mutually adjusted associations of physical activity volume (average-acceleration) and intensity distribution (intensity-gradient) with bone outcomes in females (n = 121).**

	1-s epoch ß (95% CI)	5-s epoch ß (95% CI)	15-s epoch ß (95% CI)	30-s epoch ß (95% CI)	60-s epoch ß (95% CI)
TBLH BMC (g)					
[a]Average-acceleration	2.54 (-36.46 to 41.53)	8.39 (-29.33 to 46.11)	5.71 (-35.88 to 47.29)	4.44 (-41.06 to 49.95)	3.54 (-48.14 to 55.23)
[b]Intensity-gradient	46.47** (18.4 to 74.55)	32.43* (0.2 to 64.66)	33.6 (-2.33 to 69.53)	31.5 (-8.54 to 71.54)	28.45 (-16.01 to 72.91)
Spine aBMD (g/cm²)					
[a]Average-acceleration	0.00 (-0.02 to 0.03)	0.00 (-0.02 to 0.03)	0.00 (-0.02 to 0.03)	0.00 (-0.02 to 0.03)	0.01 (-0.03 to 0.04)
[b]Intensity-gradient	0.01 (-0.01 to 0.03)	0.01 (-0.01 to 0.03)	0.01 (-0.01 to 0.04)	0.01 (-0.02 to 0.04)	0.01 (-0.03 to 0.04)
Total hip aBMD (g/cm²)					
[a]Average-acceleration	0.01 (-0.01 to 0.03)	0.01 (-0.01 to 0.03)	0.01 (-0.02 to 0.03)	0.01 (-0.02 to 0.04)	0.01 (-0.03 to 0.04)
[b]Intensity-gradient	0.02* (0.00 to 0.04)	0.02 (0.00 to 0.04)	0.02 (0.00 to 0.04)	0.02 (-0.01 to 0.05)	0.02 (-0.01 to 0.05)
Femoral neck cross-sectional area (cm²)					
[a]Average-acceleration	0.02 (-0.06 to 0.09)	0.02 (-0.06 to 0.1)	0.01 (-0.07 to 0.09)	0.02 (-0.07 to 0.11)	0.02 (-0.08 to 0.13)
[b]Intensity-gradient	0.06* (0.01 to 0.12)	0.06 (0.00 to 0.12)	0.06 (-0.01 to 0.13)	0.05 (-0.03 to 0.13)	0.03 (-0.06 to 0.13)
Femoral neck section modulus (cm³)					
[a]Average-acceleration	0.03 (-0.02 to 0.07)	0.03 (-0.02 to 0.08)	0.02 (-0.03 to 0.08)	0.03 (-0.03 to 0.09)	0.02 (-0.04 to 0.09)
[b]Intensity-gradient	0.02 (-0.03 to 0.06)	0.00 (-0.04 to 0.05)	0.02 (-0.03 to 0.06)	0.00 (-0.05 to 0.06)	0.02 (-0.04 to 0.07)

Values are regression coefficients (ß) and their 95% confidence intervals (CI) from linear regression models. Regression coefficients are adjusted for age at wave 9, stature at wave 9, mass at wave 9, years from peak height velocity at wave 9, the proportion of the 24-hour cycle the accelerometer was worn, the mean age for physical activity measures, and the alternate activity metric (intensity-gradient or average-acceleration). Activity metrics were standardised before entry into analysis, so values represent the change in the outcome associated with a 1 standard deviation change in the activity metric.
[a]Average-acceleration (average of waves 6 to 9) is the mean acceleration across wear-time.
[b]Intensity-gradient (average of waves 6 to 9) calculated, with imputing zeros for non-wear during the night, as the regression line from log-log plot of intensity (x) and time accumulated (y). * $p < 0.05$. ** $p < 0.01$. *TBLH,* total body less head; *BMC,* bone mineral content; *aBMD,* areal bone mineral density.

Table 4. **The mutually adjusted associations of physical activity volume (average-acceleration) and intensity distribution (intensity-gradient) with bone outcomes in males (n = 96).**

	1-s epoch ß (95% CI)	5-s epoch ß (95% CI)	15-s epoch ß (95% CI)	30-s epoch ß (95% CI)	60-s epoch ß (95% CI)
TBLH BMC (g)					
[a]Average-acceleration	78.11* (18.54 to 137.69)	78.31** (19.68 to 136.95)	80.82** (24.36 to 137.27)	79.96** (23.96 to 135.95)	71.77* (14.03 to 129.51)
[b]Intensity-gradient	56.23 (-10.85 to 123.3)	49.8 (-19 to 118.59)	35.57 (-32.41 to 103.54)	37.39 (-29.82 to 104.6)	50.17 (-24.25 to 124.6)
Spine aBMD (g/cm²)					
[a]Average-acceleration	0.02* (0.01 to 0.04)	0.03** (0.01 to 0.04)	0.03** (0.01 to 0.05)	0.03** (0.01 to 0.04)	0.02** (0.01 to 0.04)
[b]Intensity-gradient	0.04** (0.01 to 0.06)	0.03* (0.00 to 0.05)	0.02 (0.00 to 0.04)	0.02 (0.00 to 0.04)	0.02 (0.00 to 0.04)
Total hip aBMD (g/cm²)					
[a]Average-acceleration	0.03 (0.00 to 0.06)	0.03* (0.00 to 0.06)	0.03* (0.01 to 0.06)	0.04* (0.01 to 0.06)	0.03* (0.00 to 0.06)
[b]Intensity-gradient	0.04* (0.01 to 0.07)	0.03 (-0.01 to 0.06)	0.02 (-0.02 to 0.05)	0.01 (-0.02 to 0.05)	0.01 (-0.02 to 0.05)
Femoral neck cross-sectional area (cm²)					
[a]Average-acceleration	0.12 (-0.01 to 0.25)	0.12 (0.00 to 0.25)	0.12* (0.00 to 0.25)	0.12 (-0.01 to 0.24)	0.1 (-0.03 to 0.22)
[b]Intensity-gradient	0.13 (0.00 to 0.27)	0.11 (-0.03 to 0.25)	0.09 (-0.04 to 0.23)	0.11 (-0.02 to 0.24)	0.14* (0.01 to 0.28)
Femoral neck section modulus (cm³)					
[a]Average-acceleration	0.06 (-0.02 to 0.14)	0.07 (-0.01 to 0.14)	0.07 (-0.01 to 0.15)	0.07 (-0.01 to 0.14)	0.05 (-0.03 to 0.13)
[b]Intensity-gradient	0.09* (0.01 to 0.17)	0.07 (-0.01 to 0.16)	0.06 (-0.02 to 0.13)	0.06 (-0.02 to 0.13)	0.09* (0.01 to 0.17)

Values are regression coefficients (ß), their 95% confidence intervals (CI), and *p* values from linear regression models. Regression coefficients are adjusted for age at wave 9, stature at wave 9, mass at wave 9, years from peak height velocity at wave 9, the proportion of the 24-hour cycle the accelerometer was worn, the mean age for physical activity measures, and the alternate activity metric (intensity-gradient or average-acceleration). Activity metrics were standardised before entry into analysis, so values represent the change in the outcome associated with a 1 standard deviation change in the activity metric.
[a]Average-acceleration (average of waves 6 to 9) is the mean acceleration across wear-time.
[b]Intensity-gradient (average of waves 6 to 9) calculated, with imputing zeros for non-wear during the night, as the regression line from log-log plot of intensity (x) and time accumulated (y). * $p < 0.05$. ** $p < 0.01$. *TBLH,* total body less head; *BMC,* bone mineral content; *aBMD,* areal bone mineral density.

Average-acceleration was positively associated with femoral neck cross-sectional area (cm^2) when entered separately into the regression (see Table, Supplementary Digital Content 2), but the association did not remain significant when adjusted for intensity-gradient, with exception of for intensity-gradient$^{15\text{-S}}$ (Table 4). Intensity-gradient from all epoch lengths were positively associated with femoral neck cross-sectional area (see Table, Supplementary Digital Content 2), but the association only remained significant for intensity-gradient$^{60\text{-S}}$ after adjustment for average-acceleration (Table 4).

Average-acceleration was positively associated with femoral neck section modulus (cm^3) when entered separately into the regression (see Table, Supplementary Digital Content 2), but the association did not remain significant when adjusted for intensity-gradient (Table 4). Intensity-gradient from all epoch lengths were positively associated with femoral neck section modulus (see Table, Supplementary Digital Content 2), but the association only remained significant for intensity-gradient$^{1\text{-S}}$ and intensity-gradient$^{60\text{-S}}$ after adjustment for average-acceleration (Table 4).

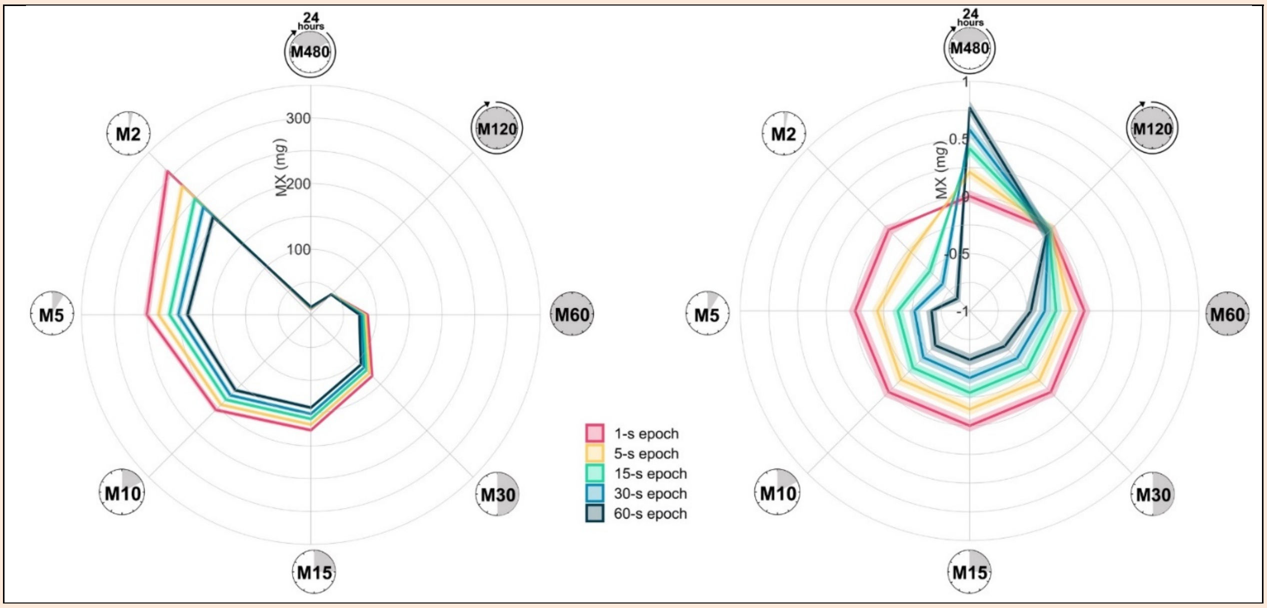

Figure 1. Illustration of the physical activity profile for raw (left) and standardised (right) MX metrics in females and males across 5 different epoch lengths. Profiles are presented for physical activity data averaged over 1-s, 5-s, 15-s, 30-s, and 60-s epoch lengths. Values are the mean; error ribbons are the standard error of the mean. Standardised metrics were standardised based on the 1-s epoch data. The MX metrics show the acceleration above which an individual's most active X minutes are accumulated. Each plot shows (clockwise) *M480,* the intensity above which an individual's most active 480 minutes are accumulated; *M120,* the intensity above which an individual's most active 120 minutes are accumulated; *M60,* the intensity above which an individual's most active 60 minutes are accumulated; *M30,* the intensity above which an individual's most active 30 minutes are accumulated; *M15,* the intensity above which an individual's most active 15 minutes are accumulated; *M10,* the intensity above which an individual's most active 10 minutes are accumulated; *M5,* the intensity above which an individual's most active 5 minutes are accumulated; *M2,* the intensity above which an individual's most active 2 minutes are accumulated.

Translational Metrics

The raw and standardised MX metrics for the total sample for the PA data averaged from 1-s, 5-s, 15-s, 30-s, and 60-s epoch lengths are presented in Figure 1. For M2, M5, M10, M15, M30 and M60, the acceleration level decreased as the epoch length increased. M120 was similar across all epoch lengths. For M480, the acceleration level increased as the epoch length increased.

Discussion

This study examined the associations between average-acceleration and intensity-gradient calculated from accelerometer data averaged over 1-s, 5-s, 15-s, 30-s, and 60-s epochs with DXA-assessed bone measures in young adults in the IBDS cohort. Intensity-gradient became less negative as epoch length increased. The correlation between average-acceleration and intensity-gradient increased as epoch length increased, indicating that the metrics had increasing shared variance, suggesting they reflected similar properties of PA when averaged over longer epochs. In females and males, greater PA intensity was associated with more favourable bone outcomes, though the associations were dampened when data were averaged over epochs longer than 1-s to 5-s, and when adjusted for volume. PA volume was not associated with bone outcomes in females. In males, greater PA volume was associated with more favourable bone outcomes, though the associations were not consistently independent of intensity, particularly when shorter epochs were used. Overall, our findings indicate that associations between volume and intensity with bone health are influenced by epoch length, though generally intensity was important for bone outcomes in females, and both volume and intensity were important for bone outcomes in males.

The associations of intensity-gradient and average-acceleration with bone outcomes (from 5-s epoch) have previously been reported and discussed in this sample (Rowlands et al., 2020). The current study extends the previous work by considering these associations across various epoch lengths. As the novelty of the present study is the varying epoch lengths, and the associations of volume and intensity with bone in this sample have been discussed previously, this discussion will primarily focus on the influence of epoch length (Rowlands et al., 2020).

Although this is, to the best of our knowledge, the first study to assess the influence of epoch length on intensity-gradient, previous research has assessed the influence of epoch length in time spent in summary measures of PA intensity (Sanders et al., 2014). We found that the intensity-gradient metric became less negative as epoch length increased. This was reflected in the MX metrics. The PA data averaged over shorter epoch lengths had greater values for M2 to M60 and lower values for M480 compared to the PA data averaged over longer epochs, with little to no differences in M120 values between epoch lengths. This reflects the dilution of activity at both extremes of the intensity continuum when activity is averaged over longer epochs, as the smoothing effect of the longer epoch shifts the data towards the middle of the intensity continuum.

Similar to our findings, in adolescents age 12 to 16 years, epoch length (5-s, 15-s, 30-s and 60-s) had a significant effect on time spent in vigorous PA, light PA (LPA) and rest, and no effect on moderate PA (MPA) (Edwardson and Gorely, 2010). Time spent in vigorous PA and rest decreased and time spent in light PA increased with increasing epoch lengths, again reflecting the dilution of PA at both extremes of the intensity continuum (Edwardson and Gorely, 2010). Likewise in adults, light PA increased and vigorous PA decreased as epoch length increased from 4-s, to 20-s, to 60-s (Ayabe et al., 2013), and time spent in moderate-to-vigorous PA has been found to be lower with longer epoch lengths, from 5-s to 60-s (Orme et al., 2014). Although the bout length of PA and sedentary time would determine the extent to which the intensity-gradient is impacted by longer epoch lengths, the findings from previous studies indicate that in children and adults longer epochs consistently under-estimate activity at very high and very low intensities, and over-estimate light activities, with some intensities towards the middle of the intensity continuum unlikely to be affected (Ayabe et al., 2013; Edwardson and Gorely, 2010; Orme et al., 2014). These over- and under-estimations of time spent in different intensities explain the increase in intensity-gradient over longer epoch lengths that we observed. Our findings indicate that, like the influence of epoch length on summary measures of PA intensity, epoch length influences the intensity-gradient metric in adolescents and young adults, and this should be considered by researchers when using the intensity-gradient metric.

Given that epoch length influences intensity-gradient, it is not surprising that our findings also indicate that epoch length influences the associations between intensity-gradient and average-acceleration with bone outcomes, particularly as bone is responsive to high intensity activity (Hart et al., 2017). In females, fewer independent associations between intensity-gradient with bone outcomes were significant with epoch lengths greater than 1-s, and no independent associations were significant with epochs greater than 5-s. In males, some independent associations between intensity-gradient with bone outcomes remained significant with 1-s, 5-s, 15-s, and 60-s epoch lengths, though similarly to the females, the most significant associations were observed when a 1-s epoch was used. This indicates that the associations between intensity-gradient and bone outcomes in females and males are influenced by epoch length, and significant independent associations may be missed when PA is averaged over epoch lengths greater than 1-s. This may also reflect the degree to which intensity-gradient and average-acceleration become less independent as epoch length increases. At longer epoch lengths intensity-gradient retained a significant relationship with bone outcomes more often when entered without adjustment for average-acceleration, but when both intensity-gradient and average-acceleration were mutually adjusted, intensity-gradient became non-significant when epoch length increased beyond 5 to 15-s. Further, when considering the associations between volume with bone outcomes in males, more independent associations between volume and bone were observed when the adjustment for intensity was from epochs longer than 1-s. This indicates that in addition to potentially underestimating the relationships between intensity and bone when using longer epochs, the independent relationships between volume and bone may be overestimated with longer epochs.

To the best of our knowledge, this is the first study to examine whether relationships between PA intensity-gradient and bone are influenced by epoch. However, previous studies have compared accelerometer counts and raw acceleration to ground reaction forces, and ground reaction forces reflect how osteogenic an activity is (Janz et al., 2003). One study found that with a 15-s epoch, accelerometer counts were positively correlated with ground reaction forces during walking and running, but no correlations were observed during drop jumps in children (Janz et al., 2003). This indicates that when accelerometer data are averaged over 15-s, the output is not reflective of the high-intensity impact loading which is likely important for bone (Janz et al., 2003). However, accelerometer data collected with a 1-s epoch and raw acceleration data with a sampling frequency of 80 Hz and 100 Hz were positively correlated with ground reaction forces across walking, running and jumping in adults (Rowlands and Stiles, 2012). Similarly, in children and adolescents, accelerometer data captured with 100 Hz sampling frequency was positively associated with ground reaction forces across walking, running, jumping, skipping and dancing (Meyer et al., 2015). Taken together, these findings suggest that accelerometer data are more predictive of osteogenic activity when captured in shorter epochs. This agrees with our findings that intensity-gradient was more often associated with bone outcomes when calculated from accelerometer data averaged over shorter epochs. Further, although considering metabolic rather than bone health, Aadland and colleagues found that the level of intensity most strongly associated with metabolic health decreased as epoch length increased from 1-s, to 10-s, to 60-s in children aged 10 years (Aadland et al., 2020). This demonstrates that epoch length influences the associations between PA intensity and metabolic health, similar to our findings relating PA intensity to bone outcomes. However, bone only adapts in response to strain magnitudes above a certain threshold (Hart et al., 2017). Although this threshold can be adapted up or down based on other strain characteristics, as high intensity weight-bearing PA is particularly important for bone health, epoch length may have a greater influence on the associations between PA and bone than between PA and metabolic health (Hart et al., 2017). Our findings emphasise the importance of considering the relationships between PA intensity and bone in context of the epoch used.

Overall, the results of the present study suggest that exploring the independent associations of intensity and volume with bone health becomes more challenging with longer epoch lengths, generally greater than 1 to 5-s, as intensity-gradient and average-acceleration reflect more similar information over longer epochs. It is difficult to suggest an upper epoch length threshold with which to use these metrics, as the extent to which intensity-gradient is impacted by longer epochs will depend on PA and sedentary behaviour bout lengths, which may be specific to the studied population. Within our sample, whilst a 1-s epoch appears best-suited for capturing associations between intensity-gradient with bone outcomes, a 5-s epoch also appears adequate. However, researchers applying these metrics should check the correlation between average-acceleration and intensity-gradient, and be aware of the potential impact of epoch length on observed independent associations between intensity-gradient and average-acceleration with health outcomes.

Although the associations between intensity-gradient and average-acceleration with bone were dependent on epoch length, the positive relationships between PA intensity and volume with bone that we observed when using a 1 to 5-s epoch are consistent with previous analyses of the IBDS cohort (Janz et al., 2014). Children who accumulated more moderate-to-vigorous PA (MVPA) from age 5 to age 17 years had more favourable bone mass and geometry at age 17 years (Janz et al., 2014). Similarly, in the Avon Longitudinal Study of Parents and Children cohort, females who accumulated greater amounts of MVPA in adolescence had greater hip aBMD at age 25 years compared to those with lower levels of MVPA in adolescence but higher levels in adulthood, and to those with consistently low levels of MVPA (Elhakeem et al., 2020). Males who accumulated greater amounts of MVPA from age 12 to 25 years had greater hip aBMD compared to those with consistently lower amounts of MVPA (Elhakeem et al., 2020). However, as MVPA and total PA volume are closely related (correlation coefficient = 0.91) (Kwon et al., 2019), previous studies have not been able to investigate the relative importance of PA intensity and volume. Our findings add to previous studies by suggesting that increasing PA intensity, whilst maintaining a similar total PA volume, is beneficial for hip aBMD and geometry in both sexes, for TBLH BMC in females, and for spine aBMD in males. Further, increasing PA volume, without increasing intensity, may be beneficial for TBLH BMC, spine aBMD and hip aBMD in males.

Strengths of this study included the longitudinal study design with bone outcomes assessed by DXA and repeated measures of PA with raw acceleration accelerometers. The high-resolution accelerometer data allowed the aggregation of PA data over varying epoch lengths, thus allowing the associations between intensity-gradient from varying epoch lengths with bone outcomes to be assessed. Further, the placement of the accelerometer at the hip means that the measure of PA in this study reflected impact-loading activity, which influences adaptive bone modelling, at the clinically relevant skeletal site of the hip (Gunter et al., 2012).

There are some limitations related to this study which should be considered. As the accelerometer wear protocol changed from waking day for waves 6 and 7 to optional 24-hour wear for waves 8 and 9, night-time non-wear was imputed for the non-24-hour data, based on the assumption this activity would be minimal intensity. Further, the use of metrics which cover the whole spectrum of PA across the day led to a relatively high proportion of invalid accelerometer data, though there were limited differences between included and excluded participants for wave 9 outcomes as reported previously (Rowlands et al., 2020). Although the use of average-acceleration and intensity-gradient facilitate the examination of PA intensity and volume as it relates to bone, it should be highlighted that there are other aspects of PA behaviour which are likely associated with bone health, such as the type and pattern of PA, which cannot be explored with these metrics. Finally, as with all observational studies, residual confounding remains a potential limitation.

Conclusion

The associations between intensity-gradient and average-acceleration from age 17 to 23 years with bone outcomes at age 23 years were influenced by epoch length, though generally intensity was important for bone outcomes in females, and both volume and intensity were important for bone outcomes in males. Our findings indicate that a 5-s epoch is adequate to detect associations with bone compared to longer epochs, though a 1-s epoch may increase sensitivity, and increase the amount of complementary information provided by these metrics. Future studies applying these metrics should consider that metrics are influenced by epoch length, and this may ultimately influence the associations with health outcomes. Furthermore, the MX metrics we examined are likely to be underestimated at high intensities by longer epochs and overestimated at light intensities by longer epochs. Researchers should consider this when applying MX metrics to characterise the PA profile. Considering both the volume and intensity of PA with methods that account for PA accumulated across the spectrum of intensity is important for better understanding the associations between PA with health outcomes, but researchers should consider the appropriateness of the intensity-gradient metric when PA data is collected over longer epochs.

Acknowledgements

The authors are grateful to the parents, children, and staff of the Iowa Bone Development Study and the Iowa Fluoride Study. The Iowa Bone Development Study was supported by the National Institute of Dental and Craniofacial Research grants R01-DE12101, R01-DE09551, P30-DE10126, R56-DE012101, and the General Clinical Research Centers Program from the National Center for Research Resources, M01-RR00059 and UL1-RR024979. The experiments comply with the current laws of the country in which they were performed. The authors have no conflict of interest to declare. The datasets generated and analyzed during the current study are not publicly available, but are available from the corresponding author who was an organizer of the study.

References

Aadland, E., Andersen, L.B., Anderssen, S.A., Resaland, G.K. and Kvalheim, O.M. (2020) Accelerometer epoch setting is decisive for associations between physical activity and metabolic health in children. *Journal of Sports Sciences* **38,** 256-263. https://doi.org/10.1080/02640414.2019.1693320

Ayabe, M., Kumahara, H., Morimura, K. and Tanaka, H. (2013) Epoch length and the physical activity bout analysis: An accelerometry research issue. *BMC Research Notes* **6,** 20. https://doi.org/10.1186/1756-0500-6-20

Baquet, G., Stratton, G., Van Praagh, E. and Berthoin, S. (2007) Improving physical activity assessment in prepubertal children with high-frequency accelerometry monitoring: a methodological issue. *Preventive Medicine* **44,** 143-147. https://doi.org/10.1016/j.ypmed.2006.10.004

Baxter-Jones, A.D.G. and Jackowski, S.A. (2021) Sex differences in bone mineral content and bone geometry accrual: a review of the Paediatric Bone Mineral Accural Study (1991–2017). *Annals of Human Biology* **48,** 503-516. https://doi.org/10.1080/03014460.2021.2014568

Bonjour, J.P., Chevalley, T., Ferrari, S. and Rizzoli, R. (2009) The importance and relevance of peak bone mass in the prevalence of osteoporosis. *Salud Pública de México* **51 Suppl 1,** 5-17. https://doi.org/10.1590/S0036-36342009000700004

Brailey, G., Metcalf, B., Lear, R., Price, L., Cumming, S. and Stiles, V. (2022) A comparison of the associations between bone health and three different intensities of accelerometer-derived habitual physical activity in children and adolescents: a systematic review. *Osteoporosis International* **33**,1191-1222. https://doi.org/10.1007/s00198-021-06218-5

Clevenger, K.A., Pfeiffer, K.A., Mackintosh, K.A., McNarry, M.A., Brønd, J., Arvidsson, D. and Montoye, A.H.K. (2019) Effect of sampling rate on acceleration and counts of hip- and wrist-worn ActiGraph accelerometers in children. *Physiological Measurement* **40,** 095008. https://doi.org/10.1088/1361-6579/ab444b

Colley, R.C. and Tremblay, M.S. (2011) Moderate and vigorous physical activity intensity cut-points for the Actical accelerometer. *Journal of Sports Sciences* **29,** 783-789. https://doi.org/10.1080/02640414.2011.557744

Edwardson, C.L. and Gorely, T. (2010) Epoch length and its effect on physical activity intensity. *Medicine & Science in Sports & Exercise* **42,** 928-934. https://doi.org/10.1249/MSS.0b013e3181c301f5

Elhakeem, A., Heron, J., Tobias, J.H. and Lawlor, D.A. (2020) Physical Activity Throughout Adolescence and Peak Hip Strength in Young Adults. *JAMA Network Open* **3,** e2013463. https://doi.org/10.1001/jamanetworkopen.2020.13463

Fairclough, S.J., Taylor, S., Rowlands, A.V., Boddy, L.M. and Noonan, R.J. (2019) Average acceleration and intensity gradient of primary school children and associations with indicators of health and well-being. *Journal of Sports Sciences* **37,** 2159-2167. https://doi.org/10.1080/02640414.2019.1624313

Gabriel, K.P., McClain, J.J., Schmid, K.K., Storti, K.L., High, R.R., Underwood, D.A., Kuller, L.H. and Kriska, A.M. (2010) Issues in accelerometer methodology: the role of epoch length on estimates of physical activity and relationships with health outcomes in overweight, post-menopausal women. *International Journal of Behavioral Nutrition and Physical Activity* **7,** 53. https://doi.org/10.1186/1479-5868-7-53

Gunter, K.B., Almstedt, H.C. and Janz, K.F. (2012) Physical activity in childhood may be the key to optimizing lifespan skeletal health. *Exercise and Sport Sciences Reviews* **40,** 13-21. https://doi.org/10.1097/JES.0b013e318236e5ee

Haapala, E.A., Vaisto, J., Veijalainen, A., Lintu, N., Wiklund, P., Westgate, K., Ekelund, U., Lindi, V., Brage, S. and Lakka, T.A. (2017) Associations of objectively measured physical activity and sedentary time with arterial stiffness in pre-pubertal children. *Pediatric Exercise Science* **29,** 326-335. https://doi.org/10.1123/pes.2016-0168

Hart, N.H., Nimphius, S., Rantalainen, T., Ireland, A., Siafarikas, A. and Newton, R.U. (2017) Mechanical basis of bone strength: influence of bone material, bone structure and muscle action. *Journal of Musculoskeletel and Neuronal Interactions* **17,** 114-139.

Heil, D.P., Brage, S. and Rothney, M.P. (2012) Modeling physical activity outcomes from wearable monitors. *Medicine & Science in Sports & Exercise* **44**, 50-60. https://doi.org/10.1249/MSS.0b013e3182399dcc

Janz, K.F., Burns, T.L., Levy, S.M., Torner, J.C., Willing, M.C., Beck, T.J., Gilmore, J.M. and Marshall, T.A. (2004) Everyday activity predicts bone geometry in children: the iowa bone development study. *Medicine & Science in Sports & Exercise* **36,** 1124-1131. https://doi.org/10.1249/01.MSS.0000132275.65378.9D

Janz, K.F., Burns, T.L., Torner, J.C., Levy, S.M., Paulos, R., Willing, M.C. and Warren, J.J. (2001) Physical activity and bone measures in young children: the Iowa bone development study. *Pediatrics* **107,** 1387-1393. https://doi.org/10.1542/peds.107.6.1387

Janz, K.F., Letuchy, E.M., Burns, T.L., Eichenberger Gilmore, J.M., Torner, J.C. and Levy, S.M. (2014) Objectively measured physical activity trajectories predict adolescent bone strength: Iowa Bone Development Study. *British Journal of Sports Medicine* **48,** 1032-1036. https://doi.org/10.1136/bjsports-2014-093574

Janz, K.F., Letuchy, E.M., Eichenberger Gilmore, J.M., Burns, T.L., Torner, J.C., Willing, M.C. and Levy, S.M. (2010) Early physical activity provides sustained bone health benefits later in childhood. *Medicine & Science in Sports & Exercise* **42,** 1072-1078. https://doi.org/10.1249/MSS.0b013e3181c619b2

Janz, K.F., Rao, S., Baumann, H.J. and Schultz, J.L. (2003) Measuring children's vertical ground reaction forces with accelerometry during walking, running, and jumping: The Iowa Bone Development Study. *Pediatric Exercise Science* **15,** 34-43. https://doi.org/10.1123/pes.15.1.34

Kwon, S., Andersen, L.B., Grøntved, A., Kolle, E., Cardon, G., Davey, R., Kriemler, S., Northstone, K., Page, A.S., Puder, J.J., Reilly, J.J., Sardinha, L.B., van Sluijs, E.M.F. and Janz, K.F. (2019) A closer look at the relationship among accelerometer-based physical activity metrics: ICAD pooled data. *International Journal of Behavioral Nutrition and Physical Activity* **16,** 40. https://doi.org/10.1186/s12966-019-0828-z

Loprinzi, P.D., Lee, H., Cardinal, B.J., Crespo, C.J., Andersen, R.E. and Smit, E. (2012) The relationship of Actigraph accelerometer cut-points for estimating physical activity with selected health outcomes. *Research Quarterly for Exercise and Sport* **83,** 422-430. https://doi.org/10.5641/027013612802573085

Maylor, B.D., Rowlands, A.V., Dawkins, N.P. and Edwardson, C.L. (2021) *Radar Plot Generator (Version 2.0) [Source code], Vol. 2022.*

Metcalf, K.M., Letuchy, E.M., Levy, S.M. and Janz, K.F. (2020) An 8-Year longitudinal analysis of physical activity and bone strength from adolescence to emerging adulthood: The Iowa Bone Development Study. *Pediatric Exercise Science* **32,** 58-64. https://doi.org/10.1123/pes.2019-0090

Meyer, U., Ernst, D., Schott, S., Riera, C., Hattendorf, J., Romkes, J., Granacher, U., Göpfert, B. and Kriemler, S. (2015) Validation of two accelerometers to determine mechanical loading of physical activities in children. *Journal of Sports Sciences* **33,** 1702-1709. https://doi.org/10.1080/02640414.2015.1004638

Migueles, J.H., Cadenas-Sanchez, C., Tudor-Locke, C., Löf, M., Esteban-Cornejo, I., Molina-Garcia, P., Mora-Gonzalez, J., Rodriguez-Ayllon, M., Garcia-Marmol, E., Ekelund, U. and Ortega, F.B. (2019a) Comparability of published cut-points for the assessment of physical activity: Implications for data harmonization. *Scandinavian Journal of Medicine & Science in Sports* **29,** 566-574. https://doi.org/10.1111/sms.13356

Migueles, J.H., Rowlands, A.V., Huber, F., Sabia, S. and van Hees, V.T. (2019b) GGIR: A research community–driven ppen source R package for generating physical activity and sleep outcomes from multi-day raw accelerometer data. *Journal for the Measurement of Physical Behaviour* **2,** 188-196. https://doi.org/10.1123/jmpb.2018-0063

Mirwald, R.L., Baxter-Jones, A.D., Bailey, D.A. and Beunen, G.P. (2002) An assessment of maturity from anthropometric measurements. *Medicine & Science in Sports & Exercise* **34,** 689-694. https://doi.org/10.1097/00005768-200204000-00020

Ness, A.R., Leary, S.D., Mattocks, C., Blair, S.N., Reilly, J.J., Wells, J., Ingle, S., Tilling, K., Smith, G.D. and Riddoch, C. (2007) Objectively measured physical activity and fat mass in a large cohort of children. *Plos Medicine* **4,** e97. https://doi.org/10.1371/journal.pmed.0040097

Nilsson, A., Ekelund, U., Yngve, A. and Sjöström, M. (2001) Assessing physical activity among children with activity monitors using different time sampling intervals and placements *Medicine & Science in Sports & Exercise* **33**. https://doi.org/10.1097/00005768-200105001-01416

Orme, M., Wijndaele, K., Sharp, S.J., Westgate, K., Ekelund, U. and Brage, S. (2014) Combined influence of epoch length, cut-point and bout duration on accelerometry-derived physical activity. *International Journal of Behavioral Nutrition and Physical Activity* **11,** 34. https://doi.org/10.1186/1479-5868-11-34

Parsons, C.M., Dennison, E.M., Fuggle, N., Breasail, M.Ó., Deere, K., Hannam, K., Tobias, J.H., Cooper, C. and Ward, K.A. (2022) Assessment of Activity Profiles in Older Adults and Lower Limb Bone Parameters: Observations from the Hertfordshire Cohort Study. *Calcified Tissue International* **111,** 13-20. https://doi.org/10.1007/s00223-022-00953-5

R Core Team. (2021). R: A Language and Environment for Statistical Computing, R Foundation for Statistical Computing, Vienna, Austria.

Rowlands, A.V., Dawkins, N.P., Maylor, B., Edwardson, C.L., Fairclough, S.J., Davies, M.J., Harrington, D.M., Khunti, K. and Yates, T. (2019a) Enhancing the value of accelerometer-assessed physical activity: meaningful visual comparisons of data-driven translational accelerometer metrics. *Sports Medicine - Open* **5,** 47. https://doi.org/10.1186/s40798-019-0225-9

Rowlands, A.V., Edwardson, C.L., Davies, M.J., Khunti, K., Harrington, D.M. and Yates, T. (2018) Beyond cut points: Accelerometer metrics that capture the physical activity profile. *Medicine & Science in Sports & Exercise* **50,** 1323-1332. https://doi.org/10.1249/MSS.0000000000001561

Rowlands, A.V., Edwardson, C.L., Dawkins, N.P., Maylor, B.D., Metcalf, K.M. and Janz, K.F. (2020) Physical activity for bone health: How much and/or how hard? *Medicine & Science in Sports & Exercise* **52,** 2331-2341. https://doi.org/10.1249/MSS.0000000000002380

Rowlands, A.V., Fairclough, S.J., Yates, T., Edwardson, C.L., Davies, M., Munir, F., Khunti, K. and Stiles, V.H. (2019b) Activity intensity, volume, and norms: utility and interpretation of accelerometer metrics. *Medicine & Science in Sports & Exercise* **51,** 2410-2422. https://doi.org/10.1249/MSS.0000000000002047

Rowlands, A.V., Sherar, L.B., Fairclough, S.J., Yates, T., Edwardson, C.L., Harrington, D.M., Davies, M.J., Munir, F., Khunti, K. and Stiles, V.H. (2019c) A data-driven, meaningful, easy to interpret, standardised accelerometer outcome variable for global surveillance. *Journal of Science and Medicine in Sport* **22,** 1132-1138. https://doi.org/10.1016/j.jsams.2019.06.016

Rowlands, A.V. and Stiles, V.H. (2012) Accelerometer counts and raw acceleration output in relation to mechanical loading. *Journal of Biomechanics* **45,** 448-454. https://doi.org/10.1016/j.jbiomech.2011.12.006

Saint-Maurice, P.F., Laurson, K., Welk, G.J., Eisenmann, J., Gracia-Marco, L., Artero, E.G., Ortega, F., Ruiz, J.R., Moreno, L.A., Vicente-Rodriguez, G. and Janz, K.F. (2018) Grip strength cutpoints for youth based on a clinically relevant bone health outcome. *Archives of Osteoporosis* **13,** 92. https://doi.org/10.1007/s11657-018-0502-0

Sanders, T., Cliff, D.P. and Lonsdale, C. (2014) Measuring adolescent boys' physical activity: bout length and the influence of accelerometer epoch length. *Plos One* **9,** e92040. https://doi.org/10.1371/journal.pone.0092040

Scheers, T., Philippaerts, R. and Lefevre, J. (2012) Variability in physical activity patterns as measured by the SenseWear Armband: how many days are needed? *European Journal of Applied Physiology* **112,** 1653-1662. https://doi.org/10.1007/s00421-011-2131-9

Sherar, L.B., Griew, P., Esliger, D.W., Cooper, A.R., Ekelund, U., Judge, K. and Riddoch, C. (2011) International children's accelerometry database (ICAD): Design and methods. *BMC Public Health* **11,** 485. https://doi.org/10.1186/1471-2458-11-485

Skinner, A.M., Vlachopoulos, D., Barker, A.R., Moore, S.A., Rowlands, A.V., Soininen, S., Haapala, E.A., Väistö, J., Westgate, K., Brage, S. and Lakka, T.A. (2023) Physical activity volume and intensity distribution in relation to bone, lean and fat mass in children. *Scandinavian Journal of Medicine & Science in Sports* **33,** 267-282. https://doi.org/10.1111/sms.14255

Stiles, V.H., Metcalf, B.S., Knapp, K.M. and Rowlands, A.V. (2017) A small amount of precisely measured high-intensity habitual physical activity predicts bone health in pre- and post-menopausal women in UK Biobank. *International Journal of Epidemiology* **46,** 1847-1856. https://doi.org/10.1093/ije/dyx080

Tobias, J. (2014) Physical Activity and Bone: May the Force be with You. *Frontiers in Endocrinology* **5**. https://doi.org/10.3389/fendo.2014.00020

Troiano, R.P., McClain, J.J., Brychta, R.J. and Chen, K.Y. (2014) Evolution of accelerometer methods for physical activity research. *British Journal of Sports Medicine* **48,** 1019-1023. https://doi.org/10.1136/bjsports-2014-093546

Trost, S.G., Loprinzi, P.D., Moore, R. and Pfeiffer, K.A. (2011) Comparison of accelerometer cut points for predicting activity intensity in youth. *Medicine & Science in Sports & Exercise* **43,** 1360-1368. https://doi.org/10.1249/MSS.0b013e318206476e

van Hees, V.T., Fang, Z., Langford, J., Assah, F., Mohammad, A., da Silva, I.C., Trenell, M.I., White, T., Wareham, N.J. and Brage, S. (2014) Autocalibration of accelerometer data for free-living physical activity assessment using local gravity and temperature: an evaluation on four continents. *Journal of Applied Physiology* **117,** 738-744. https://doi.org/10.1152/japplphysiol.00421.2014

Ward, R.C., Janz, K.F., Letuchy, E.M., Peterson, C. and Levy, S.M. (2019) Contribution of high school sport participation to young adult bone strength. *Medicine & Science in Sports & Exercise* **51,** 1064-1072. https://doi.org/10.1249/MSS.0000000000001870

Zymbal, V., Baptista, F., Letuchy, E.M., Janz, K.F. and Levy, S.M. (2019) Mediating effect of muscle on the relationship of physical activity and bone. *Medicine & Science in Sports & Exercise* **51,** 202-210. https://doi.org/10.1249/MSS.0000000000001759

Key points

- Novel accelerometer metrics can be used to assess the mutually-adjusted associations of physical activity volume and intensity distribution with bone health, but it is unknown whether these associations are dependent on accelerometer epoch length.
- Intensity-gradient, reflective of physical activity intensity distribution, was positively associated with total body less head bone mineral content in females, with spine areal bone mineral density in males, and with hip areal bone mineral density and geometry in both sexes, when a 1 to 5-s epoch was used, indicating physical activity intensity was important for bone outcomes in both sexes.
- Average-acceleration, a proxy measure for physical activity volume, was positively associated with total body less head bone mineral content, spine areal bone mineral density and hip areal bone mineral density in males, though this was generally when the adjustment for intensity-gradient was from > 1-s epochs, indicating physical activity volume was important for bone outcomes in males.
- A 1 to 5-s epoch length was most appropriate to assess the mutually adjusted associations of intensity-gradient and average-acceleration with bone outcomes in young adults. Future studies applying these metrics should consider that metrics are influenced by epoch length, and this may ultimately influence the associations with health outcomes.

AUTHOR BIOGRAPHY

Annie M. SKINNER
Employment
Institutional Affiliation: Children's Health and Exercise Research Centre, University of Exeter, Exeter, UK.
Degree
MSc
Research interests
Physical activity and musculoskeletal health
E-mail: ac857@exeter.ac.uk

Alex V. ROWLANDS
Employment
Assessment of Movement Behaviours Group (AMBer), Leicester Lifestyle and Health Research Group, Diabetes Research Centre, University of Leicester, Leicester, UK; NIHR Leicester Biomedical Research Centre, UK; Alliance for Research in Exercise, Nutrition and Activity (ARENA), Sansom Institute for Health Research, Division of Health Sciences, University of South Australia, Adelaide, Australia.
Degree
PhD
Research interests
Physical activity and health
E-mail: alex.rowlands@leicester.ac.uk

Dimitris VLACHOPOULOS
Employment
Children's Health and Exercise Research Centre, University of Exeter, Exeter, UK.
Degree
PhD
Research interests
Physical activity, sports participation and musculoskeletal health
E-mail: D.Vlachopoulos@exeter.ac

Alan R. BARKER
Employment
Children's Health and Exercise Research Centre, University of Exeter, Exeter, UK.
Degree
PhD
Research interests
Physical activity, fitness and health, paediatric exercise science
E-mail: A.R.Barker@exeter.ac.uk

Kathleen F. JANZ
Employment
Department of Health and Human Physiology, The University of Iowa, Iowa City, IA; Department of Epidemiology, The University of Iowa, Iowa City, IA
Degree
Ed.D.
Research interests
Physical activity, fitness, health, paediatrics
E-mail: kathleen-janz@uiowa.edu

Sarah A. MOORE
Employment
School of Health and Human Performance, Dalhousie University, Halifax, Canada.
Degree
PhD
Research interests
Pediatric exercise science, musculoskeletal health, childhood disability
E-mail: Sarah.Moore@dal.ca

✉ **Annie M. Skinner**
Children's Health and Exercise Research Centre, University of Exeter, St Luke's Campus, Heavitree Road, Exeter, Devon, EX1 2LU, UK

Supplementary Contents

Supplementary Content 1. Associations of physical activity volume (average-acceleration) and intensity distribution (intensity-gradient) with bone outcomes in females (n = 121).

	1-s epoch				5-s epoch				15-s epoch				30-s epoch				60-s epoch			
	Model 1		Model 2		Model 1		Model 2		Model 1		Model 2		Model 1		Model 2		Model 1		Model 2	
	β (95% CI)	*p*	β (95% CI)	*p*	β (95% CI)	*p*	β (95% CI)	*p*	β (95% CI)	*p*	β (95% CI)	*p*	β (95% CI)	*p*	β (95% CI)	*p*	β (95% CI)	*p*	β (95% CI)	*p*
TBLH BMC (g)																				
Average-acceleration	25.61 (-10.02 to 61.25)	0.16	2.54 (-36.46 to 41.53)	0.90	25.61 (-10.02 to 61.25)	0.16	8.39 (-29.33 to 46.11)	0.66	25.61 (-10.02 to 61.25)	0.16	5.71 (-35.88 to 47.29)	0.79	25.61 (-10.02 to 61.25)	0.16	4.44 (-41.06 to 49.95)	0.85	25.61 (-10.02 to 61.25)	0.16	3.54 (-48.14 to 55.23)	0.89
Intensity-gradient	**47.64 (24.11 to 71.17)**	**< 0.001**	**46.47 (18.40 to 74.55)**	**0.001**	**36.32 (6.67 to 65.96)**	**0.02**	**32.43 (0.20 to 64.66)**	**0.05**	**36.47 (7.14 to 65.81)**	**0.02**	33.60 (-2.33 to 69.53)	0.07	**34.14 (3.95 to 64.32)**	**0.03**	31.50 (-8.54 to 71.54)	0.12	**30.77 (1.27 to 60.27)**	**0.04**	28.45 (-16.01 to 72.91)	0.21
Spine aBMD (g/cm²)																				
Average-acceleration	0.01 (-0.01 to 0.03)	0.40	0.00 (-0.02 to 0.03)	0.74	0.01 (-0.01 to 0.03)	0.40	0.00 (-0.02 to 0.03)	0.78	0.01 (-0.01 to 0.03)	0.40	0.00 (-0.02 to 0.03)	0.77	0.01 (-0.01 to 0.03)	0.40	0.00 (-0.02 to 0.03)	0.75	0.01 (-0.01 to 0.03)	0.40	0.01 (-0.03 to 0.04)	0.75
Intensity-gradient	0.01 (-0.01 to 0.03)	0.17	0.01 (-0.01 to 0.03)	0.24	0.01 (-0.01 to 0.04)	0.19	0.01 (-0.01 to 0.03)	0.24	0.01 (-0.01 to 0.03)	0.27	0.01 (-0.01 to 0.04)	0.39	0.01 (-0.01 to 0.03)	0.36	0.01 (-0.02 to 0.04)	0.58	0.01 (-0.01 to 0.03)	0.40	0.01 (-0.03 to 0.04)	0.70
Spine BMC (g)																				
Average-acceleration	1.09 (-0.58 to 2.75)	0.20	0.57 (-1.22 to 2.35)	0.53	1.09 (-0.58 to 2.75)	0.20	0.30 (-1.39 to 1.99)	0.72	1.09 (-0.58 to 2.75)	0.20	0.21 (-1.62 to 2.03)	0.82	1.09 (-0.58 to 2.75)	0.20	0.20 (-1.88 to 2.28)	0.85	1.09 (-0.58 to 2.75)	0.20	0.43 (-1.93 to 2.8)	0.72
Intensity-gradient	1.31 (-0.12 to 2.73)	0.07	1.05 (-0.05 to 2.59)	0.18	**1.62 (0.09 to 3.14)**	**0.04**	1.48 (-0.14 to 3.09)	0.07	1.59 (-0.02 to 3.19)	0.05	1.48 (-0.37 to 3.34)	0.12	1.44 (-0.20 to 3.08)	0.09	1.32 (-0.08 to 3.44)	0.22	1.13 (-0.48 to 2.74)	0.17	0.84 (-1.47 to 3.16)	0.47
Total hip aBMD (g/cm²)																				
Average-acceleration	0.02 (-0.00 to 0.04)	0.09	0.01 (-0.01 to 0.03)	0.44	0.02 (-0.00 to 0.04)	0.09	0.01 (-0.01 to 0.03)	0.45	0.02 (-0.00 to 0.04)	0.09	0.01 (-0.02 to 0.03)	0.63	0.02 (-0.00 to 0.04)	0.09	0.01 (-0.02 to 0.04)	0.70	0.02 (-0.00 to 0.04)	0.09	0.01 (-0.03 to 0.04)	0.74
Intensity-gradient	**0.02 (0.01 to 0.04)**	**0.006**	**0.02 (0.00 to 0.04)**	**0.05**	**0.02 (0.00 to 0.04)**	**0.02**	0.02 (-0.00 to 0.04)	0.08	**0.03 (0.01 to 0.04)**	**0.009**	0.02 (-0.00 to 0.04)	0.06	**0.02 (0.00 to 0.04)**	**0.02**	0.02 (-0.01 to 0.05)	0.15	**0.02 (0.00 to 0.04)**	**0.04**	0.02 (-0.01 to 0.05)	0.25
Total hip BMC (g)																				
Average-acceleration	0.73 (-0.21 to 1.67)	0.12	0.27 (-0.77 to 1.30)	0.61	0.73 (-0.21 to 1.67)	0.12	0.37 (-0.63 to 1.38)	0.47	0.73 (-0.21 to 1.67)	0.12	0.22 (-0.91 to 1.34)	0.71	0.73 (-0.21 to 1.67)	0.12	0.28 (-1.01 to 1.57)	0.67	0.73 (-0.21 to 1.67)	0.12	0.52 (-0.94 to 1.97)	0.48
Intensity-gradient	**1.06 (0.39 to 1.72)**	**0.002**	**0.94 (0.17 to 1.71)**	**0.02**	**0.85 (0.11 to 1.59)**	**0.03**	0.68 (-0.12 to 1.47)	0.09	**0.98 (0.24 to 1.72)**	**0.01**	0.87 (-0.06 to 1.80)	0.07	**0.84 (0.05 to 1.63)**	**0.04**	0.67 (-0.44 to 1.79)	0.24	0.62 (-0.18 to 1.41)	0.13	0.28 (-0.96 to 1.52)	0.66

Values are regression coefficients (ß), their 95% confidence intervals (CI), and *p* values from linear regression models. Activity metrics were standardised before entry into analysis, so values represent the change in the outcome associated with a 1 standard deviation change in the activity metric.

[a]Average-acceleration (average of waves 6 to 9) is the mean acceleration across wear-time.

[b]Intensity-gradient (average of waves 6 to 9) calculated, with imputing zeros for non-wear during the night, as the regression line from log-log plot of intensity (x) and time accumulated (y).

Model 1 includes the activity variable (average-acceleration or intensity-gradient) adjusted for age at wave 9, stature at wave 9, mass at wave 9, years from peak height velocity at wave 9, the proportion of the 24-hour cycle the accelerometer was worn, and the mean age for physical activity measures. Model 2 includes both activity variables in the same model (average-acceleration and intensity-gradient).

Bold emphasis indicates statistical significance at $p < 0.05$.

TBLH, total body less head; *BMC,* bone mineral content; *aBMD,* areal bone mineral density.

Supplementary Content 1. **Continued ....**

	1-s epoch				5-s epoch				15-s epoch				30-s epoch				60-s epoch			
	Model 1		**Model 2**		**Model 1**		**Model 2**		**Model 1**		**Model 2**		**Model 1**		**Model 2**		**Model 1**		**Model 2**	
	β (95% CI)	***p***	**β (95% CI)**	***p***	**β (95% CI)**	***p***	**β (95% CI)**	***p***	**β (95% CI)**	***p***	**β (95% CI)**	***p***	**β (95% CI)**	***p***	**β (95% CI)**	***p***	**β (95% CI)**	***p***	**β (95% CI)**	***p***
Femoral neck cross-sectional area (cm^2)																				
Average-accelera-tion	0.05 (-0.02 to 0.12)	0.17	0.02 (-0.06 to 0.09)	0.65	0.05 (-0.02 to 0.12)	0.17	0.02 (-0.06 to 0.10)	0.63	0.05 (-0.02 to 0.12)	0.17	0.01 (-0.07 to 0.09)	0.77	0.05 (-0.02 to 0.12)	0.17	0.02 (-0.07 to 0.11)	0.73	0.05 (-0.02 to 0.12)	0.17	0.02 (-0.08 to 0.13)	0.66
Intensity-gradient	**0.07 (0.02 to 0.13)**	**0.01**	**0.06 (0.01 to 0.12)**	**0.03**	**0.07 (0.01 to 0.13)**	**0.03**	0.06 (-0.00 to 0.12)	0.07	**0.07 (0.01 to 0.13)**	**0.03**	0.06 (-0.01 to 0.13)	0.07	0.06 (-0.01 to 0.13)	0.07	0.05 (-0.03 to 0.13)	0.23	0.05 (-0.02 to 0.12)	0.13	0.03 (-0.06 to 0.13)	0.47
Femoral neck section modulus (cm^3)																				
Average-accelera-tion	0.03 (-0.01 to 0.08)	0.14	0.03 (-0.02 to 0.07)	0.30	0.03 (-0.01 to 0.08)	0.14	0.03 (-0.02 to 0.08)	0.22	0.03 (-0.01 to 0.08)	0.14	0.02 (-0.03 to 0.08)	0.37	0.03 (-0.01 to 0.08)	0.14	0.03 (-0.03 to 0.09)	0.31	0.03 (-0.01 to 0.08)	0.14	0.02 (-0.04 to 0.09)	0.52
Intensity-gradient	0.03 (-0.02 to 0.07)	0.20	0.02 (-0.03 to 0.06)	0.47	0.02 (-0.02 to 0.06)	0.34	0.00 (-0.04 to 0.05)	0.82	0.03 (-0.01 to 0.07)	0.16	0.02 (-0.03 to 0.06)	0.51	0.02 (-0.02 to 0.06)	0.26	0.00 (-0.05 to 0.06)	0.86	0.03 (-0.01 to 0.07)	0.13	0.02 (-0.04 to 0.07)	0.59

Values are regression coefficients (ß), their 95% confidence intervals (CI), and *p* values from linear regression models. Activity metrics were standardised before entry into analysis, so values represent the change in the outcome associated with a 1 standard deviation change in the activity metric.

[a]Average-acceleration (average of waves 6 to 9) is the mean acceleration across wear-time.

[b]Intensity-gradient (average of waves 6 to 9) calculated, with imputing zeros for non-wear during the night, as the regression line from log-log plot of intensity (x) and time accumulated (y).

Model 1 includes the activity variable (average-acceleration or intensity-gradient) adjusted for age at wave 9, stature at wave 9, mass at wave 9, years from peak height velocity at wave 9, the proportion of the 24-hour cycle the accelerometer was worn, and the mean age for physical activity measures. Model 2 includes both activity variables in the same model (average-acceleration and intensity-gradient).

Bold emphasis indicates statistical significance at $p < 0.05$.

TBLH, total body less head; *BMC,* bone mineral content; *aBMD,* areal bone mineral density.

Supplementary Content 2. Associations of physical activity volume (average-acceleration) and intensity distribution (intensity-gradient) with bone outcomes in males (n = 96).

	1-s epoch				5-s epoch				15-s epoch				30-s epoch				60-s epoch			
	Model 1		Model 2		Model 1		Model 2		Model 1		Model 2		Model 1		Model 2		Model 1		Model 2	
	β (95% CI)	*p*	β (95% CI)	*p*	β (95% CI)	*p*	β (95% CI)	*p*	β (95% CI)	*p*	β (95% CI)	*p*	β (95% CI)	*p*	β (95% CI)	*p*	β (95% CI)	*p*	β (95% CI)	*p*
TBLH BMC (g)																				
Average-acceleration	**92.17 (37.9 to 146.44)**	**0.001**	**78.11 (18.54 to 137.69)**	**0.01**	**92.17 (37.91 to 146.44)**	**0.001**	**78.31 (19.68 to 136.95)**	**0.009**	**92.17 (37.91 to 146.44)**	**0.001**	**80.82 (24.36 to 137.27)**	**0.006**	**92.17 (37.91 to 146.44)**	**0.001**	**79.96 (23.96 to 135.95)**	**0.006**	**92.17 (37.91 to 146.44)**	**0.001**	**71.77 (14.03 to 129.51)**	**0.02**
Intensity-gradient	**79.16 (12.0 to 146.34)**	**0.021**	56.23 (-10.85 to 123.30)	0.10	**76.94 (10.53 to 143.35)**	**0.02**	49.80 (-19.00 to 118.59)	0.15	**67.85 (1.42 to 134.28)**	**0.05**	35.57 (-32.41 to 103.54)	0.30	**69.02 (2.97 to 135.07)**	**0.04**	37.39 (-29.82 to 104.60)	0.27	**86.53 (17.33 to 155.74)**	**0.02**	50.17 (-24.25 to 124.60)	0.18
Spine aBMD (g/cm²)																				
Average-acceleration	**0.03 (0.02 to 0.05)**	**< 0.001**	**0.02 (0.01 to 0.04)**	**0.01**	**0.03 (0.02 to 0.05)**	**< 0.001**	**0.03 (0.01 to 0.04)**	**0.005**	**0.03 (0.02 to 0.05)**	**<0.001**	**0.03 (0.01 to 0.05)**	**0.003**	**0.03 (0.02 to 0.05)**	**<0.001**	**0.03 (0.01 to 0.04)**	**0.004**	**0.03 (0.02 to 0.05)**	**<0.001**	**0.02 (0.01 to 0.04)**	**0.009**
Intensity-gradient	**0.04 (0.02 to 0.06)**	**< 0.001**	**0.04 (0.01 to 0.06)**	**0.001**	**0.03 (0.01 to 0.06)**	**0.002**	**0.03 (0.00 to 0.05)**	**0.02**	**0.03 (0.01 to 0.05)**	**0.008**	0.02 (-0.00 to 0.04)	0.09	**0.03 (0.01 to 0.05)**	**0.004**	0.02 (-0.00 to 0.04)	0.06	**0.03 (0.01 to 0.05)**	**0.001**	0.02 (-0.00 to 0.04)	0.06
Spine BMC (g)																				
Average-acceleration	**3.69 (2.13 to 5.25)**	**< 0.001**	**2.91 (1.31 to 4.50)**	**0.001**	**3.69 (2.13 to 5.25)**	**< 0.001**	**2.89 (1.24 to 4.53)**	**0.001**	**3.69 (2.13 to 5.25)**	**<0.001**	**2.98 (1.36 to 4.60)**	**<0.001**	**3.69 (2.13 to 5.25)**	**<0.001**	**2.96 (1.34 to 4.58)**	**<0.001**	**3.69 (2.13 to 5.25)**	**<0.001**	**2.68 (1.00 to 4.35)**	**0.002**
Intensity-gradient	**3.99 (1.86 to 6.11)**	**< 0.001**	**3.13 (1.15 to 5.12)**	**0.002**	**3.88 (1.80 to 5.97)**	**< 0.001**	**2.88 (0.84 to 4.92)**	**0.006**	**3.41 (1.32 to 5.51)**	**0.002**	**2.22 (0.14 to 4.30)**	**0.04**	**3.40 (1.34 to 5.46)**	**0.002**	**2.23 (0.16 to 4.30)**	**0.04**	**3.85 (1.91 to 5.79)**	**<0.001**	**2.49 (0.38 to 4.61)**	**0.02**
Total hip aBMD (g/cm²)																				
Average-acceleration	**0.04 (0.01 to 0.07)**	**0.005**	0.03 (-.00 to 0.06)	0.06	**0.04 (0.01 to 0.07)**	**0.005**	**0.03 (0.00 to 0.06)**	**0.04**	**0.04 (0.01 to 0.07)**	**0.005**	**0.03 (0.01 to 0.06)**	**0.02**	**0.04 (0.01 to 0.07)**	**0.005**	**0.04 (0.01 to 0.06)**	**0.02**	**0.04 (0.01 to 0.07)**	**0.005**	**0.03 (0.00 to 0.06)**	**0.03**
Intensity-gradient	**0.05 (0.02 to 0.08)**	**0.002**	**0.04 (0.01 to 0.07)**	**0.02**	**0.04 (0.01 to 0.07)**	**0.02**	0.03 (-0.01 to 0.06)	0.11	0.03 (-0.00 to 0.07)	0.076	0.02 (-0.02 to 0.05)	0.34	0.03 (-0.01 to 0.06)	0.11	0.01 (-0.02 to 0.05)	0.46	0.03 (-0.00 to 0.06)	0.05	0.01 (-0.02 to 0.05)	0.41
Total hip BMC (g)																				
Average-acceleration	**2.54 (0.93 to 4.14)**	**0.002**	**2.19 (0.47 to 3.91)**	**0.013**	**2.54 (0.93 to 4.14)**	**0.002**	**2.34 (0.66 to 4.02)**	**0.007**	**2.54 (0.93 to 4.14)**	**0.002**	**2.42 (0.79 to 4.05)**	**0.004**	**2.54 (0.93 to 4.14)**	**0.002**	**2.36 (0.69 to 4.02)**	**0.006**	**2.54 (0.93 to 4.14)**	**0.002**	**2.19 (0.47 to 3.92)**	**0.013**
Intensity-gradient	**2.05 (0.32 to 3.78)**	**0.02**	1.41 (-0.28 to 3.10)	0.10	1.52 (-0.36 to 3.41)	0.11	0.71 (-1.18 to 2.60)	0.46	1.33 (-0.47 to 3.14)	0.15	0.36 (-1.39 to 2.12)	0.68	1.49 (-0.30 to 3.27)	0.10	0.55 (-1.20 to 2.31)	0.53	**1.96 (0.21 to 3.70)**	**0.03**	0.85 (-1.01 to 2.70)	0.37

Values are regression coefficients (ß), their 95% confidence intervals (CI), and *p* values from linear regression models. Activity metrics were standardised before entry into analysis, so values represent the change in the outcome associated with a 1 standard deviation change in the activity metric.

[a]Average-acceleration (average of waves 6 to 9) is the mean acceleration across wear-time.

[b]Intensity-gradient (average of waves 6 to 9) calculated, with imputing zeros for non-wear during the night, as the regression line from log-log plot of intensity (x) and time accumulated (y).

Model 1 includes the activity variable (average-acceleration or intensity-gradient) adjusted for age at wave 9, stature at wave 9, mass at wave 9, years from peak height velocity at wave 9, the proportion of the 24-hour cycle the accelerometer was worn, and the mean age for physical activity measures. Model 2 includes both activity variables in the same model (average-acceleration and intensity-gradient).

Bold emphasis indicates statistical significance at $p < 0.05$.

TBLH, total body less head; *BMC*, bone mineral content; *aBMD*, areal bone mineral density.

Supplementary Content 2. **Continued ....**

	1-s epoch				5-s epoch				15-s epoch				30-s epoch				60-s epoch			
	Model 1		**Model 2**		**Model 1**		**Model 2**		**Model 1**		**Model 2**		**Model 1**		**Model 2**		**Model 1**		**Model 2**	
	β (95% CI)	***p***	**β (95% CI)**	***p***	**β (95% CI)**	***p***	**β (95% CI)**	***p***	**β (95% CI)**	***p***	**β (95% CI)**	***p***	**β (95% CI)**	***p***	**β (95% CI)**	***p***	**β (95% CI)**	***p***	**β (95% CI)**	***p***
Femoral neck cross-sectional area (cm^2)																				
Average-acceleration	**0.15 (0.04 to 0.27)**	**0.008**	0.12 (-0.01 to 0.25)	0.06	**0.15 (0.04 to 0.27)**	**0.008**	0.12 (-0.00 to 0.25)	0.06	**0.15 (0.04 to 0.27)**	**0.008**	**0.12 (0.00 to 0.25)**	**0.05**	**0.15 (0.04 to 0.27)**	**0.008**	0.12 (-0.01 to 0.24)	0.06	**0.15 (0.04 to 0.27)**	**0.008**	0.10 (-0.03 to 0.22)	0.13
Intensity-gradient	**0.17 (0.04 to 0.29)**	**0.01**	0.13 (-0.00 to 0.27)	0.06	**0.15 (0.02 to 0.28)**	**0.02**	0.11 (-0.03 to 0.25)	0.13	**0.14 (0.02 to 0.27)**	**0.02**	0.09 (-0.04 to 0.23)	0.17	**0.16 (0.04 to 0.28)**	**0.01**	0.11 (-0.02 to 0.24)	0.09	**0.19 (0.07 to 0.31)**	**0.002**	**0.14 (0.01 to 0.28)**	**0.04**
Femoral neck section modulus (cm^3)																				
Average-acceleration	**0.09 (0.01 to 0.16)**	**0.03**	0.06 (-0.02 to 0.14)	0.11	**0.09 (0.01 to 0.16)**	**0.03**	0.07 (-0.01 to 0.14)	0.10	**0.09 (0.01 to 0.16)**	**0.03**	0.07 (-0.01 to 0.15)	0.09	**0.09 (0.01 to 0.16)**	**0.03**	0.07 (-0.01 to 0.14)	0.09	**0.09 (0.01 to 0.16)**	**0.03**	0.05 (-0.03 to 0.13)	0.21
Intensity-gradient	**0.11 (0.03 to 0.19)**	**0.01**	**0.09 (0.01 to 0.17)**	**0.03**	**0.10 (0.01 to 0.18)**	**0.02**	0.07 (-0.01 to 0.16)	0.09	**0.08 (0.01 to 0.16)**	**0.03**	0.06 (-0.02 to 0.13)	0.14	**0.09 (0.01 to 0.16)**	**0.02**	0.06 (-0.02 to 0.13)	0.12	**0.11 (0.04 to 0.19)**	**0.004**	**0.09 (0.01 to 0.17)**	**0.03**

Values are regression coefficients (ß), their 95% confidence intervals (CI), and *p* values from linear regression models. Activity metrics were standardised before entry into analysis, so values represent the change in the outcome associated with a 1 standard deviation change in the activity metric.

[a]Average-acceleration (average of waves 6 to 9) is the mean acceleration across wear-time.

[b]Intensity-gradient (average of waves 6 to 9) calculated, with imputing zeros for non-wear during the night, as the regression line from log-log plot of intensity (x) and time accumulated (y).

Model 1 includes the activity variable (average-acceleration or intensity-gradient) adjusted for age at wave 9, stature at wave 9, mass at wave 9, years from peak height velocity at wave 9, the proportion of the 24-hour cycle the accelerometer was worn, and the mean age for physical activity measures. Model 2 includes both activity variables in the same model (average-acceleration and intensity-gradient).

Bold emphasis indicates statistical significance at $p < 0.05$.

TBLH, total body less head; *BMC,* bone mineral content; *aBMD,* areal bone mineral density.