Title: The "Goldilocks Day" for children's skeletal health: compositional data analysis of 24-hour activity behaviors

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Running title: Best day for skeletal health

Disclosure Page

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Declaration of Conflicting Interests

The authors declare that there is no conflict of interest

Data availability statement:

The LSAC and CheckPoint data are available under licence at https://growingupinaustralia.gov.au/data-and-documentation/accessing-lsac-data.

Abstract

Optimization of children's activity behaviors for skeletal health is a key public health priority, yet it is unknown how many hours of moderate-to vigorous physical activity (MVPA), light physical activity (LPA), sedentary behavior or sleep constitute the best day – the "Goldilocks Day" – for children's bone structure and function. To describe the best day for children's skeletal health, we used data from the cross-sectional Child Health CheckPoint. Included participants (n = 804, aged 10.7-12.9 y, 50% male) underwent tibial peripheral quantitative CT to assesses cross-sectional area, trabecular and cortical density, periosteal and endosteal circumference and stress-strain indices. Average daily time-use composition (MVPA, LPA, sedentary time and sleep) was assessed through 8-day, 24-hour accelerometry. Skeletal outcomes were regressed against time-use compositions expressed as isometric log ratios (with quadratic terms where indicated), adjusted for sex, age, pubertal status and socioeconomic position. The models were used to predict optimal time-use compositions (associated with best 5% of each skeletal outcome), which were plotted in three-dimensional quaternary figures. The center of the overlapping area was considered the Goldilocks Day for skeletal health. Children's time-use composition was associated with all skeletal measures (all $p \leq 0.001$) except cross-sectional area ($p = 0.72$). Days with more sleep and MVPA, less sedentary time and moderate LPA were beneficially associated with skeletal measures, except cortical density which was adversely associated. The Goldilocks daily time-use composition for overall skeletal health was (center [range]): 10.9 [10.5; 11.5] hours sleep; 8.2 [7.8; 8.8] hours sedentary time; 3.4 [2.8; 4.2] hours LPA, and 1.5 [1.3; 1.5] hours MVPA. Estimated optimal sleep duration is consistent with current international guidelines (9-11 hours), while estimated optimal MVPA exceeds recommendations of at least 60 min/d. This is the first study to describe optimal durations of daily activities for children's skeletal health, providing evidence to underpin public health guidelines.

Key words: ANALYSIS/QUANTITATION OF BONE: Bone QCT/μCT; EPIDEMIOLOGY: General population studies; EXERCISE; PRACTICE/POLICY-RELATED ISSUES: Fracture prevention

Introduction

Optimising bone health in childhood should be a potent protector against osteoporosis, the leading preventable cause of fracture in adults[1-3] and a major public health problem with considerable economic and societal costs. Global estimates suggest low bone mineral density affects >50% of adults aged >50 years.[4] One of the strongest predictors of adult skeletal health is skeletal health during childhood.[5,6] The greatest acquisition of bone mass occurs during adolescence[7] and up to 90% of peak bone mass is acquired by the age 18-20 years.[8]

Physical activity and sedentary time are modifiable lifestyle behaviors that could improve children's skeletal health. More time spent in moderate-to-vigorous physical activity (MVPA) has consistently been associated with better measures of bone structure and function.[9] More sedentary time has been associated with poorer skeletal health, but findings are less consistent[10-12] and in some studies attenuate after adjustment for MVPA.[13] MVPA and sedentary time are likely to be inversely correlated, because they constitute mutually exclusive parts of the 24-h day.

The remaining time in any day can be attributed to light physical activity (LPA) or sleep. Taken together, these four behaviors – sleep, sedentary time, LPA and MVPA – exhaustively account for a complete 24-h day. Any change to MVPA will result in an equivalent opposite change across the remaining three behaviors. Because of this, it is not logical to consider associations between MVPA and skeletal health without also considering the other behaviors. To date, little is known about the relationships between children's LPA or sleep and bone outcomes, but more LPA and longer sleep have been beneficially associated in older adults.[14,15] Instead of focusing on individual behaviors, public health translation efforts may benefit from a whole-of-day approach.

In order to study such associations, reliable measures are needed not only of 24-h time use but also of skeletal health. Whereas dual-energy X-ray absorptiometry (DXA) measures mainly density and is significantly confounded by tall/short stature, peripheral quantitative CT (pQCT) assesses both the density and geometry (circumference, thickness) of trabecular and cortical compartments, with a short scanning time and minimal radiation exposure. pQCT enables calculation of stress-strain index (SSI), which appears to be a better predictor of fracture than

bone density alone.[16,17] SSI has been positively associated with MVPA but not sedentary time in Australian school-aged children.[12]

This study aimed to use a 24-h time-use approach to explore the associations between MVPA, LPA, sedentary time and sleep with pQCT-derived measures of bone density, geometry and strength among a large, population-based sample of Australian school-aged children. It aimed to describe the best day – the "Goldilocks Day" – for bone health, where the mix of these four behaviors is "just right" using novel analytical methods based on compositional data analysis.

Materials and Methods

Study design and participants

Participants were from the Child Health CheckPoint study,[18,19] a cross-sectional module nested between Waves 6 and 7 of the Longitudinal Study of Australian Children (LSAC).[20] LSAC began in 2004 with a nationally-representative birth cohort (n = 5107 infants), recruited by a two-stage random sampling design (57% recruitment rate). Participants are followed in biennial waves. In 2014 (Wave 6), 3513 of the 3764 retained families gave permission for their contact details to be given to the Child Health CheckPoint team. In 2015, a CheckPoint information pack was mailed to these families, which was followed up by a recruitment phone call. Informed consent was provided by a parent/guardian. Data were collected from 1874 children between February 2015 and March 2016. There were no exclusion criteria. Ethical approval was gained from The Royal Children's Hospital (Melbourne) Human Research Ethics Committee (HREC33225) and the Australian Institute of Family Studies Ethics Committee (AIFS14-26).

Measurements

Measurements were taken at a 3.5 h visit to a CheckPoint Assessment Centre in one of Australia's seven major cities. Participants assessed at a 2.5 h visit to a Mini Centre in one of eight small regional cities or a home visit did not have access to the pQCT. Study data were collected and managed using REDCap electronic data capture tools[21,22] hosted at Murdoch Children's Research Institute.

Exposure: Daily activity composition

Participants were fitted with a GENEActiv accelerometer (Activinsights Ltd., UK) on their non-dominant wrist at the end of the visit.[23] They were requested to wear it for 8 days, 24 hours a day. Participants were asked to complete a paper-based log to record bed and wake times, and the time and reason for accelerometer removal. Accelerometry data were downloaded at a 50 Hz sampling frequency using GENEActiv PC Software (Activinsights, UK), and converted to 60-second epoch files. Sleep and non-wear time were identified through visual inspection of daily accelerometer traces and self-reported data from the paper-based logs, using *Cobra*, a MATLAB-based customized software program. When participants recorded sport as the reason for removing the accelerometer, the corresponding non-wear period was replaced with 50% MVPA, 30% light physical activity and 20% sedentary time.[24]

The 60-second epochs were classified using cut-points for GENEActiv devices that have been previously validated in school-aged children.[25] These cut-points were linearly adjusted to account for the 50 Hz sampling frequency, to 244 gravity minutes (g.min, i.e., acceleration because of gravity multiplied by minutes) for sedentary time, 878 g.min for light physical activity and 2175 g.min for MVPA. Days were considered invalid if waking wear time was ≤ 10 h, sleep duration ≤ 200 min/d or sedentary time ≥ 1000 min/d. Participants with at least four valid days were included in the analysis.

Outcome: Bone measures

Skeletal health was determined by pQCT scan (single Stratec XCT 2000L pQCT scanner, Medizintechnik, Germany). Comprehensive detail of the measurement procedure is reported elsewhere.[26] Scans were conducted on the non-dominant leg (tibia), and taken at the 4% (ankle) and 66% (shin) sites. One tomographic image was taken at each site, at a scan speed of 20 mm/s, slice thickness of 2.4 mm and voxel side of 0.4 mm. Images were processed using Stratec XCT 2000 software (V.6.20C). Regions of interest around each bone image were manually contoured by one of two research assistants, before generating bone health measures with the MACRO analysis function with almost perfect inter-rater agreement (intraclass correlation coefficient

>0.99). Skeletal health measures included volumetric bone mineral density and bone geometric parameters. The circular ring model was used. Measures obtained from the 4% site were trabecular bone mineral density (mg/cm^3) and total cross-sectional area (mm^2). Measures obtained from the 66% site were cortical bone mineral density (mg/cm^3), endosteal circumference and periosteal circumference. Measures of bone resistance against torsional load and bending, SSI resistance and SSI inertia were derived from geometry and density measures at the 66% site using a threshold of 480 (mg/cm^3). The SSI measures are considered to be predictors of functional bone strength[27] and are associated with fracture risk.[16] All bone measures were expressed as sample-specific z-scores. For all density, size and strength values, we took the largest value to indicate the 'best' skeletal health. Supplementary File 1 shows the correlation matrix between bone indices. It can be seen that most bone metrics were positively correlated, with the exception of cortical density which was negatively correlated with both circumference (bone size) measures and SSI (bone strength) measures.

Covariates

Covariates were selected due to their potential impact on activity behaviors and bone measures. Age, sex and family-level socioeconomic position (SEP) were obtained from LSAC. The SEP variable is a *z*-score released with each wave of LSAC data, derived from parental income, occupation and education.[28] Participants self-reported pubertal signs using an iPad version of the Pubertal Development Scale, which enabled classification as either pre-pubertal, early pubertal, mid-pubertal, late pubertal or post-pubertal.[29] Pubertal development was treated as a continuous variable in analyses. Body mass (kg) was measured in light clothing without shoes or socks using the InBody230 four-limb segmental body composition bioelectric impedance scale (Biospace, Seoul, Korea).[30] Body mass was chosen due to its potential contribution to adaptive bone remodeling via static loading,[31] and its known associations with activity behaviors.[32] Tibial length was included as an indicator of body size. It was measured (with standard measuring tape), as the distance between the superior edge of the medial malleolus and the medial edge of the tibial plateau (both landmarks had been marked with pen upon palpation by the research assistant).

Analysis

Participants were included if they had complete and valid data for all measures. All analyses were conducted in R[33] using the Compositions,[34] zCompositions,[35] robustbase[36] and rgl[37] packages. An average 24-h time-use composition was created for each participant, consisting of four parts: Sleep, sedentary time, LPA and MVPA. The time-use composition was described by the compositional center, which is calculated as the geometric means of the parts, linearly adjusted to sum to 1440 minutes (or 24 hours). Included participants were compared with excluded participants (and included boys vs included girls) using t-tests for continuous variables, chi-squared test for categorical variables and compositional MANOVA[38] for the activity composition.

Models to explore the relationship between time use and bone measures

Participants' average 24-h time-use composition (sleep, sedentary time, LPA and MVPA) was expressed as a set of isometric log ratios (*ilrs*) to allow compositional data analysis (CoDA).[39-41] Two participants recorded zero min MVPA. As per published procedures, these zero values were replaced with a small value (4.7 seconds) to enable log-ratio transformation. This value is 65% of the smallest possible value (1 minute/8 days).[42] Linear regression models with robust estimators were used to regress time-use composition *ilrs* against bone outcome *z*-scores.[43] If model diagnostic plots suggested a non-linear relationship, squared terms for the composition were tested and retained if they improved the model fit (partial F test $p<0.1$). All models were adjusted for sex, age, pubertal status, family SEP *z*-score and body mass.

A predictive set of time-use compositions was created to represent every possible combination of activity behaviors (in 10-minute increments) within the average daily ranges observed in the sample (the empirical time-use footprint). This created a 3-D grid of equally spaced datapoints representing hypothetical children, all with different time-use compositions. The outer boundaries of the 3-D grid of were truncated at ±3SD of the behaviors' univariate distributions, resulting in 6330 unique predictive time-use compositions. The limits (in min/d) of the predictive set of compositions were: Sleep = 430-700; Sedentary = 470-880; LPA = 40-300; MVPA = 10-90 (Note, although MVPA durations of 0 min/day were within -3SD of the sample mean, zero

values could not be included in our hypothetical compositions because all activities had to be expressed as log ratios before being used as new data for prediction in the compositional models). The compositional regression models described above were used to predict bone outcomes for the set of predictive time-use compositions (expressed as *ilrs*).

Model-predicted values for the bone measures were plotted against the complete range of each individual daily activity behavior from the predictive set of time-use compositions, and loess curves were fitted to illustrate the shape of the relationship.

Finding the best daily activity composition for bone health

The predicted bone outcomes for all possible daily compositions (with 10-minute granularity, within the bounds observed in the sample) were sorted from best to worst, and the compositional center [range] of the top 5% were described as the "best bone zones". The 5% best bone zone cut-off was chosen to reflect contemporary cut-offs for statistical and clinical significance (e.g., alpha of 0.05, 95th percentile), and to achieve overlap between the best bone zones for individual measures. The overlapping area was considered to be the best overall bone zone, i.e., the time-use compositions for which all measures were predicted to be in the best 5%.

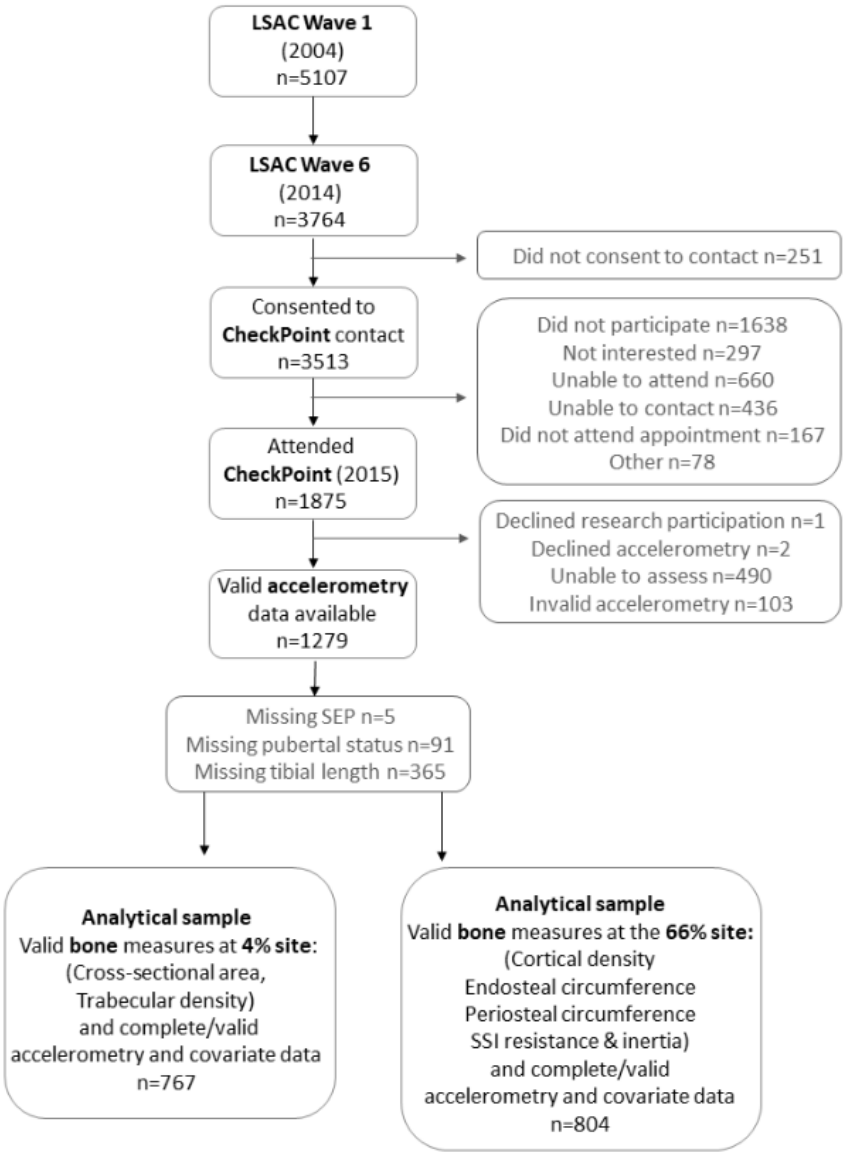
The best bone zones were plotted in 3-D quaternary plots, and the region where all best bone zones overlapped ("best overall bone zone") was described by its compositional center [range]. This best overall bone zone was considered to describe the mix of daily behaviors associated with optimal skeletal health.

Supplementary analyses repeated the above models in sex-stratified samples (Supplementary File 2). Interactions between activity composition and puberty were explored by using the model-based predictions to generate dose-response curves across different levels of puberty.

Results

Of 1874 participating children, 1279 provided complete and valid accelerometry data. Of these, 818 also had complete covariate data (age, sex, puberty, SEP, mass and tibial length). The final analytical samples included those who also had valid bone scan data at the 66% site (cortical

density, endosteal and periosteal circumference and SSI: inertia and resistance) (n=804), and valid data at the 4% site (cross-sectional area and trabecular density) (n=767). Figure 1 shows the participant flow.



Characteristics of the largest analytical sample are presented in Table 1. Included participants differed from excluded participants in Wave 6 of LSAC by having a higher SEP *z*-score (0.32 ± 0.98 vs. -0.09 ± 0.99; $t = -10.4$, $p < 0.001$). The compositional center of included children's time

use differed to that of excluded children (n = 475) ($F = 6.7$, $p < 0.001$), having higher sleep (579 vs 569 min/d), lower LPA (159 vs 165 min/d, slightly lower sedentary time (683 vs 686 min/d), but the same MVPA (20 min/d).

Boys differed from girls by pubertal stage (more likely to be in earlier stages of puberty, $p < 0.001$), less MVPA ($p < 0.001$), lower trabecular ($p = 0.008$) and cortical ($p < 0.001$) density and higher endosteal ($p < 0.001$) and periosteal ($p = 0.002$) circumference.

Table 1. Participant characteristics

Characteristic	Included (n=804)	Boys (n=399)	Girls (n=405)
Age, y (mean (SD))	11.9 (0.4)	11.9 (0.4)	11.9 (0.4)
Sex = Male/Female (%)	399/405 (49.6/50.4)		
SEP *z*-score (mean (SD))	0.32 (0.98)	0.34 (0.99)	0.30 (0.98)
Pubertal stage (n (%))			
Pre-pubertal	92 (11.4)	69 (17.3)	23 (5.7)
Early puberty	200 (24.9)	167 (41.9)	33 (8.1)
Mid-pubertal	411 (51.1)	150 (37.6)	261 (64.4)
Late puberty	97 (12.1)	13 (3.3)	84 (20.7)
Post-pubertal	4 (0.5)	0 (0.0)	4 (1.0)
Puberty (continuous)	2.65 (0.54)	2.27 (0.78)	3.02 (0.74)
Body mass, kg (mean (SD))	44.9 (10.4)	44.3 (10.8)	45.4 (10.1)
Tibial length, mm (mean (SD))	361 (26)	359 (27)	362 (25)
Activity variables, min/d (arithmetic means (SD))			
Sleep	569.1 (47.3)	567.5 (47.3)	570.6 (47.3)
Sedentary time	672.4 (71.9)	667.9 (74.6)	676.8 (69.0)
LPA	162.3 (46.4)	163.6 (45.6)	161.0 (47.2)
MVPA	28.7 (22.5)	35.7 (25.3)	21.8 (16.7)
Activity variables, min/d (compositional center (95% bootstrapped CI))[b]			
Sleep	578.9 (575.6; 582.2)	576.8 (571.8; 581.9)	580.5 (575.4; 585.2)
Sedentary time	682.5 (677.6; 687.2)	677.0 (669.0; 684.8)	687.2 (680.4; 694.0)
LPA	158.5 (155.5; 161.9)	160.1 (155.2; 165.0)	156.8 (152.3; 161.9)
MVPA	20.0 (18.7; 21.5)	26.1 (23.6; 28.8)	15.4 (14.0; 17.2)
Bone variables (mean (SD))			
Measures at the 4% site			
Cross-sectional area[a], mm^2	706.9 (123.7) [n=767]	707.5 (130.2) [n=382]	706.2 (117.1) [n=385]
Trabecular density[a], mg/cm^3	197.7 (26.0) [n=767]	195.2 (23.3) [n=382]	200.2 (28.2) [n=385]
Measures at the 66% site			
Cortical density, mg/cm^3	1019.0 (37.3)	1010.4 (35.7)	1027.5 (36.9)
Endosteal circumference, mm	62.0 (8.4)	63.2 (8.6)	60.8 (8.0)
Periosteal circumference, mm	81.2 (7.3)	82.0 (7.7)	80.4 (6.9)
Polar SSI inertia, mm^3	30007 (9315)	30357 (9917)	29661 (8680)
Polar SSI resistance, mm^3	1704 (394)	1714 (407)	1692 (382)

[a]n = 767 for outcomes measured at 4% site. SEP = socioeconomic position; LPA = light physical activity; MVPA = moderate-to-vigorous physical activity; SSI = stress-strain index. [b]Compositional center is calculated by finding the geometric mean of each activity variable, and then linearly adjusting these means so that they collective sum to 1440 minutes.

Relationship between time-use composition and bone measures

The activity composition *ilrs* were significantly associated with all bone measures (all $p \leq 0.01$) except cross-sectional area ($p = 0.72$) (Table 2). Quadratic relationships between activity composition and bone measures were indicated for both circumference (endosteal, periosteal) and bone strength (SSI inertia and resistance) outcomes.

Table 2. Association between activity composition *ilrs* and bone variables, and best bone zones (best 5% of time-use compositions within the observed range of activity behaviors).

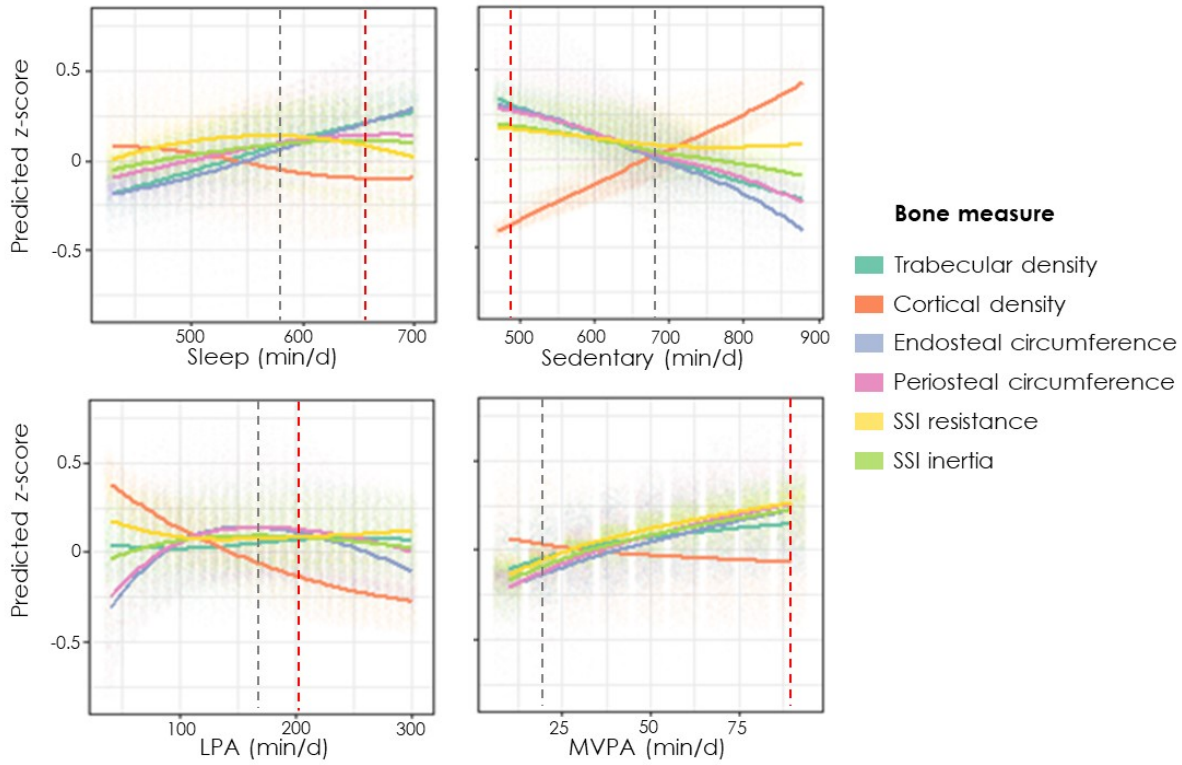
	Model summary (for *ilrs*)		Activity mean [range] associated with top 5% of bone outcomes (min/d)			
Measure	F[a]	*p*	Sleep (sample center=579)	Sedentary (sample center =683)	LPA (sample center =159)	MVPA (sample center =20)
Cross-sectional Area	0.7	0.57	NS	NS	NS	NS
Trabecular Density	4.1	0.007	664 [570: 700]	501 [470: 580]	201 [70: 300]	73 [30: 90]
Cortical Density	7.5	<0.001	521 [430: 700]	836 [690: 880]	50 [40: 100]	32 [10: 90]
Endosteal Circumference[b]	4.5	<0.001	670 [610: 700]	540 [470: 620]	149 [70: 240]	81 [60: 90]
Periosteal Circumference[b]	5.5	<0.001	653 [580: 700]	534 [470: 620]	169 [90: 270]	84 [70: 90]
SSI Inertia[b]	4.3	<0.001	639 [570: 700]	539 [470: 640]	176 [100: 300]	87 [80: 90]
SSI Resistance[b]	3.9	<0.001	600 [510: 670]	547 [470: 660]	205 [90: 300]	88 [80: 90]

[a]Multiple correlation coefficient for overall activity composition (set of isometric log ratios), adjusted for age, sex, pubertal status, family socioeconomic position and body mass. [b]Squared term for isometric log ratios. *Ilr*=isometric log ratio; PA= light physical activity; MVPA= moderate-to-vigorous physical activity; SSI= polar stress-strain index.

Figure 2 shows how the bone measure *z*-scores were associated with individual activity behavior components, as estimated by the compositional regression models. When interpreting this figure, it must be remembered that one activity cannot increase or decrease without compensation in the remaining activities as there must always be 24 hours in a day. The vertical spread of datapoints (range of predicted bone *z*-scores) for any duration of activity (e.g., 30 min/d MVPA) indicates that predicted bone health at 30 min/d MVPA varies depending on the duration of the remaining activities. The shapes of the fitted loess curves provide an indication of the average situation for each activity behavior, taking all possible durations of the remaining activities into account.

Sleep and MVPA appear positively associated, and sedentary time negatively associated, with all bone measures except cortical density. For both SSI measures, there seems to be an inverted-U-shaped relationship with sleep, with an optimum duration of about 575 min/d (9.6 h/d). The shape of associations between LPA and bone measures appear quite flat, except for the

circumference measures which seem to have an optimum duration of about 150 min/d, or 2.5 h/d (inverted-U-shape). As expected, due to its inverse correlation with the circumference (bone size) measures, associations between cortical density and activity behaviors were in opposite directions to those observed for all other bone measures.



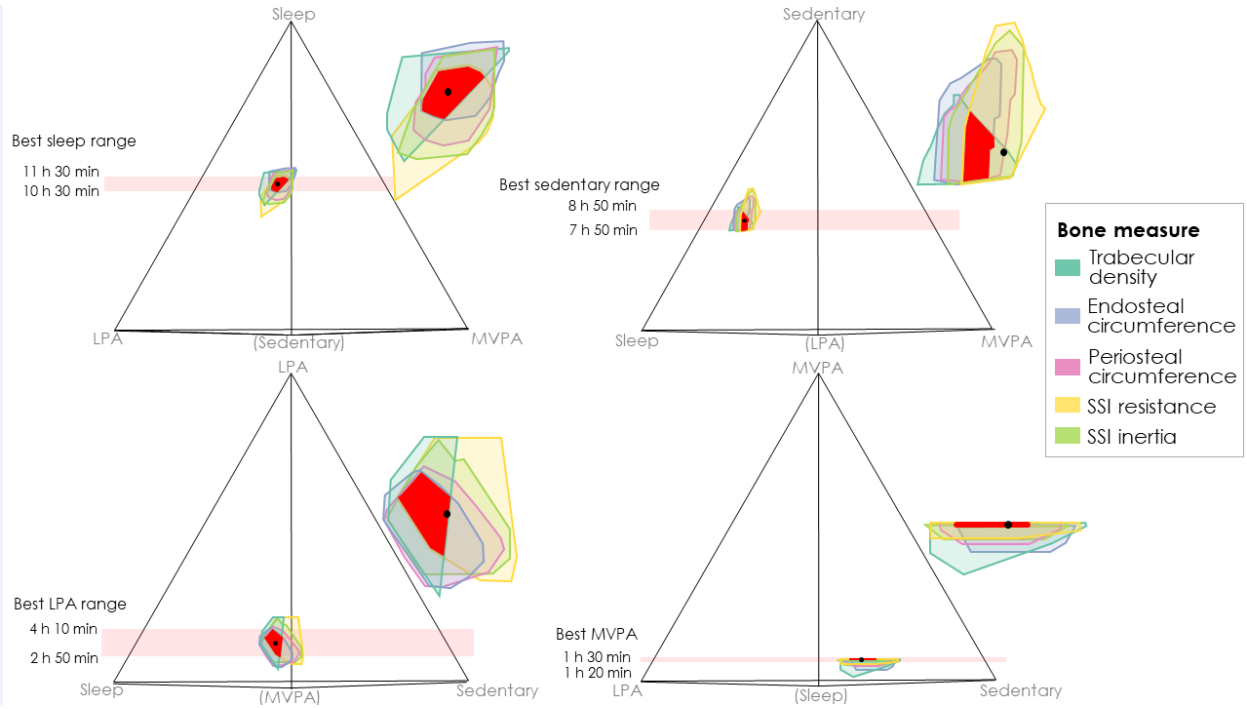
Similar patterns were observed in sex-stratified analyses (Supplementary File 2). In both sexes, there was a beneficial association between more time in MVPA and all bone health measures (except cortical density) (Supplementary File 2, Figure S1). Beneficial associations were observed for lower more light physical activity and less sedentary time for most bone outcomes. Associations between sleep duration and bone SSI measures appeared to differ between the sexes, with higher sleep being beneficially associated in boys but not in girls. Among boys, there were no significant interactions between the activity composition and puberty for any of the bone health measures (Supplementary File 2, Figure S2). Among girls, puberty-interactions were identified in the trabecular density ($p = 0.03$), endosteal ($p = 0.03$) and periosteal ($p = 0.003$) circumference and SSI inertia and resistance (both $p < 0.001$) models (Supplementary File 2, Figure S3). Typically, higher MVPA and lower light physical activity was more beneficially

associated among girls less advanced in puberty, while the opposite was observed among girls of higher sexual maturity. Longer sleep (and less consistently, longer sedentary time) was beneficially associated with bone circumference and SSI measures in less mature girls, while shorter sleep and sedentary time was beneficial in more mature girls.

Best daily time-use composition for bone health

The center (compositional mean) and range [min; max] of the set of predictive time-use compositions associated with the best 5% (95th percentile) of bone measures are presented in Table 2. Cross-sectional area is not included as the time-use composition was not a significant predictor. The best bone zones were similar for all outcomes except cortical density. For all outcomes except cortical density, the best bone zones maximized MVPA and (to a lesser extent) sleep, and minimized sedentary time. In the best bone zones, LPA was near its sample mean.

To describe the overall best bone zone, the "Goldilocks day" for optimal bone health, the overlapping area of the best individual bone measure zones was described (Figure 3). Cortical density was not included because of its seemingly paradoxical relationship with the activity behaviors. The center of the overall best bone zone for 11-12 year olds was an 'optimal' 24-h day that comprises (center [range]): 10.9 [10.5; 11.5] hours sleeping, 8.2 [7.8; 8.8] hours of sedentary time, 3.4 [2.8; 4.2] hours in LPA, and 1.5 [1.3; 1.5] hours in MVPA.



Sex-stratified analyses suggested that the best composition for overall bone health for boys was different to that of girls (Supplementary File 2, Tables S1 and S2). The Goldilocks Day for boys had 2.4 h more sleep, 1.7 h less sedentary time, 0.6 h less LPA and 0.1 h less MVPA than the Goldilocks Day for girls.

Discussion

Principal findings

Children's daily time-use composition (sleep, sedentary time, LPA and MVPA) was associated with measures of their bone structure and function. Days that maximize the feasible time spent in MVPA (a ceiling of 1.5 h, the boundary of the empirical activity footprint) and minimize sedentary time while achieving sufficient sleep (>10.3 h) and several hours (approximately 3.4 h) of LPA appear to be the best for overall skeletal health.

Comparison with previous literature

Beneficial associations between children's MVPA and skeletal health have been observed in numerous previous studies.[44,45] The mechanisms underpinning this relationship may include an adaptive bone re-modelling response to functional skeletal loading. Because muscles attach to bone (via tendons), repeated activation of the bone-muscle unit caused by muscle contraction during MVPA produces repeated strain on the bone that induces deposition of bone and to strengthen the bone.[31] In addition, children's habitual MVPA is likely to include exercises such as leaping, hopping and running, which provide extra skeletal loading through high ground reaction forces and have been shown to increase children's bone strength in intervention studies.[46] LPA does not appear to be produce enough stimulus for a bone-remodelling response in children,[47] although very few studies have explored this. Figure 2 shows beneficial associations between LPA and endosteal/periosteal circumference measures among those with low LPA levels (<100 min), suggesting that some activity (which is likely to include weightbearing) is better than none.

The relationship between sleep duration and measures of skeletal health have received less attention in children, and few studies have explored these associations in adult or elderly populations. Short sleep duration has been associated with lower bone mineral density in post-menopausal women.[14,48,49] Lack of sleep may be associated with poorer bone outcomes due to disruption to metabolic and endocrine functions which regulate bone deposition and remodeling.[49] Several studies among older women have found excessive sleep (≥8h) to also be associated with lower bone mineral density.[50,51] The inverted U-shaped relationship for bone strength measures (SSI inertia and resistance) found in this study suggests that there may be an optimal duration of sleep for children, beyond which its beneficial associations with bone function may decline. This may be because excessive sleep means children have less time available for weight-bearing activities and MVPA.

Negative associations between children's sedentary time and skeletal health have been reported in several studies.[13] It is possible that these associations are explained by what the child is *not* doing during sedentary time, rather than the sedentary time itself. When children are sedentary, they are benefiting from neither the activities (MVPA, LPA) nor metabolic/endocrine processes (sleep) that are conducive to adaptive bone deposition and strengthening.

Best time-use compositions were somewhat different for boys and girls, particularly the associations between sleep duration and SSI measures. In boys, sleep duration appeared more beneficially associated with bone strength than in girls. Further exploration of interaction by pubertal status suggested sleep to be less beneficially associated among girls at later pubertal stages. Because girls were typically more sexually mature than boys (Table 1), the sex-differences observed in the associations between sleep and SSI measures may be attributed to pubertal development rather than sex. It is possible that during early stages of puberty and pubertal transition, longer sleep duration is more important for better hormonal regulation of bone remodeling than at later pubertal stages when hormonal changes become more stable. This, (and the lack of interaction between sex and activity composition) suggests that separate guidelines for boys and girls are not warranted. Perhaps guidelines for sleep should recommend longer durations for less sexually mature children compared to more sexually mature children, but this would be difficult (and perhaps inappropriate) to implement in the context of public health or general practice.

Associations between activity behaviors and cortical density were in the opposing direction to those of all other skeletal health measures (Figure 2), in keeping with its negative association with endosteal circumference. We also noted this phenomenon in our non-compositional analysis of MVPA and bone measures in the same sample.[12] While the opposing associations for cortical density were expected from the correlation matrix, we wonder if this apparently paradoxical relationship is why cortical density outcomes have been rarely reported in the activity behavior literature. The paradoxical associations could be due to transient decreases in cortical density among children with higher MVPA/lower sedentary time, as their bones undergo accelerated remodeling in response to both physical activity and rapid skeletal growth. It also seems likely that larger bones and those with thicker cortices (i.e., relatively smaller endosteal in the face of larger periosteal circumferences) are stronger despite greater cortical porosity that limits density and thus heaviness. A few studies have reported cortical density to be paradoxically associated with other predictors, for example, in the Avon Longitudinal Study of Parents and Children (ALSPAC) (n = 4152, 15.5 y), children's cortical density was negatively associated with their birth weight, while periosteal circumference was positively associated.[52]

Strengths and limitations

Strengths of this study include its large population-based sample and the high-quality measures of outcomes and exposures. Novel applications of analytical models suited for 24-h data (CoDA) allowed all daily activities to be considered simultaneously. A number of recent studies have used compositional data analysis to explore relationships between daily activity and bone health in other age groups,[53-56] but to our knowledge this is the first study to find the best-fitting models (including quadratic terms where indicated) to describe the shape of associations between time-use composition and health outcomes. It is the first to seek to describe the best mix of daily activities for skeletal health.

This study used cross-sectional data, meaning that reverse-causality is possible since poorer skeletal health may be associated with factors that influence time-use behaviors. Generalizability may be limited by the narrow age range (10.7 – 12.9 y) and differences in SEP and adiposity of included participants compared to excluded participants from the population-representative LSAC sample. Whilst we adjusted for potential confounders, their remains a possibility of residual confounding due to unincluded factors such as medications or nutritional intake. We adjusted for total body mass, which includes bone mass. However, variation in bone mass is small[57] compared to variation in total body mass, suggesting any potential confounding would be minimal. In the absence of published values defining optimal values for the skeletal measures, we took larger values to represent better bone health. This may not always be the case, for example larger endosteal circumference (if together with smaller periosteal circumference) may indicate thinner cortices, and high densities may indicate heavier but not necessarily stronger bones. Estimates of optimal durations are directly dependent on the values measured in the sample. Different accelerometers, different data processing procedures and different samples are likely to lead to different estimates of optimal durations. Average daily MVPA was considerably less in the present study compared to other studies using different accelerometer protocols. For example, the International Study of Childhood Obesity, Lifestyle and the Environment used hip-worn Actigraph GT3X+, Evenson et al's cut points and a 15-s epoch length.[58] Average daily MVPA in the Australian cohort was 65 (SD = 23).[59] Unfortunately, although accelerometry is considered a gold-standard measure of activity behavior, there are numerous decisions made by researchers which can lead to widely diverging estimates.[60] It should also be considered that we

collected activity data over the span of a year, meaning that seasonality may have influenced children's activity patterns. Not many children (3%) in this sample achieved the estimated optimal durations of 1.5 h/d MVPA, only 20 % obtained >1h, and the mean duration (compositional center was only 20 min/d. Thus, we cannot draw any conclusions about the benefits or harms of more than 1.5 h/d of MVPA, and even this may be essentially beyond what Australian children can achieve.

Interpretation and implications

The findings suggest that interventions encouraging healthy time-use behaviors over a 24-h day (incorporating MVPA and sleep as well as sedentary time and LPA) may be advantageous to children's skeletal health and therefore may lead to better adult skeletal health and mitigate facture risk in later life. They are the first to suggest that sleep duration may be an important factor to consider for optimization of children's bone structure and function, and that there may be benefit associated with accumulating several hours of LPA each day.

Estimated durations for optimal MVPA are higher than published recommendations (Australian 24-Hour Movement Guidelines for Children and Young People), which recommend at least 60 minutes of MVPA per day, with vigorous activities, including those that strengthen muscles and bone, to be incorporated at least three days/week.[61] This may be because existing guidelines are dominated by the goal of reducing adiposity, whose own 'Goldilocks Day' might be quite different than that for bone health. This high level of MVPA for bone health might also come at the cost of other dimensions of health, such as wellbeing and academic performance; it is possible that compromises may be needed to optimize overall health.

Future directions

Future studies may explore the interaction of activity and body composition (lean mass/muscle mass, truncal fat, non-truncal fat) in relation to skeletal health. Longitudinal and intervention studies are required to confirm the causal relationships observed in this study, noting that it is very difficult to shift time use greatly within individuals. The relationships between bone health

and individual activities described the average situation, considering every possible permutation of the remaining activities. The association for swapping time between two activities only (e.g., reallocating 30 minutes from sedentary time to MVPA) could be explored using compositional isotemporal substitution. In addition, as vigorous physical activity may be more conducive to adaptive bone remodeling than moderate physical activity, future studies could differentiate between these intensities. It may also be profitable to explore characteristics of activity accumulation (e.g., bout length, fragmentation, timing, consistency). Further exploration of microarchitecture in future studies using strategies like HR-pQCT may assist in exploring the apparent paradoxical relationship between activity behaviors and cortical density. Studies may explore what the Goldilocks Day looks like for different health outcomes, such as adiposity, cognition and quality of life.

Conclusion

This study suggests that the Goldilocks Day for bone health should maximize MVPA and minimize sedentary time, whilst achieving sufficient sleep and several hours of LPA. Current international guidelines are in line with this study's estimates of optimal sleep duration and LPA, but our estimate of optimal MVPA for skeletal health appears higher than that of published recommendations. Application of this study's novel analytical approach to a comprehensive range of health outcomes may provide evidence to underpin public health guidelines that optimize the recommended daily durations of activity behaviors taking into account multiple competing outcomes of value to children, families and society.

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Author contributions

Study design: MW, PS, TO and DB. Study conduct: MW, PS, TO and DB. Data collection: MW, PS, and TO. Data analysis: DD. Data interpretation: DD, TO, PS, MW, DB, MJ, FW and CM. Drafting manuscript: DD and TO. Revising manuscript content: DD, TO, PS, MW, DB, MJ, FW and CM. Approving final version of manuscript: DD, TO, PS, MW, DB, MJ, FW and CM. DD takes responsibility for the integrity of the data analysis.

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Figure legends

Figure 1. Participant flow.

SSI = stress-strain index; SEP = socioeconomic position

Figure 2. Estimated relationship between individual activity behaviors on the x-axis and bone measures (*z*-scores) on the y-axis

Models adjusted for age, sex, pubertal status, family socioeconomic position, body mass and tibial length. Grey broken line shows compositional mean value of behavior in the sample, and red broken line shows value of behavior at estimated optimal composition. LPA = light physical activity; MVPA = moderate-to-vigorous physical activity; SSI = stress-strain index.

Figure 3. Best bone zones

Models adjusted for age, sex, pubertal status, family socioeconomic position, body mass and tibial length. LPA = light physical activity, MVPA = moderate-to-vigorous physical activity, SSI = stress-strain index. Each panel shows a different face of the same quaternary tetrahedron. Activities are at 100% (24 h) at the corresponding apices of the tetrahedron, and 0% at the opposite base. A datapoint in the exact center of the tetrahedron would have equal shares of each activity (25%, or 6 h). Each of the polygons represents the compositions associated with the top 5% of bone measures (cross-sectional area and cortical density are not included). Insets show magnified best bone zones. The compositional mean of the overlap zone between the polygons (shown in red) is indicated by the black dot (h/d): Sleep = 10.9; Sedentary time = 8.2; LPA = 3.4; MVPA = 1.5.