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Associations of volumes and patterns of physical activity with metabolic health in children: a multivariate pattern analysis approach

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Abstract

Physical activity (PA) favorably affects metabolic health in children, but it is unclear how total volumes versus patterns (bouts and breaks) of PA relate to health. By means of multivariate pattern analysis that can handle collinear variables, we determined the associations of PA volumes and patterns with children's metabolic health using different epoch settings. A sample of 841 Norwegian children (age 10.2 ± 0.3 years) provided in 2014 data on accelerometry (ActiGraph GT3X+), using epoch settings of 1, 10, and 60 seconds and several indices of metabolic health used to create a composite metabolic health score. We created 355 PA indices covering the whole intensity and bout duration spectrum, and used multivariate pattern analysis to analyze the data. Findings showed that bouts of PA added information about childhood health beyond total volumes of PA for all epoch settings. Yet, associations of PA patterns with metabolic health were completely dependent on the epoch settings used. Vigorous PA was strongly associated with metabolic health, while associations of light and moderate PA were weak to moderate, and associations of sedentary time with metabolic health was non-existing. Short intermittent bursts of PA were favorably associated with children's metabolic health, whereas associations of prolonged bouts were weak. This study is the first to determine the multivariate physical activity association pattern related to metabolic health in children across the whole PA intensity and bout duration spectrum. The findings challenge our understanding of PA patterns, and are of major importance for the analysis of accelerometry data.

Keywords

Multivariate pattern analysis; metabolic risk factors; pediatric; childhood; pre-pubertal; accelerometer; bouts; breaks

Introduction

Moderate-to-vigorous physical activity (MVPA) has consistently been associated with metabolic health outcomes (i.e., risk factors for cardiovascular diseases) in childhood [1-3]. Additionally, sedentary time (SED) [4] has received much attention for possibly being detrimental to health beyond overall physical activity (PA) or MVPA [5 6]. The majority of pediatric studies investigating relationships between PA and health have restricted their exposure variables to these two [2], resulting in a great loss of information and ignoring the possible influence of other PA indices on health outcomes.

Given the potential influence of the patterns (i.e., bouts and breaks) compared to the overall volumes (i.e., total time) of PA and SED in children [3 5-7], these indices should be directly compared across the intensity spectrum [3 8]. Studies that have compared total PA and bouts of MVPA, or sporadic (1–5 minutes) with longer bouts (≥ 5 and 10 minutes) of MVPA, show that these indices perform rather similarly as markers of health in both adults [9-11] and children [12-15], although some child studies conclude that bouts add independently to total volumes in terms of explaining variation in fatness [13 16 17]. The evidence for an influence of SED on metabolic health in children, beyond MVPA, is weak [1 7].

While studies have investigated whether sustained bouts (> 1–10 minutes) of PA are associated with metabolic health, children's PA is characterized by sporadic and intermittent bursts of PA generally lasting less than 10 seconds [18-20]. Thus, studies consistently show that SED, vigorous PA (VPA), and MVPA are underestimated, whereas light PA (LPA) is overestimated, when epoch duration increases from 1 to 60 seconds [20-24]. These findings suggest that short epoch settings are recommended. However, using very short epochs might capture small bursts of PA, or "noise", which are not meaningful for health, and thus be counterproductive for increasing knowledge of PA and health. Moreover, different epoch settings for accelerometry will likely cause a substantially altered distribution of PA across different bout durations [20 23 25], which is crucial to our understanding of PA patterns and the relation to childhood health. There is therefore a need to investigate the influence of PA bouts on metabolic health in childhood across the whole spectrum of durations, both shorter and longer than 1 minute. Broadening our understanding in this way merges two lines of research: one focusing on choosing the most optimal epoch setting for measuring PA, and one focusing on whether childhood PA recommendations should include structured exercise training.

Determining the relative importance of PA volumes and patterns is however difficult, given the multi-collinearity among the PA indices. To avoid loss of information and residual confounding [8], all indices must be included in the same statistical model. Because common univariate statistical methods (i.e., ordinary least squares regression models) cannot handle highly correlated variables, we need new

statistical methods to overcome this shortcoming [26]. Multivariate pattern analysis is widely applied in pharmaceutical [27] and metabolomics studies [28], as well as in other fields of biomedical research, such as treatment and diagnosis of diseases [29], with the objective of revealing patterns and important biomarkers among hundreds or thousands of highly interrelated variables. Thus, this statistical approach is well suited to solve the issue of collinearity in accelerometer-derived PA variables.

By means of multivariate pattern analysis, the aim of the present study was to determine the associations of PA volumes and patterns with children's metabolic health, across the intensity and bout duration spectrum, using different epoch settings. This novel statistical approach, as applied to PA accelerometry data, allows addressing questions that have not been possible to answer previously.

Methods

Participants

The present analyses are based on baseline data obtained in fifth grade children from the Active Smarter Kids (ASK) study, conducted in Norway during 2014–2015 [30 31]. Sixty schools, encompassing 1202 fifth-grade children, fulfilled the inclusion criteria, and agreed to participate. This sample represented 86.2% of the population of 10-year-olds in the county, and 95.2% of those eligible for recruitment. Later, three schools encompassing 27 children declined to participate. Thus, 1145 (97.4 %) of 1175 available children from 57 schools agreed to participate in the study.

Our procedures and methods conform to ethical guidelines defined by the World Medical Association's Declaration of Helsinki and its subsequent revisions. The Regional Committee for Medical Research Ethics approved the study protocol. We obtained written informed consent from each child's parents or legal guardian and from the responsible school authorities prior to all testing. The study is registered in Clinicaltrials.gov with identification number: NCT02132494.

Procedures

We have previously published a detailed description of the study [30], and provide only a brief overview of the relevant procedures herein.

Physical activity

Physical activity was measured using the ActiGraph GT3X+ accelerometer (Pensacola, FL, USA) [32]. Participants were instructed to wear the accelerometer over seven consecutive days, except during water activities (swimming, showering) or while sleeping. Units were initialized at a sampling rate of 30 Hz. Files were analyzed at 1, 10, and 60-second epochs using the KineSoft analytical software version 3.3.80 (KineSoft, Loughborough, UK). Data was restricted to hours between 06:00 and 23:59. In all analyses, consecutive periods of ≥ 60 minutes of zero counts were defined as non-wear time [33] [34]. We applied wear time requirements of ≥ 8 hours/day and ≥ 4 days/week to constitute a valid measurement.

We created PA variables to capture volumes and patterns of movement across the intensity spectrum (SED to VPA range). We used the Evenson et al cut points of 0–99, 100–2295, 2296–4011, ≥ 4012, and ≥ 2296 cpm to define SED, LPA, moderate PA (MPA), VPA, and MVPA [35] [36], respectively. We defined 15 different bout durations between 1 second and ≥ 60 minutes: 1 second, 2–4 seconds, 5–9 seconds, 10–19 seconds, 20–29 seconds, 30–39 seconds, 40–59 seconds, 1.0–1.4 minutes, 1.5–1.9 minutes, 2.0-2.9 minutes, 3–4 minutes, 5–9 minutes, 10–29 minutes, 30–59 minutes, and ≥ 60 minutes. All 15 bout durations were used for files analyzed at 1-second epoch, whereas 10-second epoch files were analyzed for 12 bout durations (≥ 10 seconds), and 60-second epoch files were analyzed for 7 bout durations (≥ 60 seconds). Bouts were further defined without allowing any exceptions (time spent outside of the bouts), and while allowing exceptions of a maximum of 20% of the bout duration (e.g., allowing up to 2 minutes drop in intensity below the intensity cut point within a 10-minute bout to account for stopping at right light etc.), to investigate sensitivity to altering the bout definition (please see Supplemental Table 1 for an overview of bout durations and exceptions analyzed). For descriptive statistics, we also reported achievement of the guideline PA level (mean of ≥ 60 minutes of MVPA/day).

Metabolic health measures

Aerobic fitness was measured with the Andersen intermittent running test [37], which was performed according to standard procedures. Children ran for as long as possible in a to-and-fro movement on a 20-meter track, touching the floor with one hand each time they turned, with 15-second work periods and 15-second breaks, for a total duration of 10 minutes. The distance covered was used as the outcome. The test has demonstrated acceptable reliability and validity in 10-year-old children [38]. Body mass was measured using an electronic scale (Seca 899, SECA GmbH, Hamburg, Germany), with

children wearing light clothing. Height was measured using a portable Seca 217 (SECA GmbH, Hamburg, Germany). Body mass index (BMI) (kg $\cdot m^{-2}$) was calculated. Waist circumference was measured with a Seca 201 (SECA GmbH, Hamburg, Germany) measuring tape two cm over the level of the umbilicus. Systolic (SBP) and diastolic blood pressures were measured using the Omron HBP-1300 automated monitor (Omron Healthcare, Inc, Vernon Hills, IL, US). Children rested quietly for ten minutes in a sitting position with no distractions before we measured blood pressures four times. We used the mean of the last three measurements for analyses. Serum blood samples were collected from the children's antecubital vein between 08:00 and 10:00 in the morning after an overnight fast. All blood samples were analyzed for total cholesterol (TC), triglyceride (TG), high-density lipoprotein cholesterol (HDL), glucose, and insulin, at the accredited Endocrine Laboratory of the VU Medical Center (VUmc; Amsterdam, the Netherlands). Low-density lipoprotein cholesterol (LDL) was estimated using the Friedewald formula [39]. We calculated the TC:HDL-ratio and homeostasis model assessment (HOMA) (glucose (mmol/L) * insulin (pmol/L) / 22.5) [40].

We calculated a composite score as the mean of six variables (SBP, TG, TC:HDL-ratio, HOMA, WC:height-ratio, and the reversed Andersen test) by averaging standardized scores after adjustment for sex and age using residuals from linear regression models. This composite score was used as the metabolic health outcome, as previously applied to children [14].

Statistical analyses

Children's characteristics were reported as frequencies, means and standard deviations (SD). Distributions of time spent in different bout durations were reported as variable means in line diagrams. We tested for differences in characteristics between boys and girls, as well as between children included and excluded from the analysis using a mixed effect model accounting for the clustering among schools. Models for PA and SED were adjusted for wear time.

Associations between PA/SED and metabolic risk were determined using Pearson's correlation coefficient (r) and multivariate pattern analysis. Partial least squares (PLS) regression analyses [41] were used to determine the multivariate PA association pattern with the composite metabolic health score, including all standardized PA variables as explanatory variables. PLS regression decomposes the explanatory variables into orthogonal linear combinations (PLS components), while simultaneously maximizing the covariance with the outcome variable. Thus, PLS regression can handle collinear variables.

Monte Carlo resampling [42] with 100 repetitions was used to select the number of PLS components optimizing the predictive performance of the models by randomly keeping 50% of the subjects as an external validation set when estimating the models. The predictive performance was calculated for an increasing number of components and the minimum median used as a criterion to determine the models' dimensions. For each cross-validated PLS regression model, a single predictive component was calculated by means of target projection, expressing all the predictive variance in the PA variables related to the metabolic response variable in a single vector[27 43]. Selectivity ratios (SRs) were obtained as the ratio of this explained predictive variance to the residual variance for each PA variable [44 45]. The results are shown in an SR plot, which quantitatively displays the PA variables' predictive and discriminatory importance for metabolic health. Cross-validated confidence intervals were constructed to assess the significance of the SR for each PA variable. The procedure for obtaining the patterns is completely data-driven with no assumptions on variable distributions or degree of correlations between variables.

We compared the association patterns related to metabolic health for bout definitions with and without allowing exceptions, and between boys and girls, by correlating the variable loadings from the separate multivariate models using Pearson's r.

Multivariate pattern analyses were performed using the commercial software Sirius version 11.0 (Pattern Recognition Systems AS, Bergen, Norway).

Results

Children's characteristics

We included 841 children who provided valid data on all relevant variables (Table 1). The children (n = 841, 50% boys) included in the present analyses did not differ from the excluded children (n = 288, 57% boys) with respect to age ($p \geq .689$) or anthropometry ($p \geq .166$). Yet, the included children performed better on the Andersen test ($p < .001$), had lower fasting insulin concentrations ($p = .001$) and HOMA scores ($p = .002$), exhibited less SED time ($p = .002$), and spent more time in PA ($p \leq .031$) than the excluded children.

Table 1. Children's characteristics for demography, anthropometry and metabolic health.

	Overall (n = 841)	Boys (n = 424)	Girls (n = 417)	p between groups
Demography				

Age (years)	10.2 (0.3)	10.2 (0.3)	10.2 (0.3)	.803
Anthropometry				
Body mass (kg)	37.0 (8.1)	36.8 (7.8)	37.2 (8.3)	.641
Height (cm)	142.9 (6.7)	143.1 (6.7)	142.6 (6.8)	.197
BMI (kg/m^2)	18.0 (3.0)	17.9 (2.9)	18.1 (3.1)	.218
Overweight and obese (%)	20.8	20.0	21.5	.583
Waist circumference (cm)	61.9 (7.5)	62.2 (7.3)	61.6 (7.7)	.169
Waist:height (ratio)	0.43 (0.05)	0.43 (0.05)	0.43 (0.05)	.322
Indices of metabolic health				
Andersen test (m)	898 (103)	925 (112)	871 (85)	< .001
Systolic blood pressure (mmHg)	105.2 (8.4)	105.3 (8.2)	105.2 (8.6)	.612
Diastolic blood pressure (mmHg)	57.7 (6.2)	57.4 (6.0)	58.1 (6.3)	.180
Total cholesterol (mmol/l)	4.46 (0.69)	4.46 (0.70)	4.46 (0.68)	.976
LDL-cholesterol (mmol/l)	2.51 (0.64)	2.50 (0.65)	2.53 (0.62)	.570
HDL-cholesterol (mmol/l)	1.59 (0.35)	1.63 (0.34)	1.55 (0.35)	.001
Total:HDL-cholesterol (ratio)	2.91 (0.71)	2.82 (0.66)	2.99 (0.74)	.001
Triglyceride (mmol/l)	0.78 (0.38)	0.72 (0.31)	0.84 (0.42)	< .001
Glucose (mmol/l)	4.98 (0.32)	5.02 (0.31)	4.94 (0.33)	.001
Insulin (pmol/l)	55.0 (29.8)	48.9 (24.1)	61.1 (33.6)	< .001
HOMA (index)	1.71 (0.98)	1.54 (0.83)	1.89 (1.09)	< .001
Composite score (1SD)*	0.00 (1.00)	0.00 (0.93)	0.00 (1.07)	-

BMI = body mass index; LDL = low density lipoprotein; HDL = high density lipoprotein; HOMA = homeostasis model assessment; *The composite score includes waist circumference, systolic blood pressure, total:HDL ratio, triglycerides, HOMA, and the Andersen test (reversed). The study was conducted in Sogn og Fjordane, Norway during 2014-2015.

Physical activity and sedentary time

Total time spent in SED, LPA, and VPA differed greatly between the epoch settings, while epoch setting had a minor influence for overall PA and moderate for MPA and MVPA. In the total sample, SED (+53%; 3.2 SDs) and VPA (+86%; 1.1 SD) increased substantially, whereas LPA decreased substantially (-64%; 4.0 SDs), when data were analyzed in 1-second compared to 60-second epochs. Moreover, the number of children achieving the guideline amount of MVPA differed substantially between epoch settings.

Table 2. Physical activity levels (mean (SD)) by epoch setting.

	Total			**Boys**			**Girls**		
	Epoch setting (seconds)								
	1	**10**	**60**	**1**	**10**	**60**	**1**	**10**	**60**
Wear time (min/day)	795 (56)	795 (56)	796 (57)	799 (59)	799 (59)	800 (59)	791 (54)	791 (54)	791 (54)
Overall (cpm)	708 (272)	707 (271)	705 (269)	754 (296)	754 (296)	751 (293)	660 (235)	660 (235)	658 (234)
SED (min/day)	597 (56)	490 (60)	390 (64)	593 (59)	488 (63)	393 (67)	601 (53)	492 (57)	388 (60)
LPA (min/day)	122 (22)	231 (38)	340 (54)	124 (23)	230 (40)	333 (55)	120 (21)	233 (37)	347 (52)
MPA (min/day)	37 (10)	44 (13)	45 (17)	39 (10)	47 (13)	50 (18)	35 (9)	40 (11)	39 (14)
VPA (min/day)	39 (15)	31 (16)	21 (16)	43 (16)	34 (17)	23 (18)	35 (18)	27 (12)	18 (13)
MVPA (min/day)	76 (23)	74 (25)	65 (28)	82 (24)	81 (27)	74 (30)	70 (19)	67 (21)	57 (22)
Guideline amount (%)	74	69	52	80	77	63	68	61	42

Intensity-specific PA is calculated using the Evenson cut point [35]; The guideline PA levels are defined as a mean of ≥ 60 min of MVPA per day. The study was conducted in Sogn og Fjordane, Norway during 2014-2015.

Time spent in different bout durations was completely dependent on the epoch setting (Figure 1). For 1 and 10-second epoch, most of the MPA (79–90%), VPA (61–75%), and MVPA (46–64%) was accumulated within the 3 shortest bout durations (1–9-second bouts for 1-second epoch and 10–39-second bouts for 10-second epoch), whereas time in SED and LPA was more spread over shorter and longer bouts. Similarly, for 60-second epoch, the accumulation of time for all variables but MPA was spread over bouts of different durations, with 40–72% of time accumulated in 3–29-minute bouts. Allowing exceptions (≤ 20% of time spent outside of a bout) increased the accumulation of time in longer bouts for all variables, especially for SED accumulated in bouts ≥ 60 minutes.

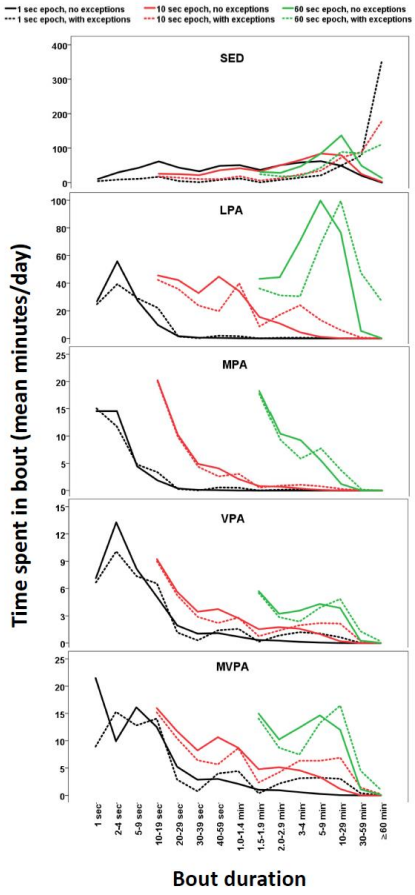

Figure 1. Distribution of physical activity in bouts of different durations based on three different epoch settings (1, 10, and 60-second epochs) and two different bout definitions (allowing and not allowing exceptions of up to 20 % of the time spent outside of a bout). The figure shows that accumulation of sedentary time and physical activity in bouts of different durations varies largely between different epoch settings. Note that activity cannot be accumulated in bouts shorter than the epoch settings allow, so that there are no bouts shorter than 10 and 60 seconds for data analyzed at 10 and 60-second epochs, respectively. The study was conducted in Sogn og Fjordane, Norway during 2014-2015.

Associations between physical activity and metabolic health

Table 3 shows bivariate associations with metabolic health for total time in PA and SED, as determined by different epoch settings, adjusted for age and sex, but not mutually adjusted for each other. While associations for overall PA, SED, and LPA were similar across epoch setting, associations for MPA and MVPA weakened with a shorter epoch duration. Associations for VPA were marginally stronger for 1 and 10-second epoch than for 60-second epoch.

Table 3. Bivariate associations with a metabolic composite score for total time in PA and SED analyzed by 3 different epoch settings.

	Epoch setting		
	1 second	**10 seconds**	**60 seconds**
Overall PA (cpm)	-0.18	-0.18	-0.18
SED (min/day)	0.07	0.09	0.09
LPA (min/day)	0.01	0.01	0.02
MPA (min/day)	-0.08	-0.16	-0.26
VPA (min/day)	-0.27	-0.28	-0.21
MVPA (min/day)	-0.22	-0.25	-0.27

Associations ≤ -.07 and ≥ .07 are significant at $p < .05$ without adjustment for multiple comparisons. The study was conducted in Sogn og Fjordane, Norway during 2014-2015.

The multivariate association patterns for total time and bouts of PA and SED with metabolic health are shown in Figure 2. Compared to models including total time only, explained variance doubled for all epoch settings when including bouts (Table 4). The association patterns were rather similar for bouts defined with and without allowing exceptions (r for variable loadings = 0.89 for 1-second epoch, r = 0.95 for 10-second epoch, r = 0.97 for 60-second epoch, all $p < .001$, Supplemental Figures 1–5). Allowing exceptions moved the association spectrum marginally to the right, in favor of longer bouts. The association patterns were similar for boys and girls (r for variable loadings = 0.95, $p < .001$).

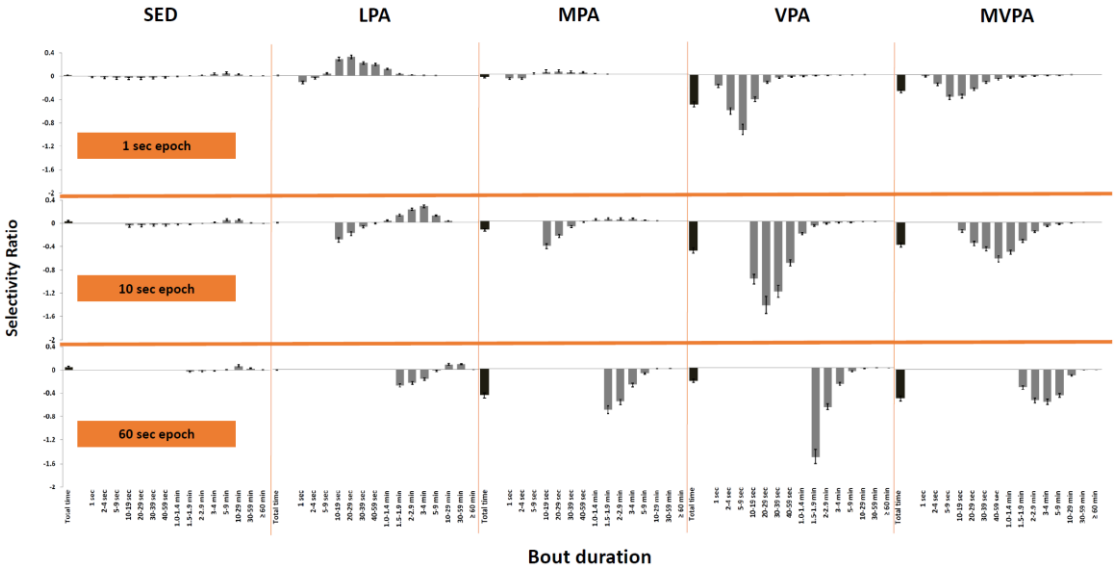

Figure 2. Multivariate associations with metabolic health composite score for intensity-specific physical activity analyzed using 1, 10, and 60-second epochs. Associations are displayed as a selectivity ratio plot. The selectivity ratio for each physical activity variable is calculated as the explained variance to residual variance on the predictive (target projected) metabolic health component. A negative bar implies that increased PA is associated with better metabolic health. 15 different bout durations were analyzed for 1-second epoch files, whereas 12 different bout durations were analyzed for 10-second epoch files, and 7 different bout durations were analyzed for 60-second epoch files. The study was conducted in Sogn og Fjordane, Norway during 2014-2015.

The association pattern with metabolic health was dominated by VPA (and MVPA), while LPA and MPA were influential too. However, the bout durations most strongly associated with health were heavily dependent on epoch settings for all PA intensities. A similar picture was seen for VPA and MVPA; while the strongest associations were seen for bout durations ≤ 30 seconds for 1-second epoch, the strongest associations were seen for bout durations ≤ 60 seconds for 10-second epoch, and the strongest associations were seen for bout durations ≤ 5 minutes for 60-second epoch. MPA was favorably associated with metabolic health when analyzed in 60-second epoch, whereas associations were completely attenuated when analyzed in 1-second epoch, as also supported by the analysis of total time (Table 3). The association patterns for LPA were bidirectional; within each epoch setting associations with metabolic health were favorable for short bouts, but unfavorable for longer bouts. SED was in general not associated with metabolic health for any bout duration.

Table 4. Model fit for the multivariate pattern analysis models analyzed by 3 different epoch settings.

	Epoch setting		
	1 second	**10 seconds**	**60 seconds**
Total time	10.1	8.1	8.0
Bouts, without exceptions	20.3	18.0	16.2
Bouts, with exceptions	21.4	18.5	16.4

Numbers refer to the explained variance (%) in the composite metabolic health score. The study was conducted in Sogn og Fjordane, Norway during 2014-2015.

Discussion

We present herein the multivariate PA association pattern, including total volumes and bouts of activity, associated with metabolic health in children. An important finding was that the accumulation of time in bouts was completely dependent on the epoch setting, which challenges our analytic approaches as well as our understanding of accumulation of PA in bouts. However, across all epoch settings, including bouts of PA added significant information about childhood metabolic health beyond total volumes of PA. We found that VPA (and MVPA) was strongly associated with metabolic health, while associations for LPA and MPA were weak to moderate, and associations for SED were non-existing. Our results suggest that short intermittent bursts of PA are favorable for children's metabolic health, whereas prolonged bouts seem to be of less importance.

Because children's and adolescents' natural PA pattern is rather sporadic, with bouts of PA generally lasting less than 10 seconds [18-20], it has been concluded that studies should apply shorter epochs than the traditional 60-second epoch duration [33] to capture PA correctly. Summation of PA over longer epoch periods leads to loss of time spent in the lower and higher end of the intensity spectrum, because time spent in these intensities is averaged over longer periods. Thus, studies consistently show that SED, VPA, and MVPA are underestimated, and LPA overestimated, when epoch duration increases [20-24]. Our findings are consistent with these previous studies, showing large differences for these variables across the epoch settings.

The loss of information accompanying long epochs suggests shorter ones are important to capture PA accurately. Of major importance, we found that associations with metabolic health for total time in VPA strengthened when using 1 (r = -0.27) and 10-second (r = -0.28) epochs, compared to 60-second epoch (r = -0.21), whereas the opposite pattern was found for MPA (r = -0.08, -0.16, and -0.26 for 1, 10 and 60-second epochs, respectively). This finding supports the use of shorter epochs to capture VPA correctly, whereas it suggests associations with MPA are spuriously high when data are analyzed using longer epochs, which is caused by misclassification of VPA as MPA when averaging PA over longer durations. The finding that only VPA is related to metabolic health using 1-second epochs challenges previous studies and recommendations [1-3 7] concluding that children should spend time in MVPA to improve their metabolic health. These findings show that a conscious use of epoch settings is fundamental to our analysis and understanding of how PA is accumulated in bouts and related to children's metabolic health.

Whether patterns (bouts and breaks) of PA are of importance for health beyond the total volumes is an interesting question relating to childhood PA guidelines. Studies that have directly compared total PA to bouts of MVPA, or sporadic bouts (1–5 minutes) with longer bouts (≥ 5 and 10 minutes) of

MVPA, show that these indices perform rather similarly as markers of health in both adults [9-11] and children [12-15], although some studies conclude bouts add independently to total volume in terms of explaining variation in fatness [13 16 17]. Our findings show that the full spectrum of bout durations doubled the explained variance in relation to metabolic health compared to models including total time only. Interestingly, there was no association for total time in LPA with metabolic health across epoch settings, whereas the association patterns indicated favorable associations for short bouts and unfavorable associations for longer bouts. The explanation for these association patterns for LPA is likely the interrelation with VPA; short bouts of LPA are positively related to VPA, whereas long bouts of LPA are negatively related to VPA (results not shown). The results for LPA constitute a good example of how patterns of PA are relevant for childhood metabolic health status beyond total volume.

In general, our results suggest children's sporadic PA is most important for health, whereas longer bouts are of less importance, although this interpretation fully depends on the epoch setting used. Importantly, the weak associations for prolonged bouts are probably a result of children accumulating low amounts of PA in longer bouts. Nevertheless, based on these findings, we argue childhood PA guidelines should focus on all PA, without respect to bouts, which we believe is beneficial to motivate children for a habitual life-long active lifestyle, given the natural sporadic and intermittent PA pattern in this age group [18-20].

The main strengths of the present study are the comprehensive analysis of accelerometry variables reporting a range of bout durations across three different epoch settings, and the use of multivariate pattern analysis, which allows for handling of all these PA indices in a joint statistical model [27 41]. Thus, the association patterns shown include all available information regarding volumes and patterns of PA provided from accelerometry, thus limiting residual confounding [8]. A limitation of the present study is the cross-sectional design. Thus, we cannot infer causality from our findings. Future studies should use a similar analytic approach applied to new large datasets in order to verify the findings.

Conclusion

This study breaks new ground by investigating the association patterns of PA volumes and patterns with childhood metabolic health, using multivariate pattern analysis. Our main conclusions were that the strongest associations with metabolic health were found for VPA, while weaker associations were evident for MPA and LPA, and no associations were evident for SED. Bouts of PA added substantial

information in relation to childhood metabolic health beyond total volumes of PA. Yet, associations with metabolic health for different bout durations were completely determined by accelerometry epoch settings. These findings challenge our understanding of how children's PA is accumulated, but suggest that processing of accelerometer data should mirror children's activity patterns to provide optimal information about children's health status. We recommend future studies use short epochs (1–10 seconds) when analyzing accelerometry data in children in order to capture VPA correctly. We further recommend that studies adapt the present multivariate analytic approach to develop the field of PA epidemiology.

Availability of data and materials

The datasets used in the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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Figure Legends

Figure 1. *Distribution of physical activity in bouts of different durations based on three different epoch settings (1, 10, and 60-second epochs) and two different bout definitions (allowing and not allowing exceptions of up to 20 % of the time spent outside of a bout). The figure shows that accumulation of sedentary time and physical activity in bouts of different durations varies largely between different epoch settings. Note that activity cannot be accumulated in shorter bouts than the epoch settings allow, so that there are no bouts shorter than 10 and 60 seconds for data analyzed at 10 and 60-second epochs, respectively.*

Figure 2. *Multivariate associations with metabolic health composite score for intensity-specific physical activity analyzed using 1, 10, and 60-second epochs. Associations are displayed as a selectivity ratio plot. The selectivity ratio for each physical activity variable is calculated as the explained variance to residual variance on the predictive (target projected) metabolic health component. A negative bar implies that increased PA is associated with better metabolic health. 15 different bout durations were analyzed for 1-second epoch files, whereas 12 different bout durations were analyzed for 10-second epoch files, and 7 different bout durations were analyzed for 60-second epoch files.*

Supplemental Figure 1-5*. Comparison of multivariate association patterns with metabolic health for SED, LPA, MPA, VPA, and MVPA bout definitions allowing and not allowing exceptions of up to 20 % of the time spent outside of a bout. Associations are displayed as a selectivity ratio plot. The selectivity ratio for each physical activity variable is calculated as the explained variance to residual variance on the predictive (target projected) metabolic health component. A negative bar implies that increased PA is associated with better metabolic health. 15 different bout durations were analyzed for 1-second epoch files, whereas 12 different bout durations were analyzed for 10-second epoch files, and 7 different bout durations were analyzed for 60-second epoch files.*