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Cross-sectional and prospective associations between physical activity, body mass index and waist circumference in children and adolescents

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Summary

Objective

To study the cross-sectional and prospective associations between physical activity (PA) of different intensities, body mass index (BMI) and waist circumference (WC) in children and adolescents using isotemporal substitution modelling.

Methods

Physical activity (accelerometry), BMI and WC were assessed in 6- (n = 970), 9- (n = 2,423) and 15-year-olds (n = 1,544) in 2005/2006 and 2011/2012. Participants aged 9 years in 2005/2006 were followed prospectively to 2011/12 (age 15). Associations between PA of different intensities (light, moderate and vigorous), BMI and WC were examined using isotemporal substitution models.

Results

Substituting 10 min per day of sedentary time with light PA was associated with higher WC (0.17 to 0.29 cm, $p \leq 0.003$)) in all age groups. Substituting 10 min per day of sedentary time with moderate PA was associated with lower WC in 6- and 9-year-olds (−0.32 to −0.47 cm, $p \leq 0.013$)). Substituting 10 min per day of sedentary time with vigorous PA was associated with lower WC in 9- and 15-year-olds (−1.08 to −1.79 cm, $p \leq 0.015$)). Associations were similar with BMI as the outcome. In prospective analyses, substituting sedentary time with light, moderate or vigorous PA at age 9 was not associated with BMI or WC at age 15.

Conclusion

Substituting sedentary time with moderate PA appears favourably associated with adiposity in children, whereas vigorous PA may be required in adolescents. Cross-sectional associations were not replicated in prospective analyses.

Keywords: Accelerometer, body mass index, physical activitysedentary timewaist circumference.

Introduction

The prevalence of overweight and obesity among children and adolescents has increased worldwide over the last 30 years (1). Because adiposity is positively associated with cardio-vascular disease risk already at a young age (2), prevention of childhood and adolescent adiposity needs high priority (3). A number of studies have found higher levels of physical activity (PA) to be favourably associated with adiposity in children and adolescents (4–6), and PA is therefore advocated to play a key role in the prevention of excessive weight gain during childhood and adolescence (7).

Because the amount of time in a day, or in any given time period, is always limited and finite, spending time on one activity (e.g. watching TV) displaces time that could be spent doing other activities (e.g. playing soccer). I.e. it is not possible to add 10 min of moderate-to-vigorous PA (MVPA) to a day without displacing 10 min from other components of PA. However, typical models used in

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observational studies examining associations between PA and adiposity do not address the isotemporal nature in which different components of PA occur. As a result, associations between PA and adiposity from commonly used models do not reflect how varying distributions of different components of PA might have heterogeneous effects on adiposity. As an example, the beta coefficient from a traditional linear regression model used to investigate the association between BMI and moderate PA (MPA) might be −0.05. I.e. persons accumulating 35 min per day of MPA have 0.5 kg m^{-2} lower BMI than persons accumulating 25 min per day of MPA. However, this beta coefficient does not take into account the daily amounts of sedentary time (ST), light PA (LPA) and vigorous PA (VPA). Thus, it is unknown how big the difference in ST, LPA and VPA is between persons accumulating 35 min per day of MPA and persons accumulating 25 min per day of MPA. Recently, however, isotemporal substitution modelling has emerged as a method to examine how substitution of time in one behaviour with an equal amount of time in another associates with adiposity and other health markers (8).

Some recent studies that have used isotemporal substitution modelling indicate that substituting ST with MVPA is favourably associated with adiposity in children (9–13), but not in adolescents (11). However, whether substituting ST with LPA associates with adiposity in children and adolescents remains unclear.

Further, few previous studies have examined isotemporal substitution of ST with time spent in PA of different intensities prospectively (12). These authors observed that substituting ST with MVPA at age 10 years was favourably associated with adiposity at age 11.5 years. However, it remains to be determined whether this association persists over longer periods.

In the Physical Activity among Norwegian Children Study (PANCS) (14), anthropometric and PA data were collected from nationally representative samples of children and adolescents in 2005/2006 (PANCS1) and 2011/2012 (PANCS2), a sub-sample of which participated in both PANCS1 (age 9) and PANCS2 (age 15). Therefore, the aim of this study was to investigate the associations between PA and markers of adiposity using isotemporal substitution modelling in cross-sectional and prospective analysis with a 6-year follow-up.

Methods

Participants

In PANCS1, nationally representative, samples of 9- and 15-year-olds were recruited using a cluster sampling technique with schools as the primary unit. When a school agreed to participate, all fourth and tenth graders were invited to take part in the study. In PANCS2, nationally representative, samples of 6- and 9-year-olds were recruited using the same cluster sampling technique as in PANCS1, whereas 15-year-olds were invited either based on previous participation in PANCS1 at age 9 (prospective sample) or from a random sample of lower secondary schools that had previously participated in PANCS1 (cross-sectional sample) (Figure S1).

The Regional Committee for Medical Research Ethics approved PANCS1, and the Norwegian Social Science Data Services approved both studies. Written informed consents were obtained from all participants and their primary guardians before the start of both data collections.

Anthropometrics

Trained personnel measured height to 0.1 cm (wall-mounted measuring tape), weight to 0.1 kg (Seca 770 and 877 scales (SECA GmbH, Hamburg, Germany)) and waist circumference (WC) to 0.1 cm (minimum circumference between the lowest rib and the iliac crest), and calculated body mass index (BMI (kg m^{-2})). All the anthropometric measurements were performed twice, and the average of the two measurements was recorded. In PANCS1, the participant wore underwear during the measurements, whereas in PANCS2, the participants wore gym shorts and a t-shirt. To accounts for this, 0.3 kg was subtracted from the participants' weight in the latter study. Body mass index criteria from the International Obesity Task Force (15) and the WHO (16) were used to find the proportion of participants affected by overweight and obesity.

Physical activity

Physical activity and ST were assessed using hip-worn ActiGraph accelerometers (ActiGraph, LLC, Pensacola, Florida, USA). In PANCS1, the CSA 7164 model was used, and the participants were instructed to wear the monitor for four consecutive days, including two weekend days. In PANCS2, the GT1M and GT3X+ models were used, and the participants were instructed to wear the monitor for seven consecutive days. The participants were instructed to remove the monitor for sleep and water-based activities only.

The accelerometers were initialized to start recording at 06:00 on the day after the participants received them, and to sampled activity counts in 10-s epochs. To initialize the monitors and to download the accelerometer files, the ActiLife software (ActiGraph, LLC, Pensacola,

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Florida, USA) was used. For further processing, KineSoft (v3.3.76; KineSoft, Rothesay, New Brunswick, Canada) was used. After exclusion of data recorded from 00:00 to 06:00 and intervals of ≥20 consecutive minutes with no activity recorded, files with ≥2 d consisting of ≥480 min d^{-1} of activity recordings were deemed eligible for analysis. Cut-points of <100, 100–1,999, 2,000–5,999 and ≥6,000 counts per minute (CPM) were used to categorize the accelerometer data into ST, LPA, moderate PA (MPA) and vigorous PA (VPA), respectively (17).

Analysis

All statistical analyses were performed using Stata 13.1 (StataCorp. 2013. Stata Statistical Software: TX: StataCorp LP.). Sex differences, differences between age groups, changes from age 9 to 15 and associations between PA, BMI and WC were analysed using linear and logistic regression. Because the participants were recruited using the aforementioned cluster sampling technique, Statas *xtreg re* command (generalized least-square random effects) was used, with school declared (xtset) as the panel. School was also incorporated as a cluster variable in all models using the *vce cluster* option to obtain robust variance estimations. In the prospective analyses, the school participants attended at baseline was used as the cluster variable.

For the cross-sectional analyses, data collected from 9- and 15-year-olds in PANCS1 and PANCS2 were pooled (6-year-olds were only included in PANCS2 (Figure S1)). To quantify the cross-sectional and prospective associations between PA of the different intensities (LPA, MPA and VPA), BMI and WC, an isotemporal substitution approach to the linear regression models was used. Isotemporal substitution modelling has been described in detail elsewhere (8). In short, all quantifiable components of a behaviour, e.g. daily macronutrient intake or PA, are entered into the model simultaneously together with the sum of all components (i.e. total caloric intake or accelerometer wear time), except for the component to be substituted. In the present study, summing time spent in all components of PA (ST + LPA + MPA + VPA = accelerometer wear time) renders time isotemporal (constant). By excluding ST from the model, but keeping accelerometer wear time, the beta coefficients for LPA, MPA and VPA represent the theoretical effect of displacing a fixed duration of ST with a fixed duration of LPA, MPA and VPA, respectively (11,12). To obtain beta coefficients representing 10 min d^{-1} substitutions, each component of PA was multiplied by a constant of 0.1 before they were entered into the models. The dependent (BMI and WC) and independent (LPA, MPA and VPA) variables were entered into the models in their continuous form.

In initial analyses, interaction terms were fitted to assess whether associations were modified by sex. Significant sex by MPA interactions were found in analyses of 6-year-olds ($p \leq 0.039$). No interactions were found in analyses of 9- or 15-year-olds, or in the prospective analyses. Consequently, analyses of 6-year-olds were stratified by sex, whereas all other analyses were performed combining girls and boys, but adjusting for sex. Because assessments were performed throughout the school year, all analyses were adjusted for age. Prospective analyses were also adjusted for the baseline value of the dependent variables (BMI and WC, respectively) and follow-up time. Socioeconomic status (SES) was included as a covariate in preliminary analyses; however because inclusion of this variable did not alter the results to any appreciable extent, it was excluded from our final models. All analyses were also run with BMI and WC *z*-scores as dependent variables (results presented as Supporting Information (Table S1)).

Last, multicollinearity was checked using Statas *correlate* (pairwise correlation) and *collin* commands (variance inflation factors and tolerance statistics). Multicollinearity is likely to be present if the pairwise correlation between two variables is >0.8 (highest observed, $r = 0.53$), if the mean variance inflation factor is >6 (highest observed mean = 1.39), if the highest individual variance inflation factor is >10 (highest observed = 1.59) or if the tolerance statistic is <0.1 (all observed to be >0.62).

Results

Cross-sectional analyses

We invited 2,818 and 5,603 youth to participate in PANCS1 and PANCS2, respectively. Of these 5,897 (70.0%) signed an informed consent and agreed to participate. The participation rates for 6-, 9- and 15-year-olds were 56.4, 79.9 and 67.6%, respectively.

Table 1 displays descriptive characteristics of the study sample by age group and sex. Body mass index did not differ significantly between girls and boys within any of the three age groups ($p \geq 0.059$). We found no difference in WC between girls and boys in the two younger age groups ($p \geq 0.390$); however, WC was significantly larger in boys than in girls in 15-year-olds ($p < 0.001$).

With the exception of VPA in boys ($p = 0.406$), ST and time in PA of different intensities differed significantly between the three age groups in both genders (adjusted

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Table 1 Descriptive characteristics (mean (SD)) of the cross-sectional study samples of 6-, 9- and 15-year-olds

	6-year-olds		9-year-olds		15-year-olds	
	Girls	Boys	Girls	Boys	Girls	Boys
n[a]	495–512	475–494	1,198–1,219	1,225–1,253	778–850	766–824
Age (years)	6.6 (0.4)	6.6 (0.4)	9.6 (0.4)	9.6 (0.4)	15.3 (0.5)	15.4 (0.6)[b]
Height (cm)	120.9 (5.4)	122.2 (5.8)[b]	138.2 (6.6)	139.3 (6.6)[b]	165.3 (6.4)	174.2 (7.7)[b]
Weight (kg)	23.8 (4.2)	24.0 (3.7)	33.8 (6.9)	33.9 (6.7)	57.7 (9.2)	63.5 (12.4)[b]
BMI (kg m^{-2})	16.2 (2.0)	16.0 (1.6)	17.6 (2.7)	17.4 (2.6)	21.1 (3.0)	20.9 (3.5)
Overweight (%)[c]	18.4	12.8[b]	21.8	17.7[b]	20.3	13.9[b]
Obese (%)[c]	4.4	2.7	4.1	4.2	2.6	3.8
Overweight (%)[d]	22.6	20.6	27.1	25.8	17.2	19.0
Obese (%)[d]	5.7	4.3	6.2	8.1[b]	2.2	6.1[b]
WC (cm)	54.4 (5.0)	54.8 (4.2)	61.1 (7.3)	61.5 (6.9)	71.1 (7.1)	74.2 (9.1)[b]
ST (min d^{-1})	392.3 (48.9)	378.4 (51.0)[b]	452.9 (62.9)	432.9 (68.5)[b]	565.6 (72.5)	551.2 (77.6)[b]
LPA (min d^{-1})	250.6 (33.7)	258.5 (33.1)	244.2 (42.6)	249.2 (46.2)	169.2 (44.9)	179.2 (47.0)[b]
MPA (min d^{-1})	73.7 (17.5)	92.2 (22.6)[b]	65.4 (18.9)	82.5 (24.6)[b]	53.4 (20.0)	58.2 (22.3)[b]
VPA (min d^{-1})	7.7 (4.8)	7.7 (5.0)	7.4 (5.0)	9.4 (6.8)[b]	6.0 (5.8)	8.8 (7.9)[b]
WT (min d^{-1})	724.3 (53.1)	736.9 (51.7)[b]	769.8 (60.1)	774.0 (60.8)	794.3 (74.6)	797.5 (80.4)

[a]All the participants displayed had valid assessments of physical activity, but the *n* varies for BMI and WC.
[b]Significantly different from girls within the same age group ($p \leq 0.035$).
[c]Based on age- and sex-specific BMI cut-points from the International Obesity Task Force (overweight includes obese) (15).
[d]Based on age- and sex-specific BMI cut-points from the WHO (overweight includes obese) (16).
BMI, body mass index; WC, waist circumference; ST, sedentary time; LPA, light physical activity; MPA, moderate physical activity; VPA, vigorous physical activity; WT, accelerometer wear time.

for accelerometer wear time, $p \leq 0.001$). Six-year-olds spent less time sedentary and more time in PA than 9- and 15-year-olds ($p < 0.001$); 9-year-olds spent less time sedentary and more time in PA than 15-year-olds ($p < 0.001$).

Table 2 displays the beta coefficients and 95% confidence intervals from the isotemporal substitution models. BMI: Substituting ST with LPA was associated with a higher BMI in 6-year-old girls and boys ($p \leq 0.012$), and in 9-year-olds ($p < 0.001$), but not in 15-year-olds ($p = 0.206$). Substituting ST with MPA was associated with a lower BMI in 6-year-old girls and 9-year-olds ($p \leq 0.034$), but not in 6-year-old boys or 15-year-olds ($p \geq 0.152$). Substituting ST with VPA was associated with a lower BMI in 9- and 15-year-olds ($p < 0.001$), but not in 6-year-olds ($p \geq 0.099$). WC: Substituting ST with LPA was associated with higher WC in 6-year-old girls, 9- and 15-year-olds ($p \leq 0.002$), but not in 6-year-old boys ($p = 0.078$). In 6-year-old girls and 9-year-olds, substituting ST with MPA was associated with lower WC ($p \leq 0.013$). This was not observed in other age- or sex groups ($p \geq 0.580$). Substituting ST with VPA was associated with lower WC in 9- and 15-year-olds ($p \leq 0.015$), but not in 6-year-olds ($p \geq 0.084$). In sensitivity analyses, substituting WC with waist-to-height ratio (18) did not change any of the observed associations (data not shown).

Prospective analyses

Of the 1,306 participating in PANCS1 at age 9 years, 1,119 were found and invited to participate in PANCS2 at age 15 years. Of these, 731 (65.3%) agreed to participate. Table 3 displays descriptive characteristics of the prospective study sample at baseline and follow-up. Of those with valid PA, BMI and WC assessments at baseline, 503 (239 girls) and 476 (223 girls) had valid BMI and WC assessments at follow-up, respectively.

From baseline to follow-up, BMI and WC increased significantly in girls and boys ($p < 0.001$). These changes were accompanied by a significant increase in ST and significant decreases in LPA, MPA and VPA ($p < 0.001$). However, substituting ST with LPA, MPA or VPA at age 9 was not associated with BMI ($p \geq 0.059$) or WC ($p \geq 0.321$) at age 15 (Table 2).

Discussion

Results from the cross-sectional analyses suggest favourable associations when substituting ST with MPA and VPA, but also somewhat counter intuitive, unfavourable associations when substituting ST with LPA. However, results from the prospective analyses do

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Table 2 Cross-sectional and prospective associations between 10 min day^{-1} substitutions of sedentary time, body mass index and waist circumference

Replacing 10 min d^{-1} of sedentary time with 10 min d^{-1} of:	*n*	Body mass index (BMI (kg m^{-2})) β (95% CI)	*n*	Waist circumference (WC (cm)) β (95% CI)
Cross-sectional analyses[a]				
6-year-old girls				
Light PA	505	0.10 (0.04, 0.17)**	495	0.29 (0.13, 0.45)**
Moderate PA	505	−0.18 (−0.35, −0.01)*	495	−0.47 (−0.85, −0.10)*
Vigorous PA	505	−0.21 (−0.58, 0.16)	495	−0.15 (−1.20, 0.90)
6-year-old boys				
Light PA	485	0.08 (0.02, 0.15)*	475	0.15 (−0.02, 0.33)
Moderate PA	485	0.03 (−0.05, 0.12)	475	0.06 (−0.16, 0.29)
Vigorous PA	485	−0.32 (−0.71, 0.06)	475	−0.79 (−1.68, 0.10)
9-year-olds				
Light PA	2,445	0.05 (0.02, 0.07)**	2,423	0.17 (0.10, 0.25)**
Moderate PA	2,445	−0.08 (−0.15, −0.02)*	2,423	−0.32 (−0.46, −0.18)**
Vigorous PA	2,445	−0.83 (1.04, −0.63)**	2,423	−1.79 (−2.36, −1.23)**
15-year-olds				
Light PA	1,592	0.03 (−0.02, 0.07)	1,544	0.17 (0.06, 0.28)**
Moderate PA	1,592	0.06 (−0.02, 0.15)	1,544	0.02 (−0.20, 0.24)
Vigorous PA	1,592	−0.56 (−0.87, −0.25)**	1,544	−1.08 (−1.94, −0.21)*
Prospective analyses[b]				
Light PA	503	0.05 (−0.00, 0.11)	476	0.07 (−0.08, 0.23)
Moderate PA	503	−0.05 (−0.14, 0.04)	476	−0.09 (−0.37, 0.20)
Vigorous PA	503	0.16 (−0.17, 0.49)	476	−0.43 (−1.29, 0.42)

[a]Adjusted for sex (not in analyses of 6-year-olds), age and accelerometer wear time.
[b]Adjusted for sex, age at baseline, follow-up time and BMI/WC at baseline.
*$p \leq 0.040$.
**$p \leq 0.003$.
CI, confidence interval; PA, physical activity.

Table 3 Descriptive characteristics (mean (SD)) of the prospective study sample at baseline (9-year-olds) and follow-up (15-year-olds)

	Girls		Boys	
	Baseline	Follow-up	Baseline	Follow-up
n[a]	223–239	223–239	253–264	253–264
Age (years)	9.6 (0.4)	15.2 (0.7)[b]	9.7 (0.4)	15.2 (0.7)[b]
Height (cm)	138.3 (6.8)	165.3 (6.2)[b]	139.9 (6.0)	173.9 (8.0)[b]
Weight (kg)	33.3 (6.7)	57.7 (9.5)[b]	33.5 (5.8)	61.8 (10.9)[b]
BMI (kg m^{-2})	17.3 (2.6)	21.1 (3.1)[b]	17.0 (2.1)	20.4 (2.9)[b]
Overweight (%)	15.9	22.9[b]	13.3	10.6
Obese (%)	3.3	3.8	1.8	1.1
WC (cm)	62.2 (7.0)	69.0 (6.2)[b]	61.3 (6.6)	72.5 (7.5)[b]
ST (min d^{-1})	426.3 (64.2)	580.2 (61.0)[b]	416.6 (70.4)	556.7 (73.8)[b]
LPA (min d^{-1})	266.6 (41.2)	152.7 (35.3)[b]	272.8 (48.6)	167.3 (39.4)[b]
MPA (min d^{-1})	67.5 (19.8)	55.2 (18.7)[b]	84.3 (25.6)	61.8 (22.6)[b]
VPA (min d^{-1})	9.4 (5.5)	5.5 (5.4)[b]	11.5 (7.5)	8.7 (7.9)[b]
WT (min d^{-1})	769.9 (63.7)	793.5 (70.5)	785.1 (59.5)	794.5 (78.1)

[a]All the participants displayed had valid assessments of physical activity at both time points, but the *n* varies for BMI and WC.
[b]Significant change from baseline ($p < 0.007$).
BMI, body mass index; WC, waist circumference; ST, sedentary time; LPA, light physical activity; MPA, moderate physical activity; VPA, vigorous physical activity.

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not confirm the cross-sectional associations observed and do not indicate that substituting ST with LPA, MPA or VPA during childhood is associated with development of adiposity between childhood and adolescence.

Compared to previous studies using isotemporal modelling to study the association between PA and adiposity in children and adolescents, our finding that substituting ST with LPA is positively associated with BMI and WC is surprising. Others, using both field-based (BMI, WC) and more comprehensive measures of adiposity (dual-energy X-ray absorptiometry (DXA)), have found either no association (10–13) or a negative association (9). However, recently presented results from the Iowa Bone Development Study have actually also indicated a positive association between LPA and adiposity (19). Other behaviours positively associated with BMI and WC may be common during LPA, e.g. consumption of energy dense snacks/beverages. This has been suggested to confound associations between TV viewing, a frequently used proxy measure for ST, and cardio-metabolic risk factors in children and youth (5,20). Similar confounding may also be present in our analyses. However, it has been shown that the classification accuracy of LPA assessed with ActiGraph accelerometers is lower than for ST and MVPA (21). Therefore, it is also possible that some of the time classified as LPA was in fact ST.

Our finding that substituting ST with MPA and/or VPA is favourably associated with BMI and WC is, to some extent, in accordance with previous studies (9–13). However, because only one previous study modelled substitution of ST with MPA and VPA separately in children (not merged into MVPA) (9), our results extend previous observations. At first glance, it might seem like the associations between MPA, BMI and WC are sex dependent in 6-year-olds, as substitution of ST with MPA was favourably associated with BMI and WC in girls, but not boys. However, this difference may be explained by the very high amount of daily MPA accumulated by boys compared to girls, and that a higher proportion of girls were classified as overweight (Table 1). Six-year-old girls and boys had similar levels of VPA, and VPA was not significantly associated with BMI or WC in either sex. In 6-year-old boys, but not girls, the 95% confidence intervals might indicate that the lack of association between VPA, BMI and WC results from a lack of statistical power.

Our finding that substitution of ST with MPA and VPA was favourably associated with BMI and WC in a dose-dependent fashion among in 9-year-olds agrees with results from a previous study in Finnish children (9). In 15-year-olds, however, our results suggest that more vigorous intensity PA is required to favourably affect BMI and WC. This difference might reflect both physiological and behavioural differences between children and adolescents that can affect adiposity (22). The lack of association between MPA, BMI and WC among 15-year-olds is supported by findings in American adolescents (11). However, that study did not model MPA and VPA separately; thus, it is unknown if the beneficial associations we observed when substituting ST with VPA translate to their study population.

None of the cross-sectional associations observed were replicated in prospective analyses. This lack of temporality is important to consider, and additional prospective analyses should investigate whether the associations between PA, BMI and WC (and other markers of adiposity) are reverse or bi-directional in children and adolescents, which has been suggested previously (5,23).

However, although our results agree with some previous studies (5,23), they contrast the one previous study using isotemporal substitution modelling to study the prospective association between PA and adiposity in children (12). They also contrast some other previous studies that used other analytical approaches (24,25). This discrepancy may possibly relate to the age of participants and the duration of follow-up. Even though our results indicate that childhood PA is a poor predictors of adolescent BMI and WC, it is possible that PA measured during early childhood can predict adiposity later in childhood (24), and that PA can predict adiposity in the short term (e.g. follow-up $\leq$2 years) (4,12,25). However, it is also possible that more sensitive adiposity measures (e.g. DXA) than used in the present study are necessary to detect prospective associations between childhood PA and adolescent adiposity (25,26). Last, it is important to consider that the exposure only represents a snapshot of habitual PA, and that the number of participants included in the prospective analyses was rather moderate.

A number of studies have found unfavourable associations between adiposity and cardio-metabolic risk in children and adolescents, and a recent systematic review concluded that whatever the definition used for abdominal adiposity and whatever the methods used for anthropometric measurements, central body fat deposition in children and adolescents increases cardio-metabolic risk (27). However, limited data on the magnitude of change in cardio-metabolic risk factors associated with absolute incremental change in BMI and WC (i.e. ±1 kg m^{-2} and ±1 cm) in children and adolescents are available. Therefore, it is difficult to translate the observed differences in adiposity markers associated with substitution of ST for MPA and VPA to small, medium or large clinical importance. However, the

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intraclass correlation coefficient for within-individual differences in accelerometer assessed PA is approximately 0.5 (28); thus, the true magnitude of the associations may be at least twice as strong as the associations observed (if we assume that all measurement error stems from within-individual variability).

Previous studies investigating how substituting ST with MPA, VPA or MVPA associates with adiposity have modelled 10, 15, 30 and 60 min d^{-1} substitutions (9–13). Unsurprisingly, modelling larger amounts of time substituted results in larger regression coefficients (multiplying the components of PA by a factor of 0.3 or 0.6 rather than 0.1 before entering them into linear models renders exactly 3 and 6 times larger beta coefficient). However, it is debatable whether 30–60 min d^{-1} substitutions are realistic, and 10 min d^{-1} substitutions may be more achievable. Mean daily VPA was considerably lower than mean daily MPA in all three age groups, but compared to substituting ST with MPA, substituting ST with VPA was associated with much larger (theoretical) decreases in BMI and WC in 9-year-olds. This suggests that efforts made to promote even small daily increases in VPA are important. The favourable associations observed when substituting ST with VPA, but not MPA, in 15-year-olds, support this further. To facilitate comparisons of our results with results from other studies that have modelled larger substitutions, we present results from 30 and 60 min d^{-1} substitutions in Tables S2 and S3 (Supporting Information).

One of the strengths of this study is the large, nationally representative samples of children and adolescents. Further, our study is novel as we used isotemporal substitution modelling to examine how substituting ST for an equal amount of LPA, MPA or VPA during childhood associates with BMI and WC measured 6 years later during adolescence. The accelerometry used to assess ST, LPA MPA and VPA, and the measurement of BMI and WC are strengths, as this reduces measurement error caused by biases associated with self-report (29).

This study also has some important limitations. First, hip-worn accelerometers mainly capture ambulatory PA. Therefore, it is unavoidable that upper body movement (e.g. throwing or climbing), load carrying activities (e.g. carrying a backpack) and other activities with little vertical hip movement (e.g. cycling) is underestimated. Further, there is currently no consensus on which cut-points that best discriminate between ST, LPA, MPA and VPA in children and adolescents, and we acknowledge that choosing other cut-points might have altered the associations (30). Also, we used the same cut-points to classify PA in data collected with three different ActiGraph models, which may cause misclassification (31). However, stratifying the analyses by accelerometer model did not change the results. Last, there is no guaranty against misclassification of time spent motionless as non-wear by the wear-time algorithms applied to accelerometer data. For children, it is common to classify fairly short bouts with no activity recorded as non-wear (32), the rationale behind this being that it seems unlikely for a child to stay absolutely still for more than 10 or 20 consecutive minutes (33). Although longer bouts do increase the risk of classifying true non-wear as ST in children, short bouts may increase the risk of classifying true ST as non-wear. There is currently no consensus on what non-wear algorithm to use for children, but the combination of non-wear, valid day and number of valid days-criteria chosen in our study has been shown to give a reliable estimate of children's habitual PA (34).

Other limitations include the use of indirect measures of adiposity and that we were unable to control for putative confounding factors such as energy intake, sleep and genetic factors. Finally, because this is an observational study, it is impossible to control for things that happened before baseline. For example, a low PA level may theoretically have caused a weight gain already before the baseline measurement in the prospective analysis.

Conclusion

This study suggests that isotemporal substitution of ST with MPA and VPA is favourably associated with BMI and WC in children. In adolescents, favourable associations were only observed when ST was substituted with VPA. However, because these cross-sectional associations were not replicated in prospective analyses, we are unable to determine the direction of associations.

Conflicts of Interest Statement

No conflict of interest was declared.

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Supporting Information

Additional Supporting Information may be found online in the supporting information tab for this article.

Figure S1: Flow-chart of the study samples in the Physical Activity among Norwegian Children Studies. * 1,119 of the 1,306 9-year-olds that participated in PANCS1 were found and invited to participate in PANCS2 as 15-year-olds. ** Includes participants from the cross-sectional samples in PANCS1 and 2, and the prospective sample followed from PANCS1 to PANCS2 (data from follow-up assessments).

Table S1: Cross-sectional and prospective associations between 10 min day^{-1} substitutions of sedentary time, BMI *z*-scoresc and WC *z*-scoresc.

Table S2: Cross-sectional and prospective associations between 30 min day^{-1} substitutions of sedentary time, body mass index and waist circumference.

Table S3: Cross-sectional and prospective associations between 60 min day^{-1} substitutions of sedentary time, body mass index and waist circumference.

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