Accelerometer-based sedentary time and physical activity from childhood through young adulthood with progressive cardiac changes: a 13-year longitudinal study

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Aims	Longitudinal evidence on the relationship of sedentary time (ST), light-intensity physical activity (LPA), and moderate-to-vigorous-intensity physical activity (MVPA) with changes in cardiac structure and function in the paediatric population is scarce. This evidence is clinically important due to the impact ST can have on the long-term prognosis of healthy young population in the lifetime continuum. This prospective observational study examined the relationships of cumulative ST, LPA, and MVPA from childhood with longitudinal changes in cardiac structure and function.
Methods and results	This is a secondary analysis from the Avon Longitudinal Study of Parents and Children, UK birth cohort of 1682 children aged 11 years. Participants who had at least one follow-up timepoints accelerometer-measured ST, LPA, and MVPA over a period of 13 years and repeated echocardiography-measured cardiac structure and function at ages 17- and 24-year clinic visit were included. Left ventricular mass indexed for height$^{2.7}$ (LVMI$^{2.7}$) and left ventricular (LV) diastolic function from mitral E/A ratio (LVDF) were computed. Among 1682 children (mean [SD] age, 11.75 [0.24] years; 1054 [62.7%] females), the cumulative one-min/day increase in ST from ages 11 to 24 years was associated with progressively increased LVMI$^{2.7}$ {effect estimate 0.002 g/m$^{2.7}$ [confidence interval (CI) 0.001–0.003], $P < 0.001$}, irrespective of sex, obesity, and hypertensive status. Cumulative one-min/day increase in LPA was associated with a decreased LVMI$^{2.7}$ (−0.005 g/m$^{2.7}$ [−0.006 to −0.003], $P < 0.0001$) but an increased LVDF. Cumulative one-minute/day increase in MVPA was associated with progressively increased LVMI$^{2.7}$ (0.003 g/m$^{2.7}$ [0.001–0.006], $P = 0.015$).
Conclusion	ST contributed +40% to the 7-year increase in cardiac mass, MVPA increased cardiac mass by +5%, but LPA reduced cardiac mass by −49%. Increased ST may have long-term pathologic effects on cardiac structure and function during growth from childhood through young adulthood; however, engaging in LPA may enhance cardiac health in the young population.
Lay summary	The aim of this longitudinal study including 1682 children and adolescents was to examine the effect of sedentary time (ST), light-intensity physical activity (LPA), moderate-to-vigorous-intensity physical activity (MVPA) on changes in cardiac structural and functional properties during growth until young adulthood.
	• Cumulative ST from childhood contributed a maximum of 40% (+1.29 g/m$^{2.7}$ out of the total 7-year increase in cardiac mass of 3 g/m$^{2.7}$) during growth from adolescence to young adulthood. Cumulative LPA from childhood was associated with decreased cardiac mass (−0.005 g/m$^{2.7}$), amounting to a −49% average reduction (−1.49 g/m$^{2.7}$ out of 3 g/m$^{2.7}$) in the increase in cardiac mass across the 7-year observation period. Each minute of cumulative MVPA from childhood was associated with a 5% progressively increased cardiac mass, amounting to +0.15 g/m$^{2.7}$ out of 3 g/m$^{2.7}$ increase during growth from adolescence to young adulthood.

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- Participation in LPA of at least 3 h/day and decreasing ST was longitudinally associated with healthier cardiac indices in the young population. The contribution of ST to increased cardiac mass is eight times more than the MVPA-associated physiological increase. Hence, progressively increasing childhood sedentariness may independently and pathologically contribute to worsening cardiac structural and functional alterations in the young population. Childhood sedentariness causes an increased body fat, inflammation, blood pressure, lipid levels, arterial stiffness, and subsequently cardiac enlargement, thereby increasing the risk of adverse cardiovascular health consequences in later life.

Graphical Abstract
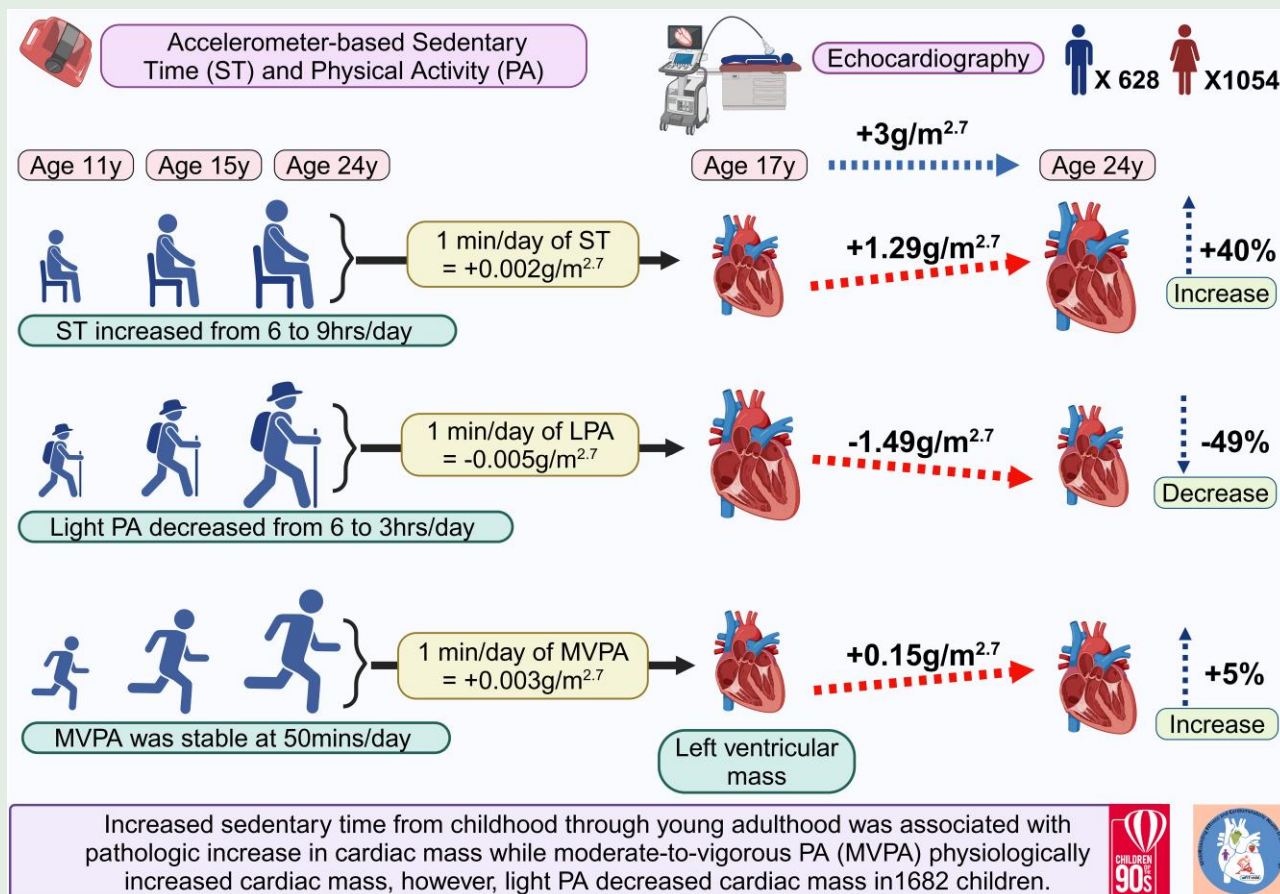
Keywords   Movement behaviour • Left ventricular hypertrophy • Paediatrics • Health guidelines • Hypertension • Obesity • Health promotion

Introduction

Among adults, higher left ventricular mass (LVM) is a strong predictor of cardiovascular mortality and regressive changes in LVM among adults have been associated with low rates of clinical events.[1,2] In the paediatric population, due to the rarity of clinical events, alterations in cardiac structure and functional indices are surrogate measures for signs of early cardiac damage.[3–7] Recently, elevated blood pressure, increasing lipids, and higher arterial stiffness in adolescence were shown to temporally precede premature cardiac damage in young adulthood.[6–8] The primary prevention of premature cardiac damage is of public health importance for the promotion of life-long cardiovascular health and decreasing the global burden of cardiovascular diseases.[6–8] The benefit of increasing physical activity (PA) on cardiometabolic and vascular health

among children and adolescents has been established, and emerging longitudinal studies are supporting this evidence.[9–15] This necessitates the recent recommendation of an average daily 60 min/day of moderate-to-vigorous-intensity PA (MVPA) in <18-year-olds but rarely do the paediatric population meet this daily threshold.[9,16]

Little is known about the independent longitudinal effect of modifiable lifestyle factors such as device-measured sedentary time (ST) and PA on changes in repeated echocardiography-measured cardiac structure and function in a general paediatric population.[9,15,17–21] Moreover, the sex-specific relationship of ST and MVPA with cardiac structural and functional indices in the paediatric population remains unclear.[22] It is also important to clarify these relationships in youth at risk of obesity and hypertension.[8,11,23,24] A recent cross-sectional study of 530 adolescents concluded that ST was associated with a 30% higher

cardiac mass, MVPA was associated with a 10% higher cardiac mass, and light-intensity PA (LPA) was associated with better cardiac function.[23] Since children and adolescents accumulate more time engaging in LPA than MVPA, it is essential to clarify whether cumulative increases in LPA and MVPA independently associate with progressively better cardiac structure and function in youth.[17,23] LPA from childhood was recently shown to be significantly more effective than MVPA in lowering fat mass, cholesterol levels, inflammation, and vascular stiffness and may be of public health importance.[11–15,25]

Due to the existing knowledge gaps, the following research questions remained unanswered: (i) what are the longitudinal relationships of each of ST, LPA, and MVPA with cardiac structural and functional indices? and (ii) do the relationships differ by sex, obesity, and hypertensive status? Thus, this present study examined the longitudinal associations of objectively and repeatedly measured ST, LPA, and MVPA from ages 11 to 24 years with cardiac structure and function in young adulthood (age 24 years) and changes in cardiac structure and function from ages 17 to 24 years (adolescence through young adulthood) using data from the Avon Longitudinal Study of Parents and Children (ALSPAC) birth cohort, England, UK.

Methods

Study cohort

Details of the ALSPAC birth cohort have been published earlier.[26–29] The ALSPAC birth cohort investigates factors that influence childhood development and growth. Altogether, 14 541 pregnancies from women residing in Avon, southwestern England, UK, who had a total of 14 676 foetuses, with an expected date of delivery between 1 April 1991 and 31 December 1992 were enrolled. When the oldest children were approximately 7 years of age, an attempt was made to bolster the initial sample with eligible cases who had failed to join the study originally resulting in 913 additional pregnancies. The total sample size for analyses using any data collected after 7 years of age was 15 454 pregnancies, resulting in 15 589 foetuses. Of these, 14 901 were alive at 1 year of age. Regular clinic visits of the children commenced at 7 years of age and are still ongoing. Study data at 24 years were collected and managed using REDCap electronic data capture tools.[30] For this analysis, 1682 participants were included who had at least one time-point measure of sedentary time (ST), light-intensity physical activity (LPA), moderate-to-vigorous-intensity physical activity (MVPA) during clinic visits at 11, 15, or 24 years and complete measure of LVM indexed for height$^{2.7}$ (LVMI$^{2.7}$), relative wall thickness (RWT), left ventricular diastolic function E/A ratio (LVDF), and left ventricular filling pressure E/e′ ratio (LVFP) measurements (*Figure 1*).

Ethical approval for the study was obtained from the ALSPAC Ethics and Law Committee and the Local Research Ethics Committees. Consent for biological samples was collected in accordance with the Human Tissue Act (2004). Informed consent for the use of data collected via questionnaires and clinics was obtained from participants following the recommendations of the ALSPAC Ethics and Law Committee at the time.

Movement behaviour measures

ST, LPA, and MVPA were assessed with MTI ActiGraph AM7164 2.2 (LLC, Fort Walton Beach, FL, USA) accelerometer worn for 7 days at 11- and 15-year clinic visits, whereas at 24 years movement behaviour was assessed using ActiGraph GT3X + accelerometer device worn for four consecutive days.[11–13] Accelerometer was worn around the waist and detects acceleration and deceleration in a vertical plane as a combined function of movement frequency and intensity. There is a strong absolute agreement between the ActiGraph^{TM} models (intra-class correlation coefficient 0.99 [95% confidence interval (CI) = 0.98–0.99], thus making it acceptable to use different models within a study.[31] The device was worn during waking hours in at least two week days and one weekend day. A valid day was defined as providing data for at least 10 h per day (excluding sequences of 10 or more min with consecutive zero counts), and children were only included in the analyses if they provided at least three valid days of recording. The devices capture movement in terms of acceleration as a combined

function of frequency and intensity. Data were recorded as counts that result from summing post-filtered accelerometer values (raw data at 30 Hz) into 60-s epoch units. Data were processed using Kinesoft software, version 3.3.75 (Kinesoft), according to established protocol. Activity counts per minute (cpm) threshold validated in young people were used to calculate the amount of time spent: for MVPA, > 2296 cpm; for LPA, 100–2296 cpm; and for ST, 0 to − < 100 cpm at ages 11 and 15 years, but 2020 cpm for the 24-year assessment.[29,32,33] The Evenson cutpoint used in stratifying activity threshold has shown the best overall performance across all intensity levels and was suggested as the most appropriate cutpoint for youth.[34,35] The MVPA established cutpoints[9] of ≥60 min/day, 40–<60 min/day, and <40 min/day as the reference category were computed at ages 11, 15, and 24 years, respectively. There are no established cutpoints for ST and LPA; therefore, categorical analyses were not presented.

Cardiac structural and functional measures

At 17 years, echocardiography was performed according to the American Society of Echocardiography guidelines[36,37] by one of two experienced echocardiographers using an HDI 5000 ultrasound machine (Phillips Healthcare, Amsterdam, The Netherlands) equipped with a P4-2 phased array ultrasound transducer. At 24 years, echocardiography was performed by two experienced echocardiographers using a Philips EPIQ 7G ultrasound system equipped with a X5-1 transducer. Philips Q-station was used for the M-mode, 2D, and Doppler echo analyses, while TomTec software was used for the 3D echo analyses.[23,38] Measures of cardiac structure were LVMI$^{2.7}$ and RWT computed from septal wall thickness, posterior wall thickness, and LV diastolic diameter as previously described.[7] Measures of cardiac function were LVDF and LVFP. Pulsed Doppler examinations of transmitral flow were recorded from the apical four-chamber view. For LV measurements, the sample volume was positioned between the mitral annulus and the tips of the mitral leaflets with the position adjusted to maintain the sample volume at an angle as near parallel to transmitral flow as possible with the participant in passive end expiration. The peak flow velocity of the early (E) and atrial (A) waves was measured from the three consecutive cardiac cycles displaying the highest measurable velocity profiles. A similar measurement (e′) was conducted at the tricuspid valve. Tissue Doppler echocardiography was performed in the four-chamber view on the lateral, inferior, and septal LV walls to obtain myocardial wall velocities. Data were acquired with the beam parallel to the wall of interest and with optimal settings to ensure no over-gain of the low-velocity signals. A 5 mm sample volume was placed at the level of the mitral valve annulus, and a loop of 8–10 cardiac cycles was recorded. The reproducibility of echocardiographic examinations was assessed by recalling 30 participants and repeating their measurements. The intra-class correlation of repeated measurements ranged from 0.75 to 0.93 (intra-observer) and 0.78 to 0.93 (inter-observer).[39]

Anthropometric, cardiometabolic, and lifestyle factors measures

Anthropometry (height and weight) of participants at ages 17 and 24 years was assessed by observing standard protocols, and body mass index (BMI) was computed as weight in kilograms per height in metres squared. BMI of ≥25 kg/m^2 was categorized as overweight and obese at age 24-year clinic visit. Heart rate and systolic and diastolic blood pressure were measured at ages 17 and 24 years using an Omron 705-IT as previously detailed.[29,40,41] Elevated and hypertensive systolic blood pressure was categorized as systolic blood pressure ≥130 mmHg.[42] Fasting blood samples at ages 17 and 24 years were collected, spun, and frozen at −80°C and later assayed for lipids, glucose, insulin, and high-sensitivity C-reactive protein as detailed previously.[29,40,43,44] Total fat mass and lean mass were assessed using a dual-energy X-ray absorptiometry scanner at 17- and 24-year clinic visits. Questionnaires to assess smoking behaviour were administered at 17- and 24-year clinic visits. Question related to smoking in the last 30 days was used as a marker of current smoking status. At 17-year clinic visit, participants were briefly asked about their personal and family (mother, father, and siblings) medical history such as a history of hypertension, diabetes, high cholesterol, and vascular disease. The participant's mother's socioeconomic status was
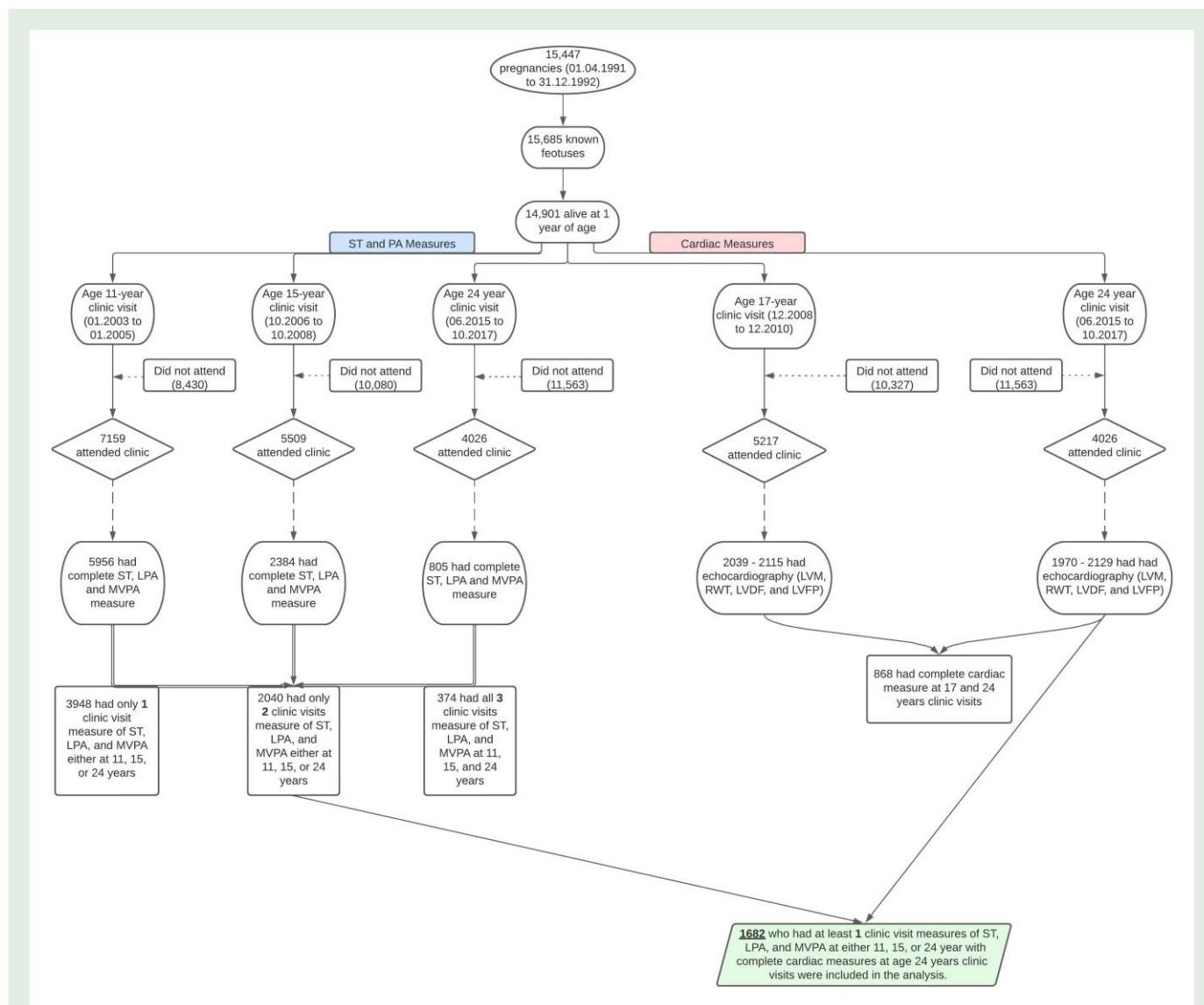
Figure 1 Flowchart of Avon Longitudinal Study of Parents and Children (ALSPAC) birth cohort participants. ST, sedentary time, LPA, light-intensity physical activity; MVPA, moderate-to-vigorous-intensity physical activity; LVDF, left ventricular diastolic function; LVFP, left ventricular filling pressure; LVM, left ventricular mass; RWT, relative wall thickness.

grouped according to the 1991 British Office of Population and Census Statistics classification.[45]

Statistical analysis

Cohort descriptive characteristics were summarized as means and standard deviation, medians and inter-quartile ranges, or frequencies and percentages. Sex differences were explored using independent t-tests, Mann–Whitney U-tests, or χ^2 tests for normally distributed, skewed, or dichotomous variables, respectively. Multicategory variables were analysed using a one-way analysis of variance. Normality was assessed by histogram curve, quantile–quantile plot, and Kolmogorov–Smirnov tests. A logarithmic transformation of skewed covariates was conducted, and normality was confirmed prior to further analysis.

The separate associations of the 13-year cumulative ST, LPA, and MVPA progression (ages 11–24 years) with each of the LVMI[2.7], RWT, LVDF, and LVFP progressive changes repeatedly measured during ages 17- and 24-year follow-up were examined using generalized linear mixed-effect models (GLMMs) for repeated measures. The GLMM is robust for handling highly correlated variables such as ST and LPA with a Pearson correlation of

−0.70. The optimal model was one with sex and predictor as a factor and a random intercept modelled on the subject level. Moreover, the best model fit was accepted for the model with the lowest Bayesian information criteria. A random effect variance component type was selected, and the effect of the predictor trajectory on the progressive change in outcome variables was determined. To test for fixed effects and coefficients, robust covariance estimation was selected to handle violations of model assumptions. A Little's missing completely at random test was conducted to ascertain data missingness and concluded that the variables were not missing completely at random.[46] While the GLMM is robust for handling missing at random predictor, covariate, and outcome data, an additional 20 cycles of multiple imputations were conducted to account for missing data predictor, covariates, and outcomes. Regression-modelled 20 cycles of multiple imputations were conducted using SPSS, version 27 (IBM Corp, Armonk, NY, USA), with 10 iterations generating 20 imputed data sets. The pooled imputed results after conducting multiple imputations and the GLMM were presented. The specified constraints for the imputation process were the observed minimum and maximum values, resulting in an estimate that was 98% efficient as computed with Rubin's formula.[11,46] The analysis strategy accounted for baseline ST, LPA, MVPA predictors, vascular outcomes,
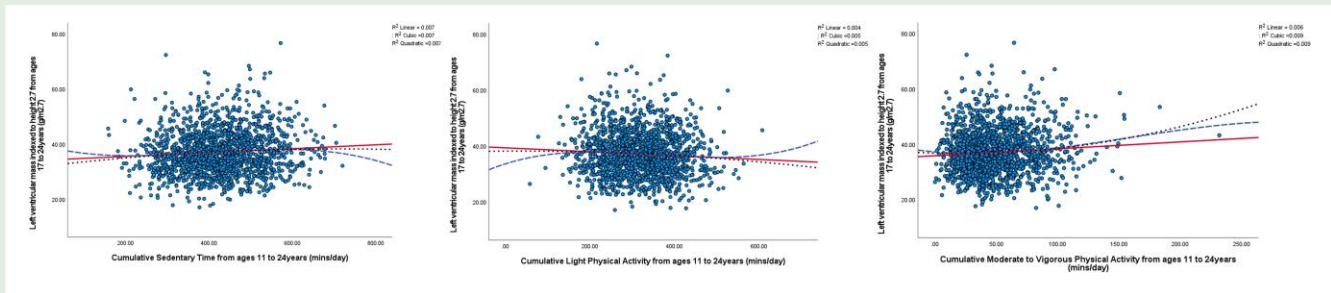
Figure 2 Unadjusted linear, cubic, and quadratic regression plots of cumulative sedentary time, light-intensity physical activity, and moderate-to-vigorous-intensity physical activity (min/day) from ages 11 to 24 years with progressive increase in left ventricular mass (g/m$^{2.7}$) from ages 17 to 24 years. Linear regression is solid line, quadratic regression is short dash line, and cubic regression is long dash line.

and covariates and their repeated measures. Model 1 was adjusted for sex, and other time-varying covariates measured at both baseline and follow-up such as age, low-density lipoprotein cholesterol, insulin, triglyceride, high-sensitivity C-reactive protein, high-density lipoprotein cholesterol, heart rate, systolic blood pressure, glucose, fat mass, lean mass, smoking status, family history of hypertension/diabetes/high cholesterol/vascular disease, and socioeconomic status. Model 2 was an additional mutual adjustment for ST, LPA, or MVPA depending on the predictor. Sex-based analyses were not adjusted for sex. Linear, cubic, and quadratic regression plots were presented for each cumulative ST, LPA, and MVPA progression (ages 11–24 years) with each of the LVMI$^{2.7}$, RWT, LVDF, and LVFP progression at ages 17–24 years to visualize the adequacy of the linearity assumption (*Figure 2* and Supplementary material online, *Figures S1–S3*).

To assess the dose–response relationships of MVPA with each of the progression in LVMI$^{2.7}$, RWT, LVDF, and LVFP measured from ages 17 through 24 years using GLMMs for repeated measures, the MVPA established cutpoints[9] of ≥60 min/day, 40– < 60 min/day, and <40 min/day as the reference category were computed at ages 11, 15, and 24 years, respectively. Each category at baseline (age 11 years) was combined with their corresponding categories at ages 15- and 24-year follow-up in a restructured format. The MVPA categorization resulted in persistent ≥60 min/day, persistent 40–<60 min/day, and persistent <40 min/day from ages 11 through 24 years.

Analyses were repeated in a subset of participants with overweight and obesity and elevated and hypertensive systolic blood pressure. Moreover, among 766 participants with at least two timepoint complete cardiac measures of ST, LPA, and MVPA at 17 years the longitudinal analyses were repeated and are presented in the Supplementary material online, Appendix. Sequential Sidak correction was applied to correct for multiple comparisons. Covariates were selected based on previous studies.[29,36,37,44,47] Collinearity diagnoses were performed and accepted results with a variance inflation factor <5. Differences and associations with a two-sided P-value <0.05 were considered statistically significant, and conclusions were made based on effect estimates and their CIs. The effect estimate for continuous predictor variable analyses describes a 1-min/day change in ST, LPA, or MVPA over 13 years in relation to the computed point estimate unit change in cardiac measure over 7 years. The effect estimates from the categorical predictor variable describe a persistent MVPA higher category in contrast to the reference or lowest category over 13 years in relation to the computed point estimate unit change in cardiac measure over 7 years. Analyses involving 20% of a sample of 10 000 ALSPAC children at 0.8 statistical power, 0.05 alpha, and two-sided P-value would show a minimum detectable difference of 0.062 standard deviations if they had relevant exposure for a normally distributed quantitative variable.[48] All statistical analyses and multiple imputations were performed using SPSS statistics software, version 27.0 (IBM Corp, Armonk, NY, USA).

Results

Cohort study characteristics

Altogether, 1682 (62.7% female) participants who had at least one-time measures of ST, LPA, and MVPA during the ages 11–24-year

observation period and complete LVMI$^{2.7}$, RWT, LVDF, and LVFP measurements at the age of 24-year clinic visit were studied (*Figure 1*). Males had ~+4 g/m$^{2.7}$ of LVM than females at both baseline and follow-up, while RWT, LVDF, and LVFP were similar in both sexes (*Table 1*). RWT decreased, while LVDF and LVFP increased over 7 years. Females had higher ST from 11 to 24 years, whereas males accumulated more MVPA minutes (*Table 1*). Other characteristics are described in *Table 1*.

Longitudinal associations of ST, LPA, and MVPA during ages 11–24 years with changes in cardiac structure and function during ages 17–24 years

The cumulative increase in ST from ages 11 to 24 years was associated with progressively increased LVMI$^{2.7}$ from ages 17 to 24 years after full adjustments in the whole cohort and among males and females (*Tables 2* and *3*). The cumulative increase in ST was associated with increased change in RWT and LVFP among males and increased LVFP among females (*Table 3*). The statistically significant relationship between the cumulative increase in ST and increased change in LVDF in males and RWT and LVDF in females was attenuated after further adjustments for cumulative LPA and MVPA (*Table 3*). Cumulative LPA was associated with a decreased change in LVMI$^{2.7}$ but increased RWT and LVDF in the whole cohort and males (*Tables 2* and *3*). Cumulative LPA was associated with increased LVMI$^{2.7}$, RWT, LVDF, and LVFP in females (*Table 3*).

Cumulative MVPA was associated with increased changes in LVMI$^{2.7}$ in the whole cohort but increased LVDF and LVFP in males (*Tables 2* and *3*). Among females, cumulative MVPA was associated with decreased LVMI$^{2.7}$ and RWT and increased LVFP. In the whole cohort, persistent MVPA of ≥60 min/day from ages 11 to 24 years was associated with decreased LVDF (*Table 2*). Persistent MVPA of 40–≤60 min/day from ages 11 to 24 years was associated with decreased LVMI$^{2.7}$ and LVDF (*Table 2*). Among males, persistent MVPA of ≥60 min/day from ages 11 to 24 years was associated with decreased LVFP; however, persistent MVPA of 40– ≤60 min/day from ages 11 to 24 years was associated with decreased LVMI$^{2.7}$, RWT, and LVDF (*Table 3*). Among females, persistent MVPA of ≥60 min/day from ages 11 to 24 years was associated with decreased LVMI$^{2.7}$ and RWT and increased LVFP; however, persistent MVPA of 40–≤60 min/day from ages 11 to 24 years was associated with decreased LVMI$^{2.7}$only (*Table 3*). The unadjusted longitudinal associations of ST, LPA, and MVPA with LVMI$^{2.7}$, RWT, LVDF, and LVFP in the total cohort are presented in *Figure 2* and Supplementary material online, *Figures S1–S3*.

In a subset of 766 participants who had at least two timepoints complete measures of ST, LPA, and MVPA during ages 11–24-year clinic visits with complete cardiac measures at 17 years, the results were largely

Table 1 Descriptive characteristics of cohort participants

Variables	17 years			24 years		
	Male (n = 577)	Female (n = 970)	P-value	Male (n = 628)	Female (n = 1054)	P-value
	Mean (SD)	Mean (SD)		Mean (SD)	Mean (SD)	
Anthropometry						
Age at clinic visit (years)	17.73 (0.36)	17.74 (0.39)	0.574	24.38 (0.58)	24.34 (0.62)	0.211
Age at 11-year clinic visit	11.75 (0.24)	11.75 (0.24)	0.381	NA		
Height (m)	1.79 (0.07)	1.65 (0.06)	<0.0001	1.80 (0.07)	1.66 (0.06)	<0.0001
*Weight (kg)	68.95 (13.40)	59.80 (12.70)	<0.0001	76.6 (16.47)	63.80 (14.90)	<0.0001
Ethnicity—White (n, %)	573 (96.8)	932 (95.8)	0.345	NA		
Body composition						
*Total fat mass (kg)	10.08 (8.84)	18.81 (9.65)	<0.0001	17.27 (9.67)	21.27 (10.66)	<0.001
*Lean mass (kg)	54.70 (8.18)	37.74 (5.09)	<0.0001	55.70 (10.33)	40.45 (6.51)	<0.0001
*Body mass index (kg/m^2)	21.24 (3.76)	21.76 (4.02)	0.010	23.40 (4.29)	23.10 (4.95)	0.167
Overweight/obese body mass index ≥25 kg/m^2 (n, %)	79 (14.1)	174 (18.3)	0.037	208 (33.1)	326 (31.0)	0.357
Fasting plasma metabolic indices						
High-density lipoprotein (mmol/L)	1.20 (0.26)	1.38 (0.31)	<0.0001	1.42 (0.36)	1.69 (0.43)	<0.0001
Low-density lipoprotein (mmol/L)	2.00 (0.58)	2.24 (0.65)	<0.0001	2.37 (0.74)	2.37 (0.73)	0.968
*Triglyceride (mmol/L)	0.73 (0.31)	0.74 (0.35)	0.351	0.86 (0.51)	0.79 (0.42)	<0.0001
Glucose (mmol/L)	5.15 (0.44)	4.91 (0.38)	<0.0001	5.55 (0.96)	5.22 (0.49)	<0.0001
*Insulin (mU/L)	5.66 (3.48)	7.29 (4.51)	<0.0001	6.90 (4.46)	7.68 (5.29)	0.001
*High-sensitivity C-reactive protein (mg/L)	0.40 (0.53)	0.59 (1.24)	<0.0001	0.59 (1.12)	0.95 (1.93)	<0.0001
Vascular measures						
Heart rate (beat/min)	63 (9)	67 (10)	<0.0001	64 (10)	68 (10)	<0.0001
Systolic blood pressure (mmHg)	119 (9)	110 (8)	<0.0001	122 (10)	111 (10)	<0.0001
Elevated/hypertensive blood pressure ≥130 mmHg (n, %)	62 (11.3)	<7 (0.5)	<0.0001	123 (19.6)	43 (4.1)	<0.0001
Diastolic blood pressure (mmHg)	63 (7)	65 (6)	<0.0001	67 (7)	66 (8)	0.101
Cardiac measures						
Left ventricular mass indexed for height (g/m$^{2.7}$)	36.94 (8.01)	34.54 (6.97)	<0.0001	40.87 (8.91)	36.61 (7.86)	<0.0001
Relative wall thickness (cm)	0.38 (0.06)	0.38 (0.06)	0.267	0.37 (0.05)	0.36 (0.06)	0.003
Left ventricular diastolic function (E/A)	1.95 (0.38)	1.92 (0.38)	0.311	1.96 (0.52)	2.01 (0.61)	0.077
Left ventricular filling pressure (E/e′)	4.79 (1.16)	4.87 (0.90)	0.234	4.86 (0.98)	5.16 (1.04)	<0.0001
Lifestyle factors						
Smoked cigarette in the last 30 days (n, %)	105 (21.2)	203 (24.3)	0.192	164 (26.5)	266 (25.4)	0.608
Family history of H–D–C–V (n, %)	152 (27.4)	293 (31.6)	0.090	NA		
Sedentary time at 11 years (min/day)	359 (70)	368 (73)	0.014	NA		
Sedentary time at 15–24 years (min/day)	466 (86)	486 (77)	<0.0001	528 (81)	523 (86)	0.450
Cumulative sedentary time from 11–24 years (min/day)	424 (104)	436 (103)	<0.0001	NA		
Light-intensity physical activity at 11 years (min/day)	366 (60)	364 (60)	0.494	NA		
Light-intensity physical activity at 15–24 years (min/day)	287 (68)	270 (61)	<0.0001	146 (58)	148 (53)	0.528
Cumulative light-intensity physical activity from 11 to 24 years (mins/day)	300 (105)	290 (104)	<0.0001	NA		
Moderate-to-vigorous-intensity physical activity at 11 years (min/day)	66 (32)	46 (20)	<0.0001	NA		
Moderate-to-vigorous-intensity physical activity at 11 years 40–<60 min/day (n, %)	153 (27.1)	315 (33.1)	<0.001	NA		
Moderate-to-vigorous-intensity physical activity at 11 years ≥60 min/day (n, %)	307 (54.3)	213 (22.4)	<0.001	NA		
Moderate-to-vigorous-intensity physical activity at 15–24 years (min/day)	55 (32)	39 (21)	<0.0001	55 (34)	47 (29)	0.002
Moderate-to-vigorous-intensity physical activity at 15–24 years 40–<60 min (n, %)	86 (28.2)	145 (27.5)	<0.001	56 (24.6)	113 (26.0)	0.007

Continued

Table 1   *Continued*

Variables	17 years			24 years		
	Male (*n* = 577)	**Female** (*n* = 970)	*P*-value	**Male** (*n* = 628)	**Female** (*n* = 1054)	*P*-value
Moderate-to-vigorous-intensity physical activity at 15–24 years ≥60 min/day (*n*, %)	116 (38.0)	85 (16.1)	<0.001	84 (36.8)	116 (26.7)	0.007
Cumulative moderate-to-vigorous-intensity physical activity from 11–24 years (min/day)	60 (33)	45 (23)	<0.0001	NA		
Maternal social economic status (*n*, %)			0.588	NA		
Professional	36 (12.2)	27 (5.5)				
Managerial and technical	114 (38.8)	208 (42.1)				
Skilled non-manual	90 (30.6)	178 (36.0)				
Skilled manual	<7 (1.4)	9 (1.8)				
Partly skilled	41 (13.9)	62 (12.6)				
Unskilled	9 (3.1)	10 (2.0)				

The values are means (standard deviations) and *median (inter-quartile range) except for lifestyle factors and ethnicity. Differences between sexes were tested using Student's *t*-test for normally distributed continuous variables, Mann–Whitney U test for skewed continuous variables, χ^2 test for dichotomous variables, and analysis of covariance for the multicategory variable. A two-sided *P* <0.05 is considered statistically significant. NA, not available/applicable; *P*-value for sex differences. H–D–C–V, hypertension, diabetes, high cholesterol, and vascular disease.

consistent in that cumulative ST and MVPA were independently associated with progressively increased LVMI[2.7], while LPA was associated with decreased LVMI[2.7] in the total cohort and males (see Supplementary material online, *Tables S1 and S2*). Among females, cumulative ST and LPA were associated with increased LVMI[2.7], while MVPA was associated with decreased LVMI[2.7].

Longitudinal associations of ST, LPA, and MVPA with cardiac structure and function based on overweight/obesity and elevated/hypertensive blood pressure status at age 24 years

Among participants who were overweight and obese at age 24 years, cumulative ST was associated with increased LVMI[2.7], RWT, and LVFP after full adjustment (*Table 4*). Cumulative LPA was associated with decreased LVMI[2.7], RWT, and LVFP but increased LVDF. Cumulative MVPA had no significant associations with all cardiac measures (*Table 4*).

Among participants with elevated and hypertensive blood pressure at age 24 years, cumulative ST was associated with increased LVMI[2.7], RWT, LVDF, and LVFP (*Table 4*). Cumulative LPA was associated with decreased LVMI[2.7] and increased LVFP. Cumulative MVPA had no significant associations with all cardiac measures (*Table 4*).

Discussion

In the largest and longest follow-up study to date, accelerometer-measured cumulative ST, LPA, and MVPA from childhood through young adulthood were independently but differently related to the changes in cardiac structure and function during growth. Cumulatively increased ST from childhood through young adulthood was associated with increased cardiac mass, whereas cumulative LPA from childhood was associated with decreased cardiac mass. Paradoxically, cumulative MVPA was associated with increased cardiac mass and decreased cardiac function. Similarly, persistent MVPA ≥60 min/day was associated with decreased cardiac function in young

adulthood, but persistent MVPA of 40–<60 min/day was associated with decreased cardiac mass.

Cumulative ST with changes in cardiac structure and function

Disparities exist in the role of self-reported sedentary behaviour on adverse cardiometabolic health in youth in comparison with device-measured ST.[9,10,22] While the former associates with worsening cardiometabolic health, the latter (device-measured ST) showed no consistent relationships.[9] There is a paucity of evidence on device-based measured ST in relation to cardiac function and structure in the paediatric population.[9] This present longitudinal study revealed that average ST increased by almost 3 h from childhood (ST = 6 h) through young adulthood (ST = 9 h) over 13 years. Likewise, LVMI increased on average by 3 g/m[2.7] during growth from adolescence to young adulthood. Each 1-min increase in ST from childhood through young adulthood was associated with a 0.002 (0.001–0.003) g/m[2.7] LVMI increase over 7 years. This suggests that cumulative ST of 431 min/day on average may maximally account for 40% of the increase in cardiac mass, i.e. +1.29 g/m[2.7] of 3 g/m[2.7] from adolescence through young adulthood. This is consistent with findings from a recent cross-sectional report where higher ST was associated with a 30% higher rise in LVMI in 17-year-old adolescents.[23] There was strong consistency in the longitudinal relationships between cumulative ST and increased cardiac mass irrespective of sex, obesity, and hypertensive status. The ST-related increase in LVMI in both cross-sectional and longitudinal study designs may be clinically significant since among adults, an ~5 g/m^{2} higher LVMI may correspond to a 7–20% increase in CVD morbidity and mortality.[49] Progressively increasing mitral E/A ratio (LVDF) and E/e′ ratio (LVFP) predict heart failure with preserved and reduced ejection fraction, acute myocardial infarction, and cardiovascular and all-cause mortality.[36,37,47,50] Cumulative ST from childhood was associated with the progressive increase in LVFP in males, females, and among participants who were overweight/obese or with elevated and hypertensive blood pressure. It was recently shown that increased ST from childhood may worsen blood pressure and accelerate premature vascular damage.[14,51] These findings reveal that the deleterious effect of childhood ST on cardiovascular structure and function may be evident from adolescence.

Table 2 Longitudinal associations of cumulative sedentary time and physical activity from ages 11 through 24 years with the progressive change in left ventricular mass and diastolic function from ages 17 through 24 years

n = 1682	LVMI$^{2.7}$ (g/m$^{2.7}$)		RWT (cm)		LVDF (E/A)		LVFP (E/e')	
	β (95% CI)	P-value	β (95% CI)	P-value	β (95% CI)	P-value	β (95% CI)	P-value
Continuous cumulative predictor variables from ages 11 to 24 years								
Sedentary time								
Model 1	0.006 (0.005–0.006)	**<0.0001**	−0.000 (−0.000 to −0.000)	**<0.0001**	0.000 (0.000–0.000)	**<0.0001**	0.000 (0.000–0.00002)	0.114
Model 2	0.002 (0.001–0.003)	**0.001**	0.000 (−0.000–0.000)	0.156	0.000 (−0.000–0.000)	0.278	0.000 (0.000–0.000)	0.642
Light-intensity physical activity								
Model 1	−0.006 (−0.007 to −0.005)	**<0.0001**	0.00001 (0.000–0.000)	**<0.0001**	0.000 (0.000–0.000)	**<0.0001**	0.000 (0.0001–0.000)	**0.029**
Model 2	−0.005 (−0.006 to −0.003)	**<0.0001**	0.000 (0.000–0.000)	**<0.0001**	0.000 (0.000–0.001)	**<0.0001**	−0.000 (0.000–0.000)	0.645
Moderate-to-vigorous-intensity physical activity								
Model 1	0.001 (−0.002–0.003)	0.492	0.000 (−0.000–0.000)	0.428	0.000 (0.000–0.0001)	0.241	0.000 (0.000–0.001)	0.485
Model 2	0.003 (0.001–0.006)	**0.015**	−0.000 (−0.000–0.000)	0.088	0.000 (0.001 to −0.000)	0.161	0.000 (0.000–0.000)	0.610
Categorical cumulative predictor variable from ages 11 to 24 years								
Moderate-to-vigorous-intensity physical activity (<40 min/day as reference)								
40–<60 mins/day	−0.232 (−0.460 to −0.003)	**0.047**	−0.001 (−0.004–0.001)	0.191	−0.021 (−0.038 to −0.005)	**0.013**	−0.007 (−0.041–0.027)	0.674
≥60 mins/day	0.054 (−0.135–0.244)	0.574	0.0001 (−0.002 to −0.002)	0.914	−0.019 (−0.033 to −0.005)	**0.007**	0.029 (0.000–0.057)	0.050

Model 1 was adjusted for sex, age at baseline, and other time-varying covariates measured at both baseline and follow-up such as low-density lipoprotein cholesterol, high-density lipoprotein cholesterol, heart rate, systolic blood pressure, glucose, fat mass, lean mass, smoking status, family history of hypertension/diabetes/high cholesterol/vascular disease, and socioeconomic status. Model 2 was additional adjustment for sedentary time, light-intensity physical activity, or moderate-to-vigorous-intensity physical activity depending on the predictor. For categorical predictor variable analyses, all the above-listed covariates were adjusted for in one model. Skewed covariates were logarithmically transformed. Regression coefficients (β) were computed from generalized linear mixed-effect model for repeated measures. A two-sided P <0.05 is considered statistically significant and bolded. Multiple testing was corrected with Sidak correction. Multiple imputations were used to account for missing variables. For continuous variable predictors (ST, LPA, and MVPA), a 1-min change is associated with the point estimate unit change in the outcome. For categorical variable predictor (MVPA), time spent in a category in relation to the reference is associated with the point estimate unit change in the outcome.
CI, confidence interval; LVDF, left ventricular diastolic function; LVFP, left ventricular filling pressure; LVMI$^{2.7}$, left ventricular mass indexed for height$^{2.7}$; RWT, relative wall thickness.

Table 3 Longitudinal associations of cumulative sedentary time and physical activity from ages 11 through 24 years with the progressive change in left ventricular mass and diastolic function from ages 17 through 24 years according to sex

	LVMI$^{2.7}$ (g/m$^{2.7}$)		RWT (cm)		LVDF (E/A)		LVFP (E/e′)	
	β (95% CI)	P-value	β (95% CI)	P-value	β (95% CI)	P-value	β (95% CI)	P-value
Male (n = 628)								
Sedentary time								
Model 1	0.011 (0.010–0.013)	**<0.0001**	−0.000 (−0.000 to −0.000)	**<0.001**	0.000 (0.000–0.000)	**<0.001**	0.000 (0.000–0.000)	0.327
Model 2	0.002 (0.000–0.004)	**0.014**	0.000 (0.000–0.000)	**<0.001**	0.000 (−0.000–0.000)	0.307	0.001 (0.000–0.001)	**<0.001**
Light-intensity physical activity								
Model 1	−0.014 (−0.015 to −0.012)	**<0.0001**	0.000 (0.000–0.000)	**<0.001**	0.000 (0.000–0.001)	**<0.0001**	0.000 (0.000 to −0.000)	0.252
Model 2	−0.012 (−0.014 to −0.010)	**<0.0001**	0.000 (0.000–0.000)	**<0.001**	0.000 (0.000–0.001)	**<0.001**	0.000 (0.000–0.001)	**0.003**
Moderate to vigorous physical activity								
Model 1	−0.011 (−0.015 to −0.007)	**<0.001**	0.000 (0.000–0.000)	**0.002**	0.001 (0.000–0.001)	**<0.001**	0.001 (0.000–0.001)	**0.030**
Model 2	0.001 (−0.003–0.005)	0.670	0.000 (−0.000–0.000)	0.125	0.000 (0.000–0.001)	**0.020**	0.001 (0.000–0.001)	**0.008**
Categorical cumulative predictor variable from ages 11 to 24 years								
Moderate-to-vigorous-intensity physical activity (<40 min/day as reference)								
40–<60 min/day	−0.415 (−0.755 to −0.755)	**0.017**	−0.003 (−0.006–0.000)	**0.042**	−0.039 (−0.061 to −0.017)	**<0.001**	0.015 (−0.035–0.065)	0.554
≥60 min/day	−0.325 (−0.653–0.003)	0.052	−0.002 (−0.005 to −0.001)	0.212	0.005 (−0.015–0.025)	0.644	0.073 (0.022–0.123)	**0.005**
Female (n = 1054)								
Sedentary time								
Model 1	0.001 (0.000–0.002)	**0.047**	−0.0001 (−0.0001 to −0.0001)	**<0.0001**	0.000 (0.000 to −0.000)	**0.011**	0.000 (−0.000–0.000)	0.063
Model 2	0.002 (0.001–0.003)	**<0.001**	0.0001 (−0.0001–0.0001)	0.470	−0.000 (0.000–0.000)	0.591	0.001 (0.000 to −0.001)	**0.013**
Light-intensity physical activity								
Model 1	0.000 (0.000–0.0001)	**<0.0001**	0.000 (0.000–0.0001)	**<0.0001**	0.000 (0.000–0.000)	**0.003**	0.000 (−0.001–0.000)	**<0.001**
Model 2	0.002 (0.001–0.003)	**0.001**	0.000 (0.000–0.0001)	**<0.0001**	0.000 (0.001–0.0001)	**0.031**	−0.001 (−0.001–0.000)	**<0.001**
Moderate-to-vigorous-intensity physical activity								
Model 1	−0.007 (−0.010 to −0.003)	**<0.001**	−0.000 (−0.000 to −0.000)	**0.007**	0.000 (0.001–0.001)	0.205	0.001 (0.000–0.001)	**0.005**
Model 2	−0.006 (−0.009 to −0.002)	**0.001**	−0.000 (0.000 to −0.000)	**<0.001**	0.000 (0.001–0.001)	0.431	0.001 (0.000–0.001)	**0.005**
Categorical cumulative predictor variable from ages 11 to 24 years								
Moderate-to-vigorous-intensity physical activity (<40 min/day as reference)								
40–<60 min/day	−0.363 (−0.612 to −0.115)	**0.004**	0.000 (−0.002–0.003)	0.928	0.001 (−0.018–0.021)	0.896.	−0.017 (−0.056–0.023)	0.411
≥60 min/day	−0.382 (−0.609 to −0.154)	**0.001**	−0.004 (−0.006 to −0.002)	**<0.001**	0.008 (−0.010–0.026)	0.356	0.043 (0.010–0.076)	**0.011**

Model 1 was adjusted for age at baseline and other time-varying covariates measured at both baseline and follow-up such as low-density lipoprotein cholesterol, insulin, triglyceride, high-sensitivity C-reactive protein, high-density lipoprotein cholesterol, heart rate, systolic blood pressure, glucose, fat mass, lean mass, smoking status, family history of hypertension/diabetes/vascular disease, and socioeconomic status. Model 2 was additional adjustment for sedentary time, light-intensity physical activity, or moderate-to-vigorous-intensity physical activity depending on the predictor. Skewed covariates were logarithmically transformed. Regression coefficients (β) were computed from generalized linear mixed-effect model for repeated measures. Multiple testing was corrected with Sidak correction. Multiple imputations were used to account for missing variables. For continuous variable predictors (ST, LPA, and MVPA), a 1-min change is associated with the point estimate unit change in the outcome. A two-sided P <0.05 is considered statistically significant and bolded.

CI, confidence interval; LVDF, left ventricular diastolic function; LVFP, left ventricular filling pressure; LVMI$^{2.7}$, left ventricular mass indexed for height$^{2.7}$; RWT, relative wall thickness.

Table 4 Longitudinal associations of cumulative sedentary time and physical activity from ages 11 through 24 years with the progressive change in left ventricular mass and diastolic function from ages 17 through 24 years according to overweight/obesity and elevated blood pressure status at age 24 years

	LVMI$^{2.7}$ (g/m$^{2.7}$)		RWT (cm)		LVDF (E/A)		LVFP (E/e')	
	β (95% CI)	P-value	β (95% CI)	P-value	β (95% CI)	P-value	β (95% CI)	P-value
Overweight/obese ≥25 kg/m² (n = 535)								
Sedentary time								
Model 1	0.011 (0.009–0.013)	**<0.0001**	0.000 (0.000–0.000)	**<0.001**	0.000 (0.000–0.001)	**<0.001**	0.001 (0.001–0.001)	**<0.001**
Model 2	0.006 (0.003–0.009)	**<0.001**	0.000 (0.000–0.000)	**0.002**	0.000 (0.000–0.000)	0.566	0.000 (0.000–0.001)	**0.040**
Light-intensity physical activity								
Model 1	−0.011 (−0.014 to −0.009)	**<0.0001**	−0.000 (−0.000 to −0.000)	**<0.001**	−0.001 (−0.001–0.000)	**<0.001**	−0.001 (−0.002 to −0.001)	**<0.001**
Model 2	−0.007 (−0.010 to −0.004)	**<0.001**	−0.000 (−0.000 to −0.000)	**0.011**	0.000 (−0.000–0.001)	**<0.001**	−0.001 (−0.001 to −0.001)	**<0.001**
Moderate to vigorous physical activity								
Model 1	−0.005 (−0.013–0.004)	0.298	−0.000 (0.000–0.000)	0.148	−0.001 (−0.001–0.000)	**0.006**	−0.001 (−0.002–0.000)	0.062
Model 2	0.004 (−0.005–0.013)	0.347	−0.000 (−0.000–0.000)	0.947	0.000 (−0.000–0.000)	0.200	0.000 (−0.001–0.001)	0.825
Elevated and hypertensive systolic blood pressure ≥130 mmHg (n = 170)								
Sedentary time								
Model 1	0.012 (0.008–0.016)	**<0.001**	0.000 (0.0001–0.000)	**<0.001**	0.000 (0.000–0.001)	**0.002**	0.001 (0.000–0.001)	**<0.001**
Model 2	0.006 (0.001–0.011)	**0.011**	0.0001 (0.0001–0.000)	**<0.001**	0.000 (0.000–0.001)	**<0.001**	0.002 (0.001–0.002)	**<0.001**
Light-intensity physical activity								
Model 1	−0.014 (−0.018 to −0.009)	**<0.001**	0.000 (0.000 to −0.0001)	**<0.001**	0.000 (0.000–0.000)	0.282	0.000 (0.000–0.001)	0.675
Model 2	−0.010 (−0.015 to −0.005)	**<0.001**	−0.000 (−0.000–0.0001)	0.076	0.000 (0.001–0.0001)	0.276	0.001 (0.001–0.002)	**<0.001**
Moderate-to-vigorous-intensity physical activity								
Model 1	−0.003 (−0.016–0.011)	0.674	−0.000 (0.000–0.000)	0.099	−0.001 (−0.001 to −0.0001)	**0.037**	0.001 (−0.001–0.003)	0.277
Model 2	0.005 (−0.008–0.018)	0.466	−0.000 (0.000–0.000)	0.638	0.000 (−0.001–0.000)	0.112	0.002 (0.000–0.004)	0.101

Model 1 was adjusted for age at baseline and other time-varying covariates measured at both baseline and follow-up such as low-density lipoprotein cholesterol, high-density lipoprotein cholesterol, insulin, triglyceride, high-sensitivity C-reactive protein, heart rate, glucose, smoking status, family history of hypertension/diabetes/high cholesterol/vascular disease, socioeconomic status in addition to systolic blood pressure and fat mass, lean mass depending on overweight or hypertensive category. Model 2 was additional adjustment for sedentary time, light-intensity physical activity, or moderate-to-vigorous-intensity physical activity depending on the predictor. Skewed covariates were logarithmically transformed. Regression coefficients (β) were computed from generalized linear mixed-effect model for repeated measures. A two-sided P <0.05 is considered statistically significant and bolded. Multiple testing was corrected with Sidak correction. Multiple imputations were used to account for missing variables. For continuous variable predictors (ST, LPA, and MVPA), a 1-min change is associated with the point estimate unit change in the outcome.

CI, confidence interval; LVDF, left ventricular diastolic function; LVFP, left ventricular filling pressure; LVMI$^{2.7}$, left ventricular mass indexed for height$^{2.7}$; RWT, relative wall thickness.

Cumulative LPA with changes in cardiac structure and function

In the latest health guideline, there was no recommendation on LPA, due to the scarcity of evidence on device-based measured LPA in youth.[9] Moreover, the relationships between LPA and cardiac indices in the paediatric population are unclear.[10] It has been established that most youths do not meet the recommended average of 60 min of MVPA per day but may accumulate a substantial amount of LPA minutes per day.[16] In the present longitudinal study, cumulative LPA was independently associated with decreased cardiac mass and LVFP. Importantly, time spent in LPA in childhood (∼6 h) decreased by nearly 60% by young adulthood. Nonetheless, each 1 min of cumulative LPA was associated with a -0.005 g/m$^{2.7}$ decrease in cardiac mass over a 7-year period, independent of ST, MVPA, and cardiometabolic and lifestyle factors. A 3 g/m$^{2.7}$ increase in LVMI during the 7-year follow-up period was observed, and the cumulative LPA exposure was 292 min/day on average during growth from childhood through young adulthood. Thus, cumulative LPA may decrease LVMI by -1.46 g/m$^{2.7}$, amounting to a circa 49% reduction in the increase in LVMI over 7 years. In a cross-sectional report, LPA had no statistically significant association with cardiac mass but with better cardiac function and LPA was inversely associated with arterial stiffness among adolescents.[15,23] The longitudinal relationships between cumulative LPA and decreased cardiac mass in males among participants who are overweight/obese or with elevated and hypertensive blood pressure were consistently strong. These findings suggest that accumulating more LPA times may significantly attenuate the deleterious effects of ST on cardiac mass. Hence, LPA may be prescribed to enhance better cardiac health in the paediatric population, even in populations at risk of obesity and hypertension.[24,29,52,53] On the contrary, among females, cumulative LPA was associated with increased LVMI, RWT, and LVDF but decreased LVFP, suggesting that LPA-related cardiac benefits may differ slightly by sex probably because of inherent physiology, but further mechanistic studies are needed to clarify these differences.

Cumulative MVPA with changes in cardiac structure and function

Cumulative MVPA from childhood was paradoxically associated with progressively increased LVM from ages 17 to 24 years in the total cohort only. Moreover, a persistent ≥60 min/day of MVPA was not associated with the progressive increase in cardiac mass either in the total cohort, in males, and among participants who were overweight/obese or had elevated or hypertensive blood pressure. Increased LVM in adults predicts higher risks of cardiovascular morbidity and mortality.[1,2,47] Importantly, accumulating 40–<60 min/day of MVPA from childhood in relation to <40 min/day of MVPA was associated with a 0.23 g/m$^{2.7}$ decreased LVMI in the total cohort and irrespective of sex across the 7-year repeated cardiac assessment. The combined effect of 40–<60 min/day of MVPA and LPA may be clinically significant since a 25.3 unit decrease in LVMI was associated with a 22% less likelihood of cardiovascular morbidity and mortality.[2]

Cardiac wall stretch from pressure overload results in concentric remodelling or hypertrophy with no change in the size of the cardiac internal cavity.[54] Cardiac volume overload leads to eccentric remodelling or hypertrophy with changes in the cardiac internal cavity.[54] Normal end-diastolic volume and an increased RWT suggest concentric hypertrophy if LVM is increased and concentric remodelling if LVM is normal.[54] High end-diastolic volume and decreased RWT suggest eccentric hypertrophy if LVM is increased and eccentric remodelling if LVM is normal.[54] In youth athletes, LV dilatation and mild concentric LV hypertrophy have been reported in cardiac adaptation to exercise training.[55] In normal living 15–17-year-old adolescents, higher MVPA was associated with 10% higher LVMI.[23] This contrasts adult athletes'

cardiac adaptation to exercise where less chamber dilatation and eccentric hypertrophy tend to occur.[55] However, both youth and adult athletes exhibit similar increases in LV relaxation and improved LVDF.[55] The present longitudinal findings in a resting state may indicate increasing chamber dilatation, LV relaxation, and increasing cardiac mass, reflecting a gradual transition from concentric remodelling to concentric hypertrophy.[54,55] There was a two-fold increase in LVMI in males (∼4 g/m$^{2.7}$) compared with females (∼2 g/m$^{2.7}$) from ages 17 through 24 years; in addition, males accumulated 15–20 min more MVPA time than females during the 13-year observation period. Thus, it appears that the relatively lesser amount of time females spent in MVPA was paradoxically associated with decreased cardiac mass. These findings suggest a sex-based tailored approach to MVPA interventions for cardiac health benefits in youth.

Among participants with either overweight/obesity or elevated blood pressure, cumulative MVPA had no statistically significant relationship with cardiac structural changes. It was recently shown that increased fat mass dampens the effect of MVPA on metabolic indices such as lipid and inflammation.[11–13] It has also been reported that MVPA significantly contributes to an increase in lean mass which is a driver of cardiac mass increase.[11,38] Recent studies have reported that MVPA's positive association with increased vascular stiffness is due to the mediating effect of lean mass.[14] Taken together, the effect of body composition on MVPA and cardiac outcomes increases the likelihood of MVPA's null effect in its relationship with cardiac structure among participants who are overweight or obese since these participants have significantly high fat mass and high lean mass.[11,41] In addition, MVPA may paradoxically increase blood pressure by increasing lean mass, which might explain the null findings between MVPA and cardiac structural changes in participants with elevated blood pressure.[51] Nonetheless, in the main analyses, blood pressure, fat mass, and lean mass were adjusted for as well as other covariates, yet cumulative MVPA was associated with increased LVMI. Increased ST has been associated with increased fat mass, blood pressure, inflammation, and elevated lipid levels which are independent causal risk factors for increased LVMI and premature cardiac damage in youth.[6,8,11,12,51] ST also paradoxically increases lean mass.[11] However, MVPA decreases fat mass and slightly lowers lipid levels and inflammation but might slightly raise blood pressure and increase lean mass.[11,13,51] Cumulative ST from childhood maximally contributed +40% (+1.29 out of the total 7-year increase 3 g/m$^{2.7}$) in LVMI from adolescence to young adulthood. This is at least eight-fold more than MVPA-induced LVMI increase. Each minute of cumulative MVPA from childhood was associated with progressively increased LVMI (+0.003 g/m$^{2.7}$), amounting to +0.15 out of 3 g/m$^{2.7}$ which is an approximate +5% increase in LVMI. Thus, MVPA-induced LVMI increase seems lean mass–driven physiological remodelling. On the contrary, ST-induced LVMI increase appears fat mass, lipid, inflammation, and blood pressure–driven pathologic remodelling, which is of clinical and public health importance.[25]

Strength and limitations

From a well-phenotyped large birth cohort (ALSPAC) with extensive repeated assessments from childhood through young adulthood, a comprehensive array of repeatedly measured covariates such as device-measured body composition such as fat mass, lean mass, and other lifestyle factors smoking, socioeconomic status, and family history of cardiovascular and metabolic diseases, it was possible to examine the independent relationships of movement behaviour with cardiac indices. A few limitations are that accelerometer was worn for 7 days, which may not be sufficient to reveal the habitual lifestyle of the participants. The possibility of a Hawthorne effect cannot be excluded where participants modify their behaviour based on their awareness of being observed. Nonetheless, the device-measured PA and ST is superior to self-reported lifestyle behaviour which is fraught with recall and report

bias.[22] Some participants with cardiac structural and functional measures at baseline did not meet the inclusion criteria because they lacked PA measures. Nonetheless, these participants had similar baseline metabolic and cardiac characteristics as those included in the present study (data not shown). Also, participants were mostly Caucasian; thus, findings may not be generalizable to other ethnicities. Residual biases such as not accounting for sleep time may not be excluded since the measures were not available.

Conclusions

Increasing LPA and decreasing ST may independently attenuate and reverse progressively worsening changes in cardiac structure and function from adolescence through young adulthood. Cumulative MVPA and spending ≥60 min of MVPA/day were paradoxically associated with increased cardiac mass and decreased cardiac function, especially in males. LPA may be prescribed and recommended in the paediatric population, especially for those with disease conditions such as hypertension and obesity and who are unwilling to participate in vigorous exercises since LPA could potentially reverse worsening cardiac indices associated with ST. ST-induced LVMI increase was eight times higher than MVPA-included LVMI increase during the growth from adolescence to young adulthood, suggesting ST-induced cardiac pathologies. These findings may be considered in updating future health guidelines.

Supplementary material

Supplementary material is available at *European Journal of Preventive Cardiology*.

Acknowledgements

Author contributions

A.O.A. had full access to all the data in the study and take responsibility for the integrity of the data and the accuracy of the data analysis, was involved in concept and design and acquisition, analysis, and interpretation of data, drafted the manuscript, contributed to critical revision of the manuscript for important intellectual content, performed statistical analysis, obtained funding, and serves as the guarantor for the contents of this paper. This publication is the work of the author.

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Data availability

The informed consent obtained from ALSPAC participants does not allow the data to be made freely available through any third-party maintained public repository. However, data used for this submission can be made available on request to the ALSPAC Executive. The ALSPAC data management plan describes in detail the policy regarding data sharing, which is through a system of managed open access. Full instructions for applying for data access can be found here: http://www.bristol.ac.uk/alspac/researchers/access/. The ALSPAC study web site contains details of all the data that are available (http://www.bristol.ac.uk/alspac/researchers/our-data/).

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