Can we walk away from cardiovascular disease risk or do we have to ‘huff and puff’? A compositional accelerometer data analysis among adults and older adults in the Copenhagen City Heart Study

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Abstract

**Background:** To decrease the risk of cardiovascular disease (CVD), it is unclear whether it is enough to walk more, or if high intensity physical activity (HIPA) is needed. It is also unclear if this differs between adults and older adults. We investigated how sedentary behaviour, walking, and HIPA, were associated with systolic blood pressure (SBP), waist circumference (WC) and low-density lipoprotein cholesterol (LDL-C) among adults and older adults in a general population sample using compositional data analysis. Specifically, the measure of association was quantified by reallocating time between sedentary behaviour and 1) walking, and 2) HIPA.

**Methods:** Cross-sectional data from the fifth examination of the Copenhagen City Heart Study was used. We estimated daily time spent in physical behaviours from accelerometer data worn 24 h/day for 7 days (i.e., right frontal thigh and iliac crest; median wear time: 6 days, 23.8 h/day) using the software Acti4. SBP, WC and LDL-C were measured during a physical examination. Eligible participants had to have ≥5 days with ≥16 h of accelerometer recordings per day, and not use antihypertensives, diuretics or cholesterol lowering medicine. The 24-hour physical behaviour composition consisted of sedentary behaviour, standing, moving, walking, HIPA (i.e., sum of climbing stairs, running, cycling and rowing), and time in bed. We used fitted values from linear regression models to predict the difference in outcome given the investigated time reallocations.

**Results:** Among the 1053 eligible participants we found an interaction between the physical behaviour composition and age. Age-stratified (i.e., </≥65 years; 773 adults, 280 older adults) analyses showed that less sedentary behaviour and more walking compared to the group-specific mean composition was marginally associated with lower SBP among older adults, but not among adults. Less sedentary behaviour and more HIPA was among both adults and older adults marginally associated with a lower SBP, associated with a
smaller WC among adults (marginally among older adults) and associated with a lower LDL-C in both age groups.

**Conclusions:** Less sedentary behaviour and more walking seems to be associated with lower risk of CVD among older adults, while HIPA types are associated with lower risk among adults.

**Background**

Almost 30% of all deaths globally are caused by cardiovascular disease (CVD) (1). Leading risk factors are high systolic blood pressure (SBP), high waist circumference (WC) and high low-density lipoprotein cholesterol (LDL-C) (2, 3). Low physical activity levels and excessive sedentary behaviour are associated with these risk factors and incident CVD (2, 4, 5). Therefore, it is essential to increase physical activity to prevent CVD (4–7).

However, there is need for improved knowledge about feasible and effective physical activity types, and how much that is required to achieve a preventive effect.

For several reasons, walking is a physical activity type that has a great potential to prevent CVD. Firstly, walking is safe and easy to integrate in everyday life (8). Secondly, walking has beneficial effects on several CVD risk factors (9, 10), and reduces the risk of all-cause and CVD-specific mortality (11, 12). Thirdly, walking may also be easier to communicate and implement in the public compared to physical activity of higher intensity (6). Walking may hence be one of the most evident physical activity types to promote on a population level to prevent CVD. However, because the age-related decline in maximal aerobic capacity ($\text{VO}_2\text{max}$) (13, 14) leads to a higher relative intensity during walking among elderly, the preventive potential of walking may be highest among older individuals (9). Younger individuals may therefore need to engage in high-intensity physical activity (HIPA) types such as cycling and running to achieve a similar relative
intensity and accompanying health benefits (11, 15-17).

Most previous studies have investigated health effects of sedentary behaviour, walking or HIPA types as being independent from other physical behaviours (5, 11, 12, 16, 18). However, because a day has a fixed duration of time, an increased time spent in one behaviour displaces time available for other behaviours. This means that physical behaviours are co-dependent and compositional in nature (19-21). Therefore, the association between walking and HIPA, and CVD risk factors depends on how much time that is spent in other physical behaviours during the day, and which of these an increase in walking or HIPA displaces (22). For example, if a person walks more and spend less time sedentary, it will likely reduce SBP (9, 23). On the other hand, if the increase in walking displaces time in HIPA, it will, hypothetically, result in higher SBP over time (24). Applying standard statistical methods to compositional data (5, 11, 12, 16, 18) has both conceptual and statistical limitations (19-21); but compositional data analysis (CoDA) provides tools to analyse such data properly (19). We are not aware of any studies that have investigated the relationship between walking and other physical behaviours (e.g., sedentary behaviour, standing, running and cycling), and risk factors for CVD using CoDA and device-based measurements of physical behaviours. It is hence unclear whether it is enough to walk more for adults and older adults, or if high-intensity physical activity (HIPA) is needed to decrease the risk of CVD.

The objectives of this study were to investigate how sedentary behaviour, walking, and HIPA, are associated with risk factors for CVD (i.e., SBP, WC, and LDL-C) among adults and older adults in a general population sample using CoDA. Specifically, the measure of association was quantified by reallocating time between 1) sedentary behaviour and walking, and 2) sedentary behaviour and HIPA, among adults and older adults.

Methods
Study design and study population

This is a cross-sectional analysis of data collected in the fifth examination (October 2011 – February 2015) of the Copenhagen City Heart Study (CCHS) (25). In total, 9215 individuals were invited of which 4543 participated (49.3%). Details about the source and study population, the invitation procedure, data collection and data processing are described elsewhere (25, 26).

Data collection

Questionnaire

The study participants filled out a questionnaire covering a wide range of domains including but not limited to socioeconomic status; general, physical and mental health; symptoms and diseases; smoking and alcohol consumption; diet; and medication use. We have made an overview of questions relevant for this study in Additional files, Table A1.

Physical examination

All participants were examined at the CCHS’s test centre at a public hospital in the Capital Region of Denmark by trained medical laboratory technicians, medical students and medical specialists.

The tests relevant for this study were measurements of blood pressure, WC, and LDL-C (i.e., our outcomes), and height, and weight (i.e., for descriptive purposes). WC was measured at the approximate midpoint between the lower margin of the last palpable rib and the top of the iliac crest. Three consecutive blood pressure measurements were taken on the participants’ non-dominant arm after five minutes of sitting with an automatic blood pressure monitor (OMRON M3, OMRON Healthcare, Hoofddorp, Netherlands). Venipunctures were taken according to standardised procedures and the level of LDL-C was determined directly (Sanofi Genzyme, Cambridge, Massachusetts, USA). Height was measured without shoes on a fixed scale to the nearest millimetre. Weight was measured
with clothes, but without shoes, on a consultation scale (Seca, Hamburg, Germany) to the nearest 100 grams.

Accelerometer-based measurements of physical behaviours

All participants were invited to participate in a sub-study that involved wearing two tri-axial accelerometers (ActiGraph GT3X+; sampling frequency: 30 Hz; ActiGraph, Pensacola, Florida, USA) 24-hours per day for seven consecutive days to measure their daily physical behaviours. In total, 2335 participants gave consent to wear the accelerometers. The accelerometers were attached on i) the anterior aspect of the right thigh midway between the greater trochanter and patella oriented along the axis of the thigh, and ii) on the lateral aspect of the right iliac crest. They were attached directly to the skin using a double-sided medical tape (Hair-Set for hairpieces; 3M, Maplewood, Minnesota, USA) and wrapped with transparent adhesive film (OpSite Flexifix; Smith & Nephew, London, UK) to ensure a fixed position during the measurement period.

During the measurement period, the participants were asked to note their leisure time, working hours, time in bed, and periods of non-wear time in a diary. The participants were also asked to only remove the accelerometers in case of adverse skin reactions, discomfort or pain, affected sleep, and when going to a sauna. After the measurement period, the participants returned the accelerometers at the test centre or by mail using a pre-paid envelope. The measurements of physical behaviours have been described in detail in a previous publication (26).

Processing of raw accelerometer data

Detection of physical activity types and stationary behaviours

The MATLAB-software Acti4 (National Research Centre for the Working Environment,
Copenhagen, Denmark) was used to detect and derive the time spent in the following physical activity types and stationary behaviours: lying, sitting, standing, moving (i.e., small movements without regular walking while in a standing posture), walking, climbing stairs (i.e., up and down), running, cycling and rowing. Acti4 detects the physical behaviours through an algorithm that uses inclinations and accelerations (27), with a high sensitivity and specificity (27, 28).

Quality control, time in bed and non-wear time

For each individual participant, we visually inspected the activity classification over time to identify and investigate any abnormalities in the data (e.g., high levels of rowing or lack of sitting). Time in bed was defined based on a combination of accelerometer and diary data (i.e., bedtime/get up time). Non-wear time was ‘operator-defined’ by diary information and visual inspection of the activity classification. In addition, Acti4 detects non-wear time automatically using a set of rules: 1) Periods <10 min without recorded movement were not regarded as non-wear time. 2) Periods between 10 and 90 min were classified as non-wear time if a) the vector sum of the standard deviation of acceleration was >0.5G for any second during a 5-second interval immediate before the period without recorded movement, and b) the accelerometer was placed in a horizontal position (±5°). 3) Periods >90 min without recorded movement were always considered as non-wear time (27). See previous publication for further details about the processing of the raw accelerometer data (26).

Eligibility criteria

Our inclusion criteria were: 1) ≥5 days of measurements with ≥16 h of accelerometer recordings per 24-hours day, 2) not using antihypertensive, diuretics or cholesterol lowering medicine, and 3) no missing values in any of the outcome variables. All reported ‘sick days’ (i.e., diary information) were excluded.
Definition of variables

Physical behaviour composition

The physical behaviour composition consisted of time (min/24-h day) spent in **sedentary behaviour** (i.e., sum of lying and sitting), **standing**, **moving**, **walking**, **HIPA** (i.e., sum of climbing stairs [up/down], running, cycling and rowing), and **time in bed**. It hence reflects participants’ 24-hour time-use. Time spent in the physical behaviours was accumulated during **waken** hours only (i.e., except for time in bed). Time spent in each behaviour was represented by the individual’s daily mean time across the measurement period standardised to 24 hours.

Physical behaviours (i.e., compositional parts) consisting of zeros cannot be included in CoDA. Due to zero time spent climbing stairs, running, cycling, and rowing for some participants, we decided to merge these behaviours into the combined activity class HIPA.

Outcomes

We used **SBP** (mm Hg), **WC** (cm), and **LDL-C** (mmol/L) as outcome variables. WC was used rather than **BMI** or waist-hip ratio since it has been suggested to be a stronger predictor for **CVD** (29).

Covariates and variables for descriptive analyses

In addition to the physical behaviour composition, we used the following covariates in the analyses: **sex**, **age**, number of years of education, smoking status, average number of alcohol units/week and self-reported use of prescribed medication for cardiovascular disease, antidepressants or sedatives, asthma or bronchitis and diabetes.

For descriptive purposes, BMI was categorised according to WHO classification (30), blood pressure according to the classification used by the European Society of Hypertension and the European Society of Cardiology (31), and WC into >88 cm for women and >94 cm for men (29).
An overview including details about how we derived these variables can be found in the Additional files (Table A2).

Statistical analysis

Descriptive statistics

We described the characteristics of the study population using frequencies and percentages (%) or medians and first and third quartiles (Q1-Q3) where appropriate. Medians were used instead of means due to skewed distributions of some of the continuous variables. We described the central tendency and dispersion of the physical behaviour composition with geometric means and a variation matrix, respectively.

Investigation of potential selection bias

The characteristics of the non-eligible participants (i.e., having accelerometer data but not fulfilling the eligibility criteria) were compared to the characteristics of the eligible participants. This was done using Mann-Whitney U test, Pearson’s Chi-squared test (i.e., p-values <0.05 were considered to indicate differences between groups) and assessing 95% confidence intervals (CI) of medians and proportions. We calculated CIs for medians and proportions using the normal approximation method and the Wilson’s score method, respectively (32).

Data transformations

Compositional data is bound to a sample space (i.e., the simplex) with a geometry that is incompatible with standard statistical methods. To allow the use of standard statistical methods, we transformed the physical behaviour composition with the isometric log-ratio (ilr) transformation based on a sequential binary partition process (19). This resulted in a set of pivot ilr-coordinates that represent the physical behaviour composition in a sample space (i.e., the real coordinate space) where standard statistical methods can be applied (20). Specifically, pivot ilr-coordinates were constructed, where the first coordinate (ilr1)
represents the first part of the composition relative to the geometric mean of the remaining parts (33).

Modelling process and time reallocations

We investigated how sedentary behaviour, walking, and HIPA, expressed as \( ilr \)-coordinates, were associated with each outcome using linear regression models (i.e., crude and adjusted analyses). Due to the \( ilr \)-transformation, the model estimates of the \( ilr \)-coordinates are not directly interpretable. A solution to this challenge was to theoretically reallocate time between 1) sedentary behaviour and walking, and 2) sedentary behaviour and HIPA and thereby, quantify the measure of association in an understandable way (20). This was conducted in the following three steps.

i) For each outcome, we fitted a multiple linear regression model with the \( ilr \)-coordinates representing the physical behaviour composition and the previously mentioned covariates (i.e., only in adjusted analyses). The physical behaviour composition as a whole was associated with SBP, WC, and LDL-C in the crude and adjusted analyses (i.e., all p-values <0.001, data not shown). We tested for and found an interaction between the physical behaviour composition and age (i.e., p-value for interaction term in the SBP-, WC- and LDL-C-model: 0.006, <0.001, and <0.001, respectively). Subsequently, all analyses were stratified by age group (i.e., adults <65 years and older adults \( \geq \)65 years). We assessed the assumptions of the linear regression models by plotting residuals vs. continuous covariates, residuals vs. fitted values and by quantile-quantile (Q-Q) plots of the residuals (i.e., assumption of linearity, homogeneous variance of residuals, and assumption of normally distributed residuals).

ii) Since the beta-coefficients of the \( ilr \)-coordinates are not directly interpretable, we used the reallocation of time between the behaviours to quantify the measure of association in an understandable way. With the age group-specific geometric mean composition as the
starting point (i.e., reference composition), we reallocated time according to our study objectives. The time reallocations were made pairwise. For example, if 10 minutes were reallocated from sedentary behaviour to walking in a theoretical reference composition consisting of 580 minutes sedentary behaviour, 190 minutes standing, 60 minutes moving, 90 minutes walking, 20 minutes HIPA and 500 minutes in bed (i.e., 24 hours), it would result in 570 minutes sedentary behaviour and 100 minutes walking, while all remaining physical behaviours were kept constant.

For reallocation 1), we reallocated time between sedentary behaviour and walking in 10-minute portions. That is, sedentary behaviour was decreased with 10 to 60 minutes with a corresponding increase in walking time. Similarly, walking was decreased alongside an increase in sedentary time, again from 10 to 60 minutes. For reallocation 2), we similarly reallocated time between sedentary behaviour and HIPA from 2 to 12 minutes in 2-minute portions.

iii) We estimated the outcome for the reference compositions and each reallocated composition using the fitted values from the regression models. Subsequently, we calculated the difference in outcome by subtracting the estimated outcome of the reference composition from the estimated outcome for each reallocated composition (20, 21).

We used the statistical software RStudio (version 1.1.463) (34) running R (version 3.5.3) for all analyses (35). Specifically, for the analyses involving CoDA, we used the following packages: compositions (36) and robCompositions (37).

Results

Descriptive statistics

The formation of the study population is illustrated in Figure 1. As previously mentioned,
we found an interaction between the physical behaviour composition and age, and have therefore stratified all analyses by age group. We have presented the characteristics of the study population in Table 1. The median accelerometer wear time was 23.8 and 23.9 h/day, and the median number of valid days was 6.0 and 6.0 days among adults and older adults, respectively. The median age was 48.3 and 72.7 years among adults and older adults, respectively. The median SBP, WC, and LDL-C was 127.0 and 143.8 mmHg, 83.0 and 89.0 cm, and 3.0 and 3.3 mmol/L among adults and older adults, respectively.

(Table 1 here)

Of a 24h-day, adults and older adults spent on average 579.8 and 589.1 min/day in sedentary behaviour, 193.4 and 186.5 min/day standing, 71.1 and 72.9 min/day moving, 85.5 and 74.9 min/day walking, 14.2 and 6.9 min/day in HIPA, and 496.1 and 509.7 min/day in bed, respectively (Table 2). Among both adults and older adults, the highest log-ratio variances were found between HIPA and sedentary behaviour, which reflect a low co-dependency between these behaviours. The lowest log-ratio variances were found between sedentary behaviour and time in bed that reflect a high co-dependency (Table A3 in Additional files).
Table 2. Geometric means of 24-hour physical behaviour composition among 773 adults and 280 older adults participating in the fifth examination of the Copenhagen City Heart Study (Denmark)

| Physical Behaviour       | Adults $n = 773$ | Older adults $n = 280$ |
|--------------------------|------------------|------------------------|
|                          | Min (%) of 24-h day | Min (%) of 24-h day |
| Sedentary behaviour      | 579.84 (40.27)    | 589.07 (40.7)          |
| Standing                 | 193.36 (13.43)    | 186.49 (12.7)          |
| Moving                   | 71.09 (4.94)      | 72.92 (5.0)            |
| Walking                  | 85.48 (5.94)      | 74.90 (5.2)            |
| HIPA                     | 14.16 (0.98)      | 6.94 (0.48)            |
| Time in bed              | 496.07 (34.45)    | 509.68 (35.3)          |
| Sum                      | 1440.00 (100.00)  | 1440.00 (100)          |

| HIPA, high-intensity physical activity which consists of climbing stairs (up/down), running, cycling and rowing |

Investigation of potential selection bias

The non-eligible study participants had a higher median age, lower level of education, lower household income, a higher proportion used prescribed medication, higher proportions rated their health as less good and poor, had a higher median SBP (and a higher proportion was classified with hypertension), higher median WC, lower median LDL-C, and higher proportions were classified as overweight and obese compared to those fulfilling the inclusion criteria. See Table A4 in Additional files for details.

Reallocation of time

We have only included estimates based on the adjusted analyses in the following. For crude estimates, see section Time reallocations in Additional files.

Systolic blood pressure

Although slightly different in size and precision, both the crude and adjusted estimates of the reallocations suggested the same associations in both age groups (see Time reallocations, Additional files).

Less sedentary behaviour and more walking compared to the reference composition was
not associated with an estimated difference in SBP among adults. However, among older adults, it was marginally associated with a lower SBP (e.g., 30 minutes: -1.92; 95% CI: -4.43, 0.58 mm Hg) (Figure 2A, Table 3 and Table A6.1.2. in Additional files). In addition, less sedentary behaviour and more HIPA relative to the reference composition was marginally associated with a lower SBP in both age groups (e.g., 6 minutes among adults: -0.39; 95% CI: -0.82, 0.04 mm Hg; 6 minutes among older adults: -1.06; 95% CI: -2.61, 0.49 mm Hg) (Figure 2B, Table 4 and Table A6.1.2. in Additional files).

**Waist circumference**

Comparing the crude and adjusted analyses, both the size and precision of the estimates differed in both reallocations and in both age groups, except for the reallocation of time between sedentary behaviour and HIPA among adults where the same associations were seen (see *Time reallocations*, Additional files).

Less sedentary behaviour and more walking relative to the reference composition was marginally associated with a larger WC among adults (e.g., 30 minutes: 0.60; 95% CI: -0.15, 1.35 cm), while no association were found among older adults (Figure 3A, Table 3 and Table A6.2.2. in Additional files). Furthermore, less sedentary behaviour and more HIPA compared to the reference composition was associated with a smaller WC among adults while only marginally associated among older adults (e.g., 6 min among adults: -0.82; 95% CI: -1.09, -0.54 cm; 6 min among older adults: -0.51; 95% CI: -1.28, 0.27 cm) (Figure 3B, Table 4 and Table A6.2.2. in Additional files).
Table 3. Overview of estimated differences in systolic blood pressure, waist circumference and low-density lipoprotein for reallocation between sedentary behaviour and walking among 773 adults and 280 older adults in the fifth examination of Copenhagen City Heart Study

| Time reallocations | Adults <br>n=773 |  | Older adult <br>n=280 |  |
|--------------------|-----------------|----------------|-----------------------|-----------------|
|                    | Estimated difference in outcome (95% CI) |  | Estimated difference (95% CI) |  |
| SBP (mm Hg)        |  |  |  |  |
| 30 min sedentary behaviour → walking | 0.500 (-0.665, 1.655) |  | -1.924 (-4.432, 0.584) |  |
| 30 min walking → sedentary behaviour | -0.826 (-2.468, 0.815) |  | 2.650 (-1.052, 6.352) |  |
| WC (cm)            |  |  |  |  |
| 30 min sedentary behaviour → walking | 0.600 (-0.152, 1.353) |  | -0.163 (-1.412, 1.086) |  |
| 30 min walking → sedentary behaviour | -0.914 (-1.975, 0.146) |  | 0.014 (-1.830, 1.857) |  |
| LDL-C (mmol/L)     |  |  |  |  |
| 30 min sedentary behaviour → walking | 0.080 (0.011, 0.148) |  | 0.049 (-0.060, 0.157) |  |
| 30 min walking → sedentary behaviour | -0.115 (-0.210, -0.019) |  | -0.075 (-0.235, 0.1) |  |

Model adjusted for age, sex, level of education, number of alcohol units/week, smoking status, use of prescribed medication. CI, confidence interval

Reallocations done relative to reference composition A) 579.8 min sedentary behaviour, 193.4 min standing, 71.1 min moving, 85.5 min walking, 14.2 min HIPA, and 496.1 min in bed among adults, and B) 589.1 min sedentary behaviour, 186.5 min standing, 74.9 min walking, 6.9 min HIPA, and 509.7 min in bed among older adults (i.e., geometric mean)

SBP, systolic blood pressure

HIPA, high-intensity physical activity which consists of climbing stairs (up/down), running, cycling and rowing

WC, waist circumference

LDL-C, low-density lipoprotein cholesterol

mm Hg, mm of mercury

mmol/L, mmol per litre

Low-density lipoprotein cholesterol

The crude and adjusted estimates of the time reallocations suggested the same overall association as described in the following (Additional files).

Among adults, less sedentary and more walking compared to the reference composition was associated with a higher LDL-C (e.g., 30 min: 0.08; 95% CI: 0.01, 0.15 mmol/L).

Among older adults, the estimates followed the same pattern but the estimated difference in LDL-C were small and the CIs included zero (Figure 4A, Table 3 and Table A6.3.2. in
Additional files). Finally, less sedentary behaviour and more HIPA relative to the reference composition was associated with a lower LDL-C in both age groups (e.g., 6 min among adults: -0.04; 95% CI: -0.06, -0.01 mmol/L; 6 min among older adults: -0.12; 95% CI: -0.18, -0.05 mmol/L) (Figure 4B, Table 4 and Table A6.3.2. in Additional files).

Table 4. Overview of estimated differences in systolic blood pressure, waist circumference and low-density lipoprotein for reallocation between sedentary behaviour and high-intensity physical activity types among 773 adults and 280 older adults in the fifth examination of the Copenhagen City Heart Study

| Time reallocations                | Adults n=773 Estimated difference in outcome (95% CI) | Older adult n=280 Estimated difference (95% CI) |
|----------------------------------|------------------------------------------------------|-------------------------------------------------|
| SBP (mm Hg)                      |                                                      |                                                 |
| 6 min sedentary behaviour → HIPA | -0.387 (-0.817, 0.042)                                | -1.062 (-2.612, 0.487)                          |
| 6 min HIPA → sedentary behaviour | 0.579 (-0.089, 1.248)                                 | 3.197 (-1.764, 8)                               |
| WC (cm)                          |                                                      |                                                 |
| 6 min sedentary behaviour → HIPA | -0.816 (-1.093, -0.538)                              | -0.506 (-1.277, 0.266)                          |
| 6 min HIPA → sedentary behaviour | 1.261 (0.829, 1.693)                                  | 1.443 (-1.027, 3.913)                           |
| LDL-C (mmol/L)                   |                                                      |                                                 |
| 6 min sedentary behaviour → HIPA | -0.039 (-0.064, -0.014)                              | -0.115 (-0.182, -0.05)                          |
| 6 min HIPA → sedentary behaviour | 0.061 (0.022, 0.100)                                 | 0.367 (0.153, 0)                                |

Model adjusted for age, sex, level of education, number of alcohol units/week, smoking status, use of prescribed medication, n, number of observations included in adjusted model, CI, confidence interval

Reallocations done relative to reference composition A) 579.8 min sedentary behaviour, 193.4 min standing, 71.1 min moving, 14.2 min HIPA, and 496.1 min in bed among adults, and B) 589.1 min sedentary behaviour, 186.5 min standing moving, 74.9 min walking, 6.9 min HIPA, and 509.7 min in bed among older adults (i.e., geometric mean)

SBP, systolic blood pressure
HIPA, high-intensity physical activity which consists of climbing stairs (up/down), running, cycling and rowing
WC, waist circumference
LDL-C, low-density lipoprotein cholesterol
mm Hg, mm of mercury
mmol/L, mmol per litre

Model validation

In the SBP- and WC-model among adults, we found slightly curved distributions of the
residuals when these were plotted against age (i.e., suggesting non-linearity). The distribution of the residuals were slightly skewed across all outcomes and both age groups, but we chose not to transform any outcome to facilitate understandable results. The variance of the residuals were assessed as homogeneous across all outcomes. See Linear regression models in Additional files for details.

Discussion

Summary of findings

We found age to modify the association between the physical behaviour composition and SBP, WC, and LDL-C. The results indicated that less sedentary behaviour and more walking compared to the group-specific mean composition was associated with a lower SBP among older adults, but not with the other outcomes in either age group. In addition, the results indicated that less sedentary behaviour and more HIPA was associated with a lower SBP and LDL-C among adults and older adults, and with a smaller WC among adults.

Interpretation of findings

We found age to modify the association between the physical behaviour composition and our outcomes. This may be most clear in the results for SBP, and indicates that cardiovascular health effects from physical behaviours are age-dependent.

A 2 mm Hg lower SBP has been estimated to lower stroke- and ischaemic heart disease (IHD)-mortality with about 10% and 7%, respectively, on a population level (38, 39). Our results suggest 60 minutes less sedentary behaviour and 60 minutes more walking (compared to the reference composition) to be associated with 3.5 mm Hg lower SBP among older adults. Among adults, 12 minutes less sedentary behaviour and 12 minutes more HIPA was marginally associated with a 0.7 mm Hg lower SBP. Less sedentary behaviour and more walking among older adults, and more HIPA among all adults, could hence potentially contribute to a lower mean SBP that leads to a shift in the SBP
distribution and a decrease in the prevalence of hypertension, which may in turn prevent incident CVD (40).

The different effects on SBP among adults and older adults from the time reallocations between sedentary behaviour and walking (Fig. 2A) may be explained by several factors. Firstly, one possible explanation to why we did not see any effect among adults may be that physical activity at work and leisure is suggested to have opposite health effects (41, 42) and most of the older adults were not working (i.e., retirement age in Denmark at time of data collection was 65 years). Secondly, as previously discussed, the age-related decrease in VO₂max (13, 14) results in a higher relative intensity of walking among older adults than adults. This offers another explanation to why walking is suggested to have beneficial effects on SBP among older adults, while adults seems to need more huffing and puffing by engaging in HIPA. We acknowledge that ‘overall’ walking may be too heterogeneous from an intensity-perspective to see an effect among adults. However, it is still possible that walking of higher pace could have a beneficial effect. The importance of intensity for SBP is also seen when the estimates are compared across the two time reallocations. For example, among older adults, replacing 4 minutes of sedentary behaviour with HIPA had a similar effect on SBP to that of replacing 10 minutes of sedentary behaviour with walking (Fig. 2B).

To our knowledge, no previous study has investigated the effect of replacing sedentary behaviour with walking for cardiovascular health using CoDA. All previous studies that have used a similar analytical approach have used stepping or light intensity physical activity (LIPA) and moderate-to-vigorous physical activity (MVPA) instead of walking. This makes it difficult to compare our results on walking with these studies. Two previous studies did not find any effect on SBP from reallocating time between sedentary behaviour and LIPA or MVPA among adults and older adults (22, 43), which is in contrast to our
results. One study found similar effects on SBP from reallocating time between sedentary behaviour and MVPA (i.e., sum of walking fast, climbing stairs, running and cycling), but not LIPA (i.e., sum of standing and walking slow) (44). Another study found that less sitting and more stepping was associated with lower SBP based on 3-month but not 12-month changes in the investigated composition (45). These findings are in line with ours, but it should be emphasised that both of these studies (44, 45) included workers, and the precision of the estimates is unclear since no CIs were reported.

We found less sedentary behaviour and more HIPA to be associated with a smaller WC in both age groups (e.g., 6 min among adults: -0.8; 95% CI: -1.1, -0.5 cm). It is unclear whether these findings potentially could decrease the CVD risk on a population-level, since the few studies that have investigated the relationship between a change in WC and CVD outcomes have inconclusive findings (46, 47). Additionally, the estimated differences were smaller than previously reported technical measurement errors of WC (48). One prospective study found less sitting and more stepping over 12 months to be associated with a decreased WC (45), which is in line with our findings from the time reallocations from sedentary behaviour to HIPA. Furthermore, one cross-sectional study did not find any difference in WC from reallocating time between sedentary behaviour and LIPA, or from sedentary behaviour to MVPA (43). However, they found less MVPA and more sedentary behaviour relative to the mean composition to be associated with a higher mean WC (43), which is in agreement with our findings.

We found that 6 minutes less sedentary behaviour and 6 minutes more HIPA was associated with a -0.04 (95% CI: -0.06, -0.01) and − 0.12 (95% CI: -0.18, -0.05) mmol/L lower LDL-C among adults and older adults, respectively. On a population-level, a 1 mmol/L lower non-high-density lipoprotein cholesterol (HDL-C) (i.e., total cholesterol minus HDL-C) has been reported to lower IHD-mortality by 30% (49). Therefore, even
small reductions in LDL-C on a population-level could in combination with improvements in other lifestyle factors (e.g., smoking, alcohol consumption and diet) prevent incident IHD (50, 51). One study found less sitting and more stepping to be marginally associated with a lower LDL-C based on 12-month changes in the investigated physical behaviour composition (45). This is in disagreement with our findings from the reallocation of time between sedentary behaviour and walking, but in agreement with the sedentary behaviour-HIPA reallocation. Another study did not find any effect on LDL-C from reallocating time between sedentary behaviour and LIPA or between sedentary behaviour and MVPA (43). This is in disagreement with our findings from the sedentary behaviour-walking reallocation.

Surprisingly, we found less sedentary behaviour and more walking relative to the reference composition to be associated with a larger WC among adults (marginally) and a higher LDL-C in both age groups (although the CIs included zero among older adults). We do not know how to explain these puzzling findings. However, among adults, one explanation could be differences in occupation, socioeconomic status and health. Specifically, occupations that involve little sedentary behaviour and much walking (i.e., not requiring a high level of education) are often held by individuals with lower socioeconomic status, which in turn is associated with poor health (52), including higher odds of overweight and dyslipidaemia (53).

Methodological considerations
We emphasise that the cross-sectional study design should be kept in mind when interpreting our results, and that the estimates should be interpreted as associational and not causal effects. In particular for WC, since evidence suggest the relationship between sedentary behaviour and physical activity, and measurements of adiposity to be bi-directional (54).
Importantly, we also emphasise that these findings should be interpreted from a primary prevention perspective since we excluded those taking antihypertensives, diuretics and cholesterol lowering medicine.

The CIs of some estimates were wide. We believe that a bigger study sample would result in better precision of the estimates, in particular among older adults, which could assist the interpretation of some of our findings.

The sensitivity and specificity of Acti4 has been found to be above 90% across all activity types and stationary behaviours during standardised and semi-standardised conditions, except for climbing stairs that has a lower sensitivity (sensitivity: 75.4%; specificity: 99.7%) (27, 28). Since Acti4 has not been validated in older populations, we acknowledge that we do not know whether this may have affected the risk of misclassification.

As in all epidemiological studies using resting blood pressure, there is a risk that some measurements are affected by white coat hypertension or masked hypertension. Future studies may consider to collect ambulatory blood pressure, since this may be a stronger predictor of incident CVD (55). We acknowledge that the magnitude of measurement error in WC is unclear (48). The LDL-C measurements were based on non-fasting blood samples, which is in line with routine clinical practice in several countries including Denmark (56). The maximal mean change in LDL-C after a habitual meal is reported to be clinically non-significant (51, 56). Therefore, we do not believe that the non-fasting measurements in this study have affected the precision of the LDL-C measurements to a high degree.

We used the group-specific mean time spent in the physical behaviours as reference in all time reallocations. This is important to consider when interpreting our results, since the effect of increasing walking or HIPA at the cost of sedentary behaviour might differ between those with extreme values in some parts of the composition. For example, the effect of reallocating 15 minutes of sedentary behaviour to walking may be different for
an individual that walks 60 minutes/day compared to the effect of the same reallocation for an individual that only walks 15 minutes/day (i.e., a 25 vs. 100% relative change in walking time). The estimated differences presented here may hence be less accurate among individuals with more extreme compositions than among those closer to the mean compositions.

Perspectives
The burden from physical inactivity-related CVD (2) requires massive efforts to get the least active more active (7). Our results highlight the potential to prevent CVD among older adults by replacing sedentary behaviour with walking, and among both adults and older adults by replacing sedentary behaviour with HIPA. Since individual behavioural change is challenging (57), a systems-based approach to increase physical activity is increasingly recognised (7, 58). This can involve multi-disciplinary collaborations between researchers and stakeholders where research is designed and solutions created across different societal ‘systems’ (e.g., environment, policy-making and regulation, work-places, communities, health-care, education, etc.) (58). There are numerous examples of what or how this can be done. For example, policy makers can make active transportation by foot or bike more attractive by improving walkability and bicycle infrastructure (59, 60), which is known to increase physical activity and prevent CVD in the population (61). Another example is national governmental-led programmes that promotes recreational physical activity, such as Get Scotland Walking (62). National or local non-profit organisations that work and advocate for healthy community-based sports environments, such as DGI in Denmark (63) and other community-based initiatives such as Parkrun (64), can play important roles on a local or community-level and should be supported. Furthermore, we believe that physical activity could become a more central part of health-care systems if incentives for this were created. Finally, mass-media campaigns may also have an effect
on activity levels when delivered in combination with environmental change and community-initiatives (60). Changes in societal systems such as these may hence influence us all to be less sedentary and walk, cycle or run more while improving our cardiovascular health.

We believe that there is a need for more studies that use larger study populations (i.e., including older individuals) and prospective data to, in particular, investigate the health effects of walking and further investigate the role of domain (i.e., work and leisure) and walking intensity (e.g., using cadence) for cardiovascular health. Finally, our findings may inform intervention studies that target a decrease in sedentary behaviour and an increase in walking or other physical activity types such as cycling and running among both adults and older adults.

Conclusions

We found age to modify the association between physical behaviours and risk factors for CVD. Our findings indicate that less sedentary behaviour and more walking is associated with a lower risk of CVD among older adults, while activity types of higher intensities seem to be associated with a lower risk among adults.

List of Abbreviations

CVD, cardiovascular disease
SBP, systolic blood pressure
WC, waist circumference
LDL-C, low-density lipoprotein cholesterol
VO$_2$max, maximal aerobic capacity
HIPA, high-intensity physical activity
CoDA, compositional data analysis
CCHS, Copenhagen City Heart Study

USA, United States of America

UK, United Kingdom

BMI, body mass index

WHO, World Health Organization

Q1-Q3, first and third quartile

CI, confidence interval

ilr, isometric log-ratio

LIPA, light intensity physical activity

MVPA, moderate-to-vigorous physical activity

IHD, ischaemic heart disease

HDL-C, high-density lipoprotein cholesterol

Declarations

Ethics approval and consent to participate

The Danish Data Protection Agency approved the analysis of the study data (approval no.: 2001-54-0280; 2007-58-0015, 2012-58-0004, HEH-2015-045, l-suite 03741). The National Committee on Health Research Ethics approved the data collection (approval no.: VEK: H-KF 01-144/01 31104). Participation was voluntary and in agreement with the Declaration of Helsinki. Written informed consent to participate in the fifth examination of the CCHS was obtained from the participants.

Consent for publication

Not applicable.

Availability of data and material

The data generated and analysed during the current study are not publicly available;
however, anybody can apply for the use of data by contacting the steering committee of the CCHS (65).

Competing interests
The authors declare that they have no competing interests.

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Authors’ contributions
PS established and designed the CCHS. PS and AH developed the initial idea, design and established funding of the accelerometer measurements in the fifth examination of the CCHS. MSJ, KS, AH and MK conceptualised and designed the present study with feedback from EP, JLM and PS. MSJ led the work with processing the raw accelerometer data, performed the analyses, the initial data interpretation, and formulated and developed the manuscript. KS, EP, JLM, PS, AH and MK critically revised the manuscript. All authors have discussed the results and have given approval to the publishing of the final version of the manuscript.

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### Tables

**Table 1. Characteristics of 773 adults and 280 older adults of the final study population participating in the fifth examination Copenhagen City Heart Study (Denmark)**

| Characteristics                                      | Adults (<65 yrs.) | Older adults (≥65 yrs.) |
|------------------------------------------------------|-------------------|-------------------------|
|                                                      | n (%) / Median (Q1-Q3) | n (%) / Median (Q1-Q3)  |
| Accelerometer wear time                              | 773 (100.0)       | 280 (100.0)             |
| Median minutes/day                                    | 1425.00 (1386.29-1440.00) | 1432.50 (1390.43)       |
| Number of valid days of measurement                  | 773 (100.0)       | 280 (100.0)             |
| Median number of days                                 | 6 (6-7)           | 6 (6-6)                 |
| Sex distribution                                     | 773 (100.0)       | 280 (100.0)             |
| Women                                                | 454 (58.73)       | 154 (55.00)             |
| Men                                                  | 319 (41.27)       | 126 (45.00)             |
| Age                                                  | 773 (100.0)       | 280 (100.0)             |
| Median years                                         | 48.26 (35.29-56.87) | 72.70 (68.63-77.70)     |
| Systolic blood pressure                              | 773 (100.0)       | 280 (100.0)             |
| Median (mm Hg)                                        | 127.00 (117.50-137.50) | 143.75 (129.38-156.50) |
| Diastolic blood pressure                             | 773 (100.0)       | 280 (100.0)             |
| Median (mm Hg)          | 77.00 (71.00-83.50) | 77.50 (70.50-) |
|------------------------|---------------------|----------------|
| Blood pressure classification |                      |                |
| Normal                  | 773 (100.0)         | 280 (100.0)    |
| Grade 1 hypertension    | 586 (75.81)         | 119 (42.5)     |
| Grade 2 or 3 hypertension| 163 (21.09)         | 126 (45.0)     |
|                        | 24 (3.10)           | 35 (12.5)      |
| Use of prescribed medication |                    |                |
| Yes                     | 773 (100.00)        | 280 (100.0)    |
|                         | 76 (9.83)           | 49 (17.5)      |
| Waist circumference     | 773 (100.0)         | 280 (100.0)    |
| Median (cm)             | 83.00 (76.00-93.00) | 89.00 (81.00-) |
| Waist circumference (women >80 cm; men >94 cm) |                      |                |
| Under cut-point         | 195/454 (42.95)     | 90/154 (58.0)  |
| Over cut-point          | 97/319 (30.41)      | 60/126 (47.0)  |
| BMI, WHO classification |                      |                |
| Underweight             | 773 (100.0)         | 280 (100.0)    |
| Normal                  | 10 (1.29)           | 1 (0.36)       |
| Overweight              | 449 (58.09)         | 143 (51.0)     |
| Obese                   | 240 (31.05)         | 105 (37.5)     |
|                        | 74 (9.57)           | 31 (11.07)     |
| Low-density lipoprotein cholesterol |        |                |
| Median (mmol/L)         | 773 (100.0)         | 280 (100.0)    |
|                        | 3.03 (2.47-3.64)    | 3.34 (2.83-3.48) |
|                        | [2.93-3.11]*        | [3.18-3.48]    |
| Years of education      | 773 (100.00)        | 274 (97.8)     |
| Median years            | 13 (12-14)          | 10 (8-12)      |
| Level of education      | 771 (99.74)         | 278 (99.2)     |
| No [further] education  | 71 (9.21)           | 31 (11.1)      |
| Short education (up to 3 years) | 57 (7.39)       | 37 (13.31)     |
| Vocational or comparable education (1-3 years) | 127 (16.47) | 83 (29.8)     |
| Higher education (≥3 years) | 207 (26.85) | 73 (26.26)    |
| University education    | 309 (40.08)         | 54 (19.4)      |
| Household income        | 762 (98.58)         | 272 (97.1)     |
| Low (<200 000 DKK)      | 111 (14.57)         | 79 (29.04)     |
| Middle (200 000-600 000 DKK) | 286 (37.53)   | 153 (56.2)     |
| High (≥600 000 DKK)     | 365 (47.90)         | 40 (14.71)     |
| Smoking status          | 758 (98.06)         | 274 (97.8)     |
| Current smoker          | 129 (17.02)         | 49 (17.88)     |
| Previous smoker         | 296 (39.05)         | 134 (48.9)     |
| Non-smoker              | 333 (43.93)         | 91 (33.21)     |
| Self-rated fitness compared to peers |          |                |
| Same                    | 771 (99.74)         | 279 (99.6)     |
| Better                  | 380 (49.29)         | 127 (45.5)     |
| Worse                   | 259 (33.59)         | 131 (46.9)     |
|                        | 132 (17.12)         | 21 (7.53)      |
| Self-rated general health|                      |                |
| Excellent or Very good  | 769 (99.48)         | 276 (98.5)     |
|                         | 363 (47.20)         | 116 (42.0)     |
| Good | Less good or Poor |
|------|------------------|
| 304 (39.53) | 130 (47.1) |
| 102 (13.26) | 30 (10.87) |

\(N/n\), number of observations

\(y\), years

Q1-Q3, first and third quartile

Blood pressure classification is based on the 2013 European Society of Hypertension/European Society of Cardiology guidelines for the management of arterial hypertension (the normal category includes high normal).

BMI, body mass index

BMI was classified according to the WHO classification (Underweight, \(<18.5\ \text{kg/m}^2\); Normal weight, \(18.5-<25.0\ \text{kg/m}^2\); Overweight, \(25.0-<30.0\ \text{kg/m}^2\); Obese, \(\geq 30\ \text{kg/m}^2\).

DKK, Danish krone

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**Invited: \(N = 9215\)**

From previous study examinations: \(n = 8234\)

Newly invited: \(n = 981\)

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**Participated: \(N = 4543\)**

From previous study examinations: \(n = 4012\)

Newly invited: \(n = 531\)

Participation rate: 49.3%

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Non-responders: \(N = 4672\)

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No accelerometer data:
Figure 1

Formation of the final study population of eligible participants in the fifth examination of the Copenhagen City Heart Study. N/n indicates number of participants.
Illustration of adjusted estimated differences in systolic blood pressure (mm Hg) given the reallocation of time between sedentary behaviour and A) walking, and B) HIPA among 773 adults and 280 older adults. A negative reallocated value reflects the pairwise reallocation of time from sedentary behaviour to walking or HIPA, while a positive value reflects the reallocation of time from walking or HIPA.
to sedentary behaviour. The origin represent the reference composition (i.e.,
group-specific geometric mean) that corresponds to ii) 579.8 min sedentary
behaviour, 193.4 min standing, 71.1 min moving, 85.5 min walking, 14.2 min
HIPA, and 496.1 min in bed among adults, and ii) 589.1 min sedentary behaviour,
186.5 min standing, 72.9 min moving, 74.9 min walking, 6.9 min HIPA, and 509.7
min in bed among older adults. Vertical lines correspond to the 95% confidence
intervals. HIPA is high-intensity physical activity (i.e., sum of climbing stairs,
running, cycling and rowing).
Figure 3

Illustration of adjusted estimated differences in waist circumference (cm) given the reallocation of time between sedentary behaviour and A) walking, and B) HIPA among 773 adults and 280 older adults. A negative reallocated value reflects the pairwise reallocation of time from sedentary behaviour to walking or HIPA, while a positive value reflects the reallocation of time from walking or HIPA to sedentary
behaviour. The origin represent the reference composition (i.e., group-specific geometric mean) that corresponds to ii) 579.8 min sedentary behaviour, 193.4 min standing, 71.1 min moving, 85.5 min walking, 14.2 min HIPA, and 496.1 min in bed among adults, and ii) 589.1 min sedentary behaviour, 186.5 min standing, 72.9 min moving, 74.9 min walking, 6.9 min HIPA, and 509.7 min in bed among older adults. Vertical lines correspond to the 95% confidence intervals. HIPA is high-intensity physical activity (i.e., sum of climbing stairs, running, cycling and rowing).
Illustration of adjusted estimated differences in low-density lipoprotein cholesterol (mmol/L) given the reallocation of time between sedentary behaviour and A) walking, and B) HIPA among 773 adults and 280 older adults. A negative reallocated value reflects the pairwise reallocation of time from sedentary behaviour to walking or HIPA, while a positive value reflects the reallocation of
time from walking or HIPA to sedentary behaviour. The origin represent the reference composition (i.e., group-specific geometric mean) that corresponds to

ii) 579.8 min sedentary behaviour, 193.4 min standing, 71.1 min moving, 85.5 min walking, 14.2 min HIPA, and 496.1 min in bed among adults, and ii) 589.1 min sedentary behaviour, 186.5 min standing, 72.9 min moving, 74.9 min walking, 6.9 min HIPA, and 509.7 min in bed among older adults. Vertical lines correspond to the 95% confidence intervals. HIPA is high-intensity physical activity (i.e., sum of climbing stairs, running, cycling and rowing).

Supplementary Files

This is a list of supplementary files associated with the primary manuscript. Click to download.

STROBE_checklist_cross-sectional_Johansson et al.pdf
Johansson et al_Additional files.pdf