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Association between accelerometer-measured physical activity, glucose metabolism, and waist circumference in older adults

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ABSTRACT

Aims: To examine the association of physical activity (PA) and sedentary time (ST) with glucose metabolism according to waist circumference (WC) in older people.

Methods: A population-based sample of 702 individuals (aged 67–70 years) wore wrist-worn accelerometers for two weeks and underwent an oral glucose tolerance test. The associations between moderate-to-vigorous (MVPA) and light (LPA) PA, ST, and glucose metabolism across the tertiles of WC were analysed using general linear regression.

Results: Among highest WC tertile, LPA negatively associated with fasting insulin (β = − 0.047, 95% CI − 0.082 to − 0.012), HOMA-IR (β = − 0.098, 95% CI − 0.184 to − 0.012), and HOMA-β (β = − 3.367, CI − 6.570 to − 0.783). ST associated with 120 min glucose (β = 0.140, CI 0.021 to 0.260). Among lowest WC tertile, MVPA negatively associated with 30 min insulin (β = − 0.086, 95% CI − 0.168 to − 0.004) and 120 min insulin (β = − 0.160, 95% CI − 0.257 to − 0.063) and positively associated with Matsuda index (β = 0.076, 95% CI 0.014 to 0.139). Light PA negatively associated with 120 min insulin (β = − 0.054, 95% CI − 0.104 to − 0.005).

Conclusion: With the limitation of the cross-sectional study, reducing ST and increasing LPA may be beneficial for glucose metabolism among abdominally obese older adults. Lean older adults could benefit more from increasing MVPA.

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1. Introduction

Physical inactivity is estimated to cause 9% of premature mortality worldwide—as a risk factor, it is similar to obesity and smoking [1]—and cost more than $67.5 billion per year [2]. Recommended levels of physical activity (PA) are associated with 30% lower risk of type 2 diabetes [3]. High sedentary time (ST) is an independent risk factor for type 2 diabetes [4], and older adults are more sedentary than their younger peers [5].

Higher levels of accelerometer-measured moderate-to-vigorous physical activity (MVPA) and light physical activity (LPA) [6] as well as lower levels of ST [7], independently after the adjustment of MVPA, are associated with lower fasting plasma glucose values in older adults and lower 120 min glucose levels in oral glucose tolerance test (OGTT) in middle-aged adults [8]. An inverse association between MVPA and fasting insulin values [6] and a positive association between ST and fasting insulin values [9] have also been reported in older people. Lower ST [10] and higher LPA [11] are associated with lower homeostatic model assessment for insulin resistance (HOMA-IR) values in older adults.

Low waist circumference (WC) is a strong predictor of good metabolic health, and high WC is a risk factor for type 2 diabetes [12,13]. In older adults, high MVPA [6,14] and LPA [6,11] are associated with lower WC, and high ST is associated with higher body mass index (BMI) [15].

Accelerometers have been found to be feasible and reliable in quantifying the habitual levels and intensity of PA and ST in older adults for large-scale epidemiologic studies [16,17]. Knowledge about the association between accelerometer or pedometer measured daily step counts and glucose metabolism in adults is inconsistent [18]. A recent prospective cohort study found a threshold of 4500 steps/day to best distinguish older adults with the lowest risk of diabetes. This is much lower than the usual recommendation of 10,000 steps [19]. However, knowledge about accelerometer-measured PA—especially LPA and ST as well as their association with health outcomes in older adults—remains insufficient [14,17].

At present, to our knowledge there have been no studies on the associations between PA, ST, glucose metabolism, and WC in older adults. The current physical activity recommendations may be challenging to fulfil, especially for older adults with obesity, physical limitations, and comorbidities. Thus, it is important to identify the high-risk older subjects for type 2 diabetes to be able to tailor PA prescriptions more individually. The aim of this population-based study was to investigate how accelerometer-measured PA and ST are related to glucose metabolism and whether these associations vary with waist circumference.

2. Subjects, material and methods

2.1. Subjects

Originally, all 1332 individuals born in 1945 living in Oulu, Finland, in 2001 (Oulu45 cohort) were invited to participate in the baseline clinical examination in 2001–2003, and 993 (75%) of them participated. Participants who were alive and whose address was known (n = 887) were invited to participate in the follow-up study in 2013–2015 (participant age 67–70 years). The final study population (n = 702) of this cross-sectional study consisted of men (n = 293) and women (n = 409) who had participated in the follow-up data collection (79% of those 887 who were invited to the follow-up study, 53% of the original study population of 1332 individuals). The glucose and insulin values of all participants without previously diagnosed diabetes were included (n = 615) in the analysis. The OGTT was successfully performed in 607 participants (120 min glucose value measured), and accelerometer-measured PA was successfully measured in 659 participants.

The follow-up study was approved by the Ethical Committee of the Northern Ostrobothnia Hospital District in Oulu, Finland (EETTMK 12/2013), and was performed in accordance with the Declaration of Helsinki. The participants were given oral and written information about the study, and all provided their written consent. The data were analysed at the group level, and the participants' personal details were replaced with identification codes.

2.2. Questionnaires

The participants answered a questionnaire on their health, health behaviours, medication, and socioeconomic situation. Alcohol consumption was investigated with multiple questions about the frequency and consumption of different beverage types, and overall consumption was calculated as grams per week [20]. Smoking status was inquired, and the participants were categorized as current smokers or nonsmokers.

The participants were asked about their perceived health status ('How would you describe your health at the moment?'), perceived physical fitness ('How would you describe your physical fitness at the moment?'), and perceived mental wellbeing ('How would you describe your mental wellbeing at the moment?'). The five response alternatives were dichotomized between satisfied (very good or pretty good) and nonsatisfied (moderate, pretty poor, or very poor).

The perceived physical performance was inquired with four questions: (1) 'At the moment, can you walk up one flight of stairs without stopping?' (2) 'At the moment, can you walk up several flights of stairs without stopping?' (3) 'At the moment, can you walk 0.5 km without stopping?' (4) 'At the moment, can you walk 2.0 km without stopping?' For analyses, the answers were classified into two categories: 'I can do it without any difficulties' and 'I can do it with difficulties or cannot do it'.

To assess lifetime PA, the participants were asked to recall their PA levels at the ages of 15, 30, and 50 years and their current age [21,22]. They reported PA frequencies (at least 15 min continuously) at different intensity levels (light, moderate, and vigorous) at each age. The answers were as follows: less than once a week (1 point), one–two times a week (2 points), three–four times a week (3 points), and at least five times a week (4 points) for each intensity level. For the summary of the results, the participants were assigned 3 (the lowest PA) to 12 (the highest PA) points to indicate their PA level at each age. For lifetime PA, the points for each age were calculated as sums, which ranged between 12 (the lowest PA) and 48 points (the highest PA).

2.3. *Clinical examination*

The participants' height (with 0.5 cm accuracy), weight (with 0.1 kg accuracy), and WC (with 0.5 cm accuracy) were measured by a trained nurse. The WC was measured three times at the midpoint between the lowest rib and the iliac crest [23], and the mean was calculated. The participants were asked to sit for 5 min, and then their blood pressure was measured twice with an automatic electronic blood pressure monitor (Omron M3, Omron Healthcare Europe BV, Netherlands) on their upper left arm, and the mean of the two measurements was used in the analyses. The participants' visceral fat area, fat percentage, and muscle mass percentage were measured via bioelectrical impedance analysis (InBody 720, InBody, Seoul, Korea). The Framingham risk score was used to estimate the 10-year risk of cardiovascular diseases [24].

Grip strength was measured by a handgrip dynamometer (SAEHAN Corporation, Korea) two times for both hands in the standing position, with elbows bent at 90° [25], to the nearest kilogram, and the higher of the two values was recorded. Average grip strength for the right and left hands was used in the analyses. Walking speed (m/s) was measured with a 10 m walking test, where the participants were asked to walk 10 m at their comfortable and habitual walking speed [26]. Lower limb strength was measured with a 30 s chair-to-stand test, where the participants were advised to stand up and sit down on a chair as many times as possible within 30 sec. The participants were advised to place their arms on their chest and to keep their feet apart at hip width [27].

2.4. *Blood samples*

For the participants without previously diagnosed diabetes (type 1 or type 2) or medication for diabetes and with fasting glucose levels < 8.0 mmol/l (Bauer Contour, Bayer Consumer Care AG, Basel, Switzerland), a standardized 75 g OGTT was performed after overnight fasting. Glucose and insulin values were measured before OGTT and during OGTT at 30 min, 60 min, and 120 min after glucose was consumed. The plasma glucose values were analysed immediately after blood samples were taken, and the samples were stored at − 70 °C for subsequent serum insulin level analysis. Glycated haemoglobin (HbA1c) was measured using whole blood samples taken after overnight fasting and analysed immediately after the samples were taken.

Glucose metabolism disorders were defined as type 2 diabetes (120 min glucose ≥ 11.1 mmol/l or fasting glucose ≥ 7.0 mmol/l or HbA1c ≥ 6.5%), impaired glucose tolerance (IGT; 120 min glucose in OGTT ≥ 7.8 mmol/l and < 11.1 mmol/l and fasting glucose < 7.0 mmol/l), and impaired fasting glucose (IFG; fasting glucose between 6.1 and 6.9 mmol/l and 120 min glucose < 7.8 mmol/l) according to the World Health Organization.

Homeostasis model assessments for pancreatic β-cell function (HOMA-β) and hepatic insulin resistance (HOMA-IR) were derived from the fasting plasma glucose and insulin concentrations. The original formulae have been modified for more complex computer-based programs [28]. The Matsuda index was used to measure insulin sensitivity: $(10{,}000/[\{\text{fasting glucose level} \times \text{fasting insulin level}\} \times \{\text{mean glucose level} \times \text{mean insulin level during the OGTT}\}]^{1/2})$ [29].

2.5. *Physical activity*

The PA and ST were measured with a uniaxial wrist-worn accelerometer (Polar Active, Polar Electro Ltd., Kempele, Finland) that provides MET values every 30 s on the basis of daily PA [30]. One MET is equal to an oxygen consumption value of 3.5 mL/kg/min. A strong correlation has been shown between energy expenditure measured by Polar Active and indirect calorimetry ($r = 0.987$) [31] as well as doubly labelled water ($r = 0.86$) [32]. The participants were instructed to wear the activity monitor on the wrist of their nondominant hand for 2 weeks (24 h/day). The activity monitor provided no feedback about the participants' activity level.

Using the thresholds supported by the manufacturer, accelerometer-measured PA was classified into five different activity levels: very light (ST) (1.00–1.99 MET), light (2.00–3.49 MET), moderate (3.50–4.99 MET), vigorous (5.00–7.99 MET), and very vigorous (≥8.00 MET). For the analysis, all activity with intensities of ≥ 3.50 MET, 2.00–3.49 MET, and 1.00–1.99 MET was classified as MVPA, LPA, and ST. All activity with intensities ≥ 1 MET was calculated on monitor wear time and activity < 1 MET as non-wear time. A valid measurement day was defined as having a monitor wear time of ≥ 600 min/day. Participants who had at least four valid days of accelerometer-measured activity were included in the analyses. The mean number of valid measurement days was 13. The first and last measurement days were excluded from the analyses. To examine the proportion of the study participants who met the current PA recommendations, self-reported data on PA was collected by a question 'How often you take part with leisure-time PA at least 30 min at a time?' and responses were categorized as ≥ 5 times a week or < 5 times a week.

2.6. *Waist circumference tertiles*

The participants were grouped into tertiles according to their WC. The grouping was based on separate WC tertiles for men and women as follows:

1) Lowest tertile (men ≤ 93.5 cm; women ≤ 84.0 cm)
2) Middle tertile (men = 93.6–103.9 cm; women = 84.1–93.9 cm)
3) Highest tertile (men ≥ 104.0 cm; women ≥ 94.0 cm)

2.7. Statistics

The results were analysed with IBM SPSS Statistics software (SPSS 24 for Windows, SPSS Inc., Chicago, Illinois), and the statistical significance was set to $p < 0.05$. One-way analysis of variance (ANOVA) for continuous variables with normal distribution (Tukey's post-hoc test for pairwise comparison), Kruskal–Wallis test (the Dunn–Bonferroni method for pairwise comparison), and chi-square test for categorical variables (z-test with Bonferroni correction for pairwise comparison) were used to examine the statistical significance of the differences among the WC classes. Participants with previously diagnosed diabetes were excluded when analysing the values of glucose, insulin, and insulin indices.

The multivariable general linear regression model was used to assess the statistical significance of the associations between MVPA, LPA, and ST and the glucose metabolism variables. The multivariable models were built separately for each WC category and made for the dependent variables that were correlated with MVPA, LPA, and/or ST in terms of WC tertile. The variables MVPA, LPA, ST, sex, diagnosed high blood pressure (yes or no), smoking habit (yes or no), and alcohol consumption (g/week) were used in the model simultaneously. Sosioeconomic factors were not included to the models because based on univariate analyses none of the glucose or insulin variables were associated with living alone or with someone else and only plasma fasting glucose was associated with satisfaction on economic situation. Multicollinearity was examined using the variance inflation factor (VIF) and none was higher than 5 suggesting no multicollinearity in variables included in the final regression model selected. Continuous variables were used as covariates in the model, and dichotomous variables were used as fixed factors. Pairwise interactions among LPA, MVPA, and ST were tested and there were no significant interactions. Insulin variables and Matsuda index values were natural log transformed because of nonnormal distribution.

3. Results

The characteristics of the study participants are presented in Table 1. Over half of the participants reported good perceived health (59.7%), and most participants reported good mental wellbeing (75.4%). Less than one-third of the study population (27.7%) were living alone, and most were satisfied with their economic situation (96.1%). The mean WC was 100 ± 12 cm for men and 90 ± 13 cm for women. One-fourth (24.5%) of the participants reported no alcohol consumption. The percentage of nonalcohol users in the lowest, middle, and highest WC tertiles was 29.3%, 17.5%, and 26.1%, respectively.

Physical activity and functional ability according to the WC tertiles are presented in Table 2. The average daily MVPA, LPA, and ST was 41 ± 29 min/day, 254 ± 79 min/day, and 703 ± 107 min/day, respectively, for the total study population. The duration of MVPA and LPA was 20 and 28 min higher, respectively, in the lowest WC tertile than that in the highest tertile. Participants in the highest WC tertile spent 52 min more in sedentary state than those in the lowest tertile. Based on self-reported PA data 34.0% of the participants met the PA recommendations (52.5% in the lowest WC tertile, 30.6% in the middle tertile and 18.4% in the highest tertile, $p < 0.001$). The mean monitor wear time was 997 ± 81 min/day. There was no significant difference in monitor wear time among

Table 1 – Characteristics of 702 study participants according to the tertiles of waist circumference. Values are numbers (%) unless otherwise stated.

	Lowest tertile of WC n = 244 (34.8%)	Middle tertile of WC n = 217 (30.9%)	Highest tertile of WC n = 241 (34.3%)	All participants n = 702
Sex, men	99 (40.6)	95 (43.8)	99 (41.1)	293 (41.7)
Age; mean (SD)	68.9 (0.5)	68.9 (0.6)	68.8 (0.6)	68.9 (0.6)
VFA (cm^2); mean (SD)	119.2 (24.5)^{ab}	151.2 (19.4)^{c}	180.8 (31.1)***	150.2 (36.3)
Fat (%); mean (SD)	27.4 (7.2)^{ab}	33.8 (6.9)^{c}	40.1 (7.0)***	33.7 (8.8)
Muscle mass (%); mean (SD)	39.7 (4.4)^{ab}	36.4 (4.3)^{c}	33.0 (4.2)***	36.4 (5.1)
Blood pressure, systolic; mean (SD)	147 (22)	147 (19)	150 (19)	148 (20)
Blood pressure, diastolic; mean (SD)	84^{b} (12)	86^{c} (11)	89 (11)***	87 (11)
Hypertension medication	75 (36.8)^{ab}	97 (50.0)^{c}	148 (68.2)***	320 (52.0)
Cholesterol medication	66 (32.4)	61 (31.4)	81 (37.3)	208 (33.8)
Previously diagnosed diabetes	12 (4.9)^{b}	22 (10.2)^{c}	52 (21.6)***	86 (12.3)
Screen-detected type 2 diabetes	5 (2.3)^{ab}	14 (7.3)	23 (12.2)**	42 (7.0)
Screen-detected IGT	41 (18.9)^{b}	42 (23.7)^{c}	66 (40.0)***	149 (26.7)
Screen-detected IFG	17 (9.7)^{b}	17 (12.6)^{c}	25 (25.3)**	59 (14.4)
Framingham risk scores; mean (SD)	18.7 (11.2)^{ab}	22.6 (12.9)^{c}	27.2 (16.3)***	22.9 (14.1)
Current smoker	23 (9.5)	27 (12.6)	26 (11.0)	76 (11.0)
Alcohol consumption (g/week); median (IQR)	1.5 (0.0–9.6)^{ab}	4.4 (0.5–13.3)	3.4 (0.0–17.5)**	2.9 (0.1–13.1)
Perceived health, good	173 (71.2)^{b}	140 (64.5)^{c}	104 (43.5)***	417 (59.7)
Perceived mental wellbeing, good	192 (79.3)^{b}	168 (77.4)	168 (69.7)*	528 (75.4)

WC: waist circumference; VFA: visceral fat area; IGT: impaired glucose tolerance; IFG: impaired fasting glucose; SD: standard deviation; IQR: interquartile range. Differences between WC tertiles analysed with χ^2-test (Pearson chi-square test) for categorical variables, one-way ANOVA for continuous variables with normal distribution, and Kruskal–Wallis test for variables with nonnormal distribution at the significance levels $^{*}p < 0.05$, $^{**}p < 0.01$, and $^{***}p < 0.001$. Only significant ($p < 0.05$) pairwise comparisons are reported: [a]lowest WC tertile compared with middle WC tertile, [b]lowest WC tertile compared with highest WC tertile, and [c]middle WC tertile compared with highest WC tertile. Values are calculated for the number of participants having data on the variable in question.

Table 2 – Physical activity and functional ability according to the tertiles of waist circumference. Values are numbers (%) unless otherwise stated.

	Lowest WC tertile n = 244 (34.8%)	Middle WC tertile n = 217 (30.9%)	Highest WC tertile n = 241 (34.3%)	All participants n = 702
ST (min/day); mean (SD)	677 (99)^{ab}	703 (93)^{c}	729 (120)***	703 (107)
LPA (min/day); mean (SD)	266 (76)^{b}	257 (73)^{c}	238 (86)**	254 (79)
MVPA (min/day); mean (SD)	51 (32)^{ab}	40 (26)^{c}	31 (24)***	41 (29)
Walking speed (m/s); mean (SD)	1.34 (0.20)^{ab}	1.25 (0.19)^{c}	1.20 (0.21)***	1.26 (0.21)
30 s chair-stand test; mean (SD)	17.4 (5.0)^{ab}	16.1 (4.1)^{c}	14.2 (4.5)***	15.9 (4.7)
Grip strength, men; mean (SD)	44.0 (7.4)	46.6 (7.7)	44.9 (8.9)	45.2 (8.1)
Grip strength, women; mean (SD)	26.6 (4.6)	27.0 (5.5)	27.0 (7.1)	26.9 (5.8)
Self-reported functional ability; good	164 (67.5)^{b}	125 (57.6)^{c}	96 (39.8)***	385 (54.9)
Stairs; 1 floor, no problems	234 (97.9)^{ab}	193 (89.4)^{c}	187 (78.6)***	614 (88.6)
Stairs; several floors, no problems	208 (87.4)^{ab}	157 (72.7)^{c}	121 (51.1)***	486 (70.3)
Walking; 0.5 km, no problems	230 (96.2)^{b}	197 (91.6)^{c}	191 (80.6)***	618 (89.4)
Walking; 2.0 km, no problems	220 (92.1)^{ab}	168 (78.1)^{c}	160 (67.8)***	548 (79.4)
Self-reported PA; 15 years old (points); mean (SD)	9.2 (2.5)	9.6 (2.3)	9.6 (2.4)	9.5 (2.4)
Self-reported PA; 30 years old (points); mean (SD)	9.1 (2.4)	9.3 (2.4)	9.2 (2.5)	9.2 (2.4)
Self-reported PA; 50 years old (points); mean (SD)	9.2 (2.2)^{b}	8.7 (2.5)	8.4 (2.4)**	8.7 (2.4)
Self-reported PA; current (points); mean (SD)	8.8 (2.2)^{ab}	7.8 (2.5)^{c}	7.0 (2.5)***	7.9 (2.5)
Self-reported lifetime PA (points); mean (SD)	36.2 (7.7)	35.4 (7.9)	34.5 (7.4)	35.3 (7.7)

WC: waist circumference; ST: sedentary time 1.00–1.99 MET; LPA: light physical activity 2.00–3.49 MET; MVPA: moderate-to-vigorous physical activity $\geq$ 3.50 MET; SD: standard deviation. Differences between WC tertiles analysed with χ^2-test (Pearson chi-square test) for categorical variables and one-way ANOVA for continuous variables at the significance levels $^{*}p < 0.05$, $^{**}p < 0.01$, and $^{***}p < 0.001$. Only significant ($p < 0.05$) pairwise comparisons are reported: ^{a}lowest WC tertile compared with middle WC tertile, ^{b}lowest WC tertile compared with highest WC tertile, and ^{c}middle WC tertile compared with highest WC tertile. Values are calculated for the number of participants having data on the variable in question. Accelerometer-measured PA was successfully measured in 659 participants.

Table 3 – Glucose and insulin levels and insulin indices in oral glucose tolerance test according to the tertiles of waist circumference for participants who had not been previously diagnosed with diabetes.

	Lowest WC tertile n = 232 (37.7%)	Middle WC tertile n = 194 (31.5%)	Highest WC tertile n = 189 (30.7%)	All participants n = 615
Fasting glucose (mmol/l)	5.5 (0.5)^{ab}	5.6 (0.5)^{c}	5.9 (0.6)***	5.7 (0.6)
30 min glucose (mmol/l)	8.5 (1.5)^{b}	8.8 (1.5)^{c}	9.3 (1.6)***	8.8 (1.6)
60 min glucose (mmol/l)	8.1 (2.5)^{ab}	8.8 (2.5)^{c}	9.8 (2.8)***	8.8 (2.7)
120 min glucose (mmol/l)	6.3 (1.7)^{ab}	6.7 (1.9)^{c}	7.7 (2.1)***	6.9 (2.0)
Fasting insulin (mU/l)	8.9 (6.8–11.7)^{ab}	12.1 (9.2–15.5)^{c}	16.8 (12.0–22.6)***	11.7 (8.3–15.9)
30 min insulin (mU/l)	49.9 (37.4–73.2)^{ab}	63.3 (47.4–96.1)^{c}	90.5 (57.2–147.4)***	62.5 (43.1–104.4)
60 min insulin (mU/l)	62.0 (46.7–100.1)^{ab}	90.5 (55.1–146.5)^{c}	130.4 (70.4–183.7)***	80.9 (52.8–148.7)
120 min insulin (mU/l)	47.5 (32.5–64.2)^{ab}	63.1 (42.9–114.1)^{c}	107.5 (56.5–181.2)***	60.5 (41.5–121.0)
HbA1c (%)	5.7 (0.3)^{b}	5.8 (0.4)^{c}	5.9 (0.6)***	5.8 (0.4)
HbA1c (mmol/mol)	39 (4)^{b}	40 (4)	41 (6)***	40 (5)
HOMA-IR	1.3 (0.6)^{ab}	1.8 (1.0)^{c}	2.5 (1.3)***	1.8 (1.1)
HOMA-β	96.4 (29.6)^{ab}	111.1 (39.7)^{c}	123.8 (42.6)***	109.5 (38.8)
Matsuda index	83.9 (60.0–106.9)^{ab}	57.1 (40.5–75.5)^{c}	37.1 (27.3–54.8)***	59.0 (38.7–88.5)

WC: waist circumference; HOMA-IR: homeostasis model assessment of insulin resistance; HOMA-β: homeostasis model assessment of β-cell function. Values are mean (SD) or median (25th–75th percentiles); SD = standard deviation. Differences between WC tertiles analysed with one-way ANOVA for variables with normal distribution and the Kruskal–Wallis test for variables with nonnormal distribution. Pairwise comparisons were made if the overall p-value was significant at the significance levels $^{*}p < 0.05$, $^{**}p < 0.01$, and $^{***}p < 0.001$. Only significant ($p < 0.05$) pairwise comparisons are reported: ^{a}lowest WC tertile compared to middle WC tertile, ^{b}lowest WC tertile compared to highest WC tertile, and ^{c}middle WC tertile compared to highest WC tertile. Values are calculated for the number of participants having data on the variable in question. The OGTT was successfully performed in 607 participants (120 min glucose value measured).

the WC tertiles. Walking speed, lower limb strength, and self-reported functional ability were lower in the highest WC tertile than in the lowest and middle WC tertiles (Table 2).

The plasma glucose and serum insulin values (Table 3) throughout the OGTT were significantly higher in the highest WC tertile than in the lowest and middle WC tertiles. Insulin

Table 4 – Final multivariable general linear models for the significant association between accelerometer-measured physical activity and sedentary time and glucose metabolism according to waist circumference tertiles in 615 older individuals.

Variable	Regression coefficient (95% CI)	p-value
Lowest waist circumference tertile (n = 232)		
30 min insulin Ln(x) (mU/l); Model $R^2 = 0.065$		
MVPA, per 30 min increase	−0.086 (−0.168 to − 0.004)	0.040
Alcohol consumption	−0.007 (−0.013 to − 0.001)	0.029
120 min insulin Ln(x) (mU/l); Model $R^2 = 0.107$		
MVPA, per 30 min increase	−0.160 (−0.257 to − 0.063)	0.001
LPA, per 30 min increase	−0.054 (−0.104 to − 0.005)	0.033
Hypertension (nonhypertension as a referent)	0.254 (0.053 to 0.456)	0.014
Matsuda index Ln(x); Model $R^2 = 0.072$		
MVPA	0.076 (0.014 to 0.139)	0.017
Hypertension	−0.148 (−0.279 to − 0.017)	0.027
Middle waist circumference tertile (n = 194)		
0 min glucose (mmol/l); Model $R^2 = 0.082$		
MVPA, per 30 min increase	0.100 (0.010 to 0.189)	0.029
120 min glucose (mmol/l); Model $R^2 = 0.105$		
LPA, per 30 min increase	−0.191 (−0.348 to − 0.035)	0.017
Alcohol consumption	0.019 (0.006 to 0.031)	0.004
Highest waist circumference tertile (n = 189)		
120 min glucose (mmol/l); Model $R^2 = 0.079$		
ST, per 30 min increase	0.140 (0.021 to 0.260)	0.022
0 min insulin Ln(x) (mU/l); Model $R^2 = 0.156$		
LPA, per 30 min increase	−0.047 (−0.082 to − 0.012)	0.009
Sex	−0.166 (−0.328 to − 0.004)	0.045
HOMA-IR; Model $R^2 = 0.184$		
LPA, per 30 min increase	−0.098 (−0.184 to − 0.012)	0.026
Sex	−0.616 (−1.014 to − 0.218)	0.003
HOMA-β; Model $R^2 = 0.160$		
LPA, per 30 min increase	−3.677 (−6.570 to − 0.783)	0.013
Smoking	−25.734 (−46.577 to − 4.890)	0.016

CI: confidence intervals; 30 min insulin Ln(x): natural log-transformed serum insulin level 30 min after drinking glucose; 120 min insulin Ln(x): natural log-transformed serum insulin level 120 min after drinking glucose; 0 min glucose: fasting glucose; 120 min glucose: plasma glucose level 120 min after drinking glucose; HOMA-IR: homeostasis model assessment of insulin resistance; HOMA-β: homeostasis model assessment of β-cell function, MVPA: moderate-to-vigorous physical activity, LPA: light physical activity, ST: sedentary time. The model controlled for MVPA, LPA, ST, sex, hypertension, smoking, and alcohol consumption (g/week). *The statistical significance variables (significance level at $p < 0.05$) are shown in the table. For MVPA, LPA, and ST, the regression coefficient (95% CI) represents every 30 min increase in the examined variable. Values are calculated for the number of participants having data on each variable in the general linear regression model.

resistance determined on the basis of HOMA-IR and HOMA-β was higher in the highest WC tertile than in the lowest and middle tertiles ($p < 0.001$). Whole body insulin sensitivity estimated on the basis of the Matsuda index was lower in the highest ($p < 0.001$) and middle WC tertiles ($p < 0.001$) than in the lowest tertile (Table 3).

The results of the multivariable general linear regression analyses are presented in Table 4. Among the participants in the lowest WC tertile, MVPA was negatively associated with 30 min and 120 min serum insulin levels ($p = 0.040$ and $p = 0.001$, respectively) and positively associated with the Matsuda index ($p = 0.017$). Furthermore, each 30 min increase in LPA was associated with a decrease in 120 min insulin levels ($p = 0.033$) in the lowest WC tertile. In the middle WC tertile, higher MVPA was significantly associated with higher fasting glucose levels ($p = 0.029$), and for each 30 min increase in LPA, there was a 0.191 mmol/l decrease in 120 min glucose value ($p = 0.017$). In the highest WC tertile, LPA was negatively associated with 0 min insulin levels ($p = 0.009$) and HOMA-IR ($p = 0.026$), and HOMA-β ($p = 0.013$) values, and each 30 min increase in ST was associated with a 0.140 mmol/l increase in 120 min glucose levels ($p = 0.022$) (Table 4).

4. Discussion

This cross-sectional population-based study showed, for the first time to our knowledge, that the association of accelerometer-measured PA and ST with glucose metabolism is dependent on WC in older adults. We found that more time spent in LPA and lower ST were independently associated with improved glucose metabolism and decreased insulin resistance, especially in the highest WC tertile. Furthermore, higher MVPA was the most significant factor associated with improved glucose metabolism in the lowest WC tertile.

A recent *meta*-analysis of cohort studies with self-reported PA showed that obese adults with low PA were at the highest risk of getting type 2 diabetes [33]. Previously, a population-based study with accelerometer-measured PA among participants (mean age 66 years) with known risk factors for type 2 diabetes showed that low MVPA in overweight men and high ST in overweight women were associated with impaired glucose metabolism [34]. On the other hand, higher BMI could be also protective especially for mortality in older adults while high WC prognosticate more accurately cardiometabolic risk [35].

The results of the present study are consistent with previous findings on negative associations between accelerometer-measured PA and WC [6,11,14]. In our study, participants in the highest WC tertile spent 52 min/day and 26 min/day more in sedentary activities than those in the lowest and middle WC tertiles, respectively. A recent study showed that obese older adults spent 40 min/day more in sedentary activities than older adults of normal weight [36]. It has also been suggested that a small increase in PA level decreases the risk of type 2 diabetes, especially in previously inactive individuals [37], which supports our findings.

In the present study, glucose and insulin levels during OGTT were higher in more abdominally obese older adults. During OGTT, the plasma glucose levels peaked at 30 min among participants in the lowest WC tertile and at 60 min among participants in the highest WC tertile, which is a sign of impaired glucose tolerance. Previously, a glucose peak later than 30 min was shown to be associated with an increased risk of prediabetes and lower β-cell function [38]. In young adults, low levels of self-reported PA are associated with later and higher glucose peaks during OGTT than high levels of PA [39]. In the linear regression model, the possible explanation behind the positive association between MVPA and plasma fasting glucose in the middle WC tertile can only be speculated and remains unknown.

The Matsuda index, an approximation of whole-body insulin sensitivity, was the lowest in the highest WC tertile. Indices for hepatic insulin resistance (HOMA-IR) and pancreatic β-cell function (HOMA-β) were the highest in the highest WC tertile. Previously, an independent association between high ST [10] and low LPA [11] with higher HOMA-IR values after BMI or WC adjustment has been reported. In the present study, muscle mass percentage was lowest in the highest WC tertile; previous research suggests that lower muscle mass is associated with higher HOMA-IR values [40] and type 2 diabetes in older adults [41].

There is a need for individually tailored PA prescriptions for older adults whose current PA status is low and who may also have multiple chronic conditions. The PA guidelines recommend that older adults should spend 150 min/week in MVPA, and if they have functional limitations, they should determine the PA intensity on the basis of their fitness level and should be as active as they can be [42]. For abdominally obese older adults, the PA guidelines with MVPA may be difficult to achieve. Our results suggest that physically inactive and abdominally obese older adults with the highest risk of type 2 diabetes could benefit from decreasing ST and increasing LPA, but larger and longitudinal studies are needed to confirm these findings.

The main strengths of this study include accelerometer-based measurement of PA and ST and the population-based study design. Device-based measurements of daily PA, especially LPA and ST in free-living conditions, are more accurate than subjective methods, which is important when examining the association between PA and glucose metabolism. In our study, the measurement period of PA was approximately 13 days, which was longer than the usual 1 week; therefore, the results may more accurately represent real-life conditions.

A few limitations of this study must be noted. Causality between PA and glucose metabolism cannot be concluded due to the cross-sectional study design. The wrist-worn accelerometers have been shown to provide less precise estimates of ST than hip-worn monitors among younger subjects [43]. Using the uniaxial accelerometer might affect the amount of PA and ST in this study. Previously it has been shown that uniaxial accelerometers produce higher values for ST and lower values for LPA and MVPA compared with triaxial accelerometers [44]. However, wrist-worn devices are highly acceptable as the data is usually of high quality [45], and the use of wrist-worn monitors has been encouraged in large population-based studies in older adults [46].

For measuring PA, we used thresholds supported by the manufacturer. Previously, it has been shown that the Polar Active monitor used here is more consistent with hip-worn monitors when using standard Polar Active thresholds instead of the widely used thresholds [47]. However, the cut-off points of the accelerometer MET values, which were higher in this study than widely used for other devices, were developed for younger adults, which may affect the measurement reliability among older adults. Higher MET cut-off values in this study could overestimate ST and underestimate measured PA. On the other hand, wrist worn accelerometers may overestimate the amount of MVPA compared to hip worn devices [47]. Generally, the absolute physical capacity of older adults is lower than in younger people and older people have to exert a higher relative effort for a given amount of work [48]. Thus, both the amount ST, LPA and MVPA could be biased by the thresholds used in this study.

This study focused on associations of PA and ST, not cardiorespiratory fitness (CRF), with glucose metabolism, while previously it has been shown that CRF, as a consequence for PA, is a stronger predictor for cardiovascular health than PA [49]. Another limitation of this follow-up study is that only those individuals who had participated in the baseline examinations were invited. It can be assumed that the unhealthiest group of the cohort withdrew already from the baseline examinations. Therefore, the participants in the follow-up study may have been more active and healthier than the whole 1945 birth cohort and the results of this study cannot be generalized to very ill or institutionalized elderly people. This is support by the fact, that in this study mean time spent in MVPA measured with wrist-worn accelerometer was 41 min which is more than in other population studies in older adults which used hip-worn devices [15,50]. On the other-hand, based on self-reported question, on of third participant of this study met physical activity recommendations while about a half of > 60 years old Europeans met the recommendations [51].

In conclusion, this population-based study showed that the association of physical activity and sedentary time with glucose metabolism was dependent on WC in older adults. High time spent in light physical activity and low sedentary time were independently associated with improved glucose metabolism and decreased insulin resistance, especially in the highest WC tertile. With the limitation of the cross-sectional design of this study, the findings suggest that reducing ST and increasing LPA may be beneficial for glucose metabolism and tolerance among older adults with abdominal obesity, whereas lean older adults could benefit more from increasing MVPA.

Authors' contributions

ML and JJ participated in the data collection, analyzing and interpreting the data, and writing the manuscript. MK, MV, and EV assisted in interpreting the data and writing the manuscript. PH helped to plan the study design and participated in the data collection. SK and RK were responsible for planning the study design, and participated in interpreting the data and writing the manuscript. All the authors revised preliminary versions of the manuscript and read and approved the final manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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The authors declare no conflict of interest. The results of this study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation.

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Data availability statement.

Oulu45 data is available from the University of Oulu, Infrastructure for Population Studies. Permission to use the data can be applied for research purposes via electronic material request portal. In the use of data, we follow the EU general data protection regulation (679/2016) and Finnish Data Protection Act. The use of personal data is based on cohort participant's written informed consent at his/her latest follow-up study, which may cause limitations to its use. Please, contact NFBC project center (NFBCprojectcenter@oulu.fi) and visit the cohort website (www.oulu.fi/nfbc) for more information.

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