Reducing prolonged sedentary time using a treadmill desk acutely improves cardiometabolic risk markers in male and female adults

Authors and affiliations: Rachael B Champion [a], Lindsey R Smith [a], Jennifer Smith[a], Bogdana Hirlav [a], Benjamin D Maylor[a], Stephanie L. White [a], Daniel P Bailey[a]

[a] Institute for Sport and Physical Activity Research, School of Sport Science and Physical Activity, University of Bedfordshire, Polhill Avenue, Bedford, MK41 9EA, UK.

Corresponding author: Dr Daniel Bailey: Institute for Sport and Physical Activity Research, School of Sport Science and Physical Activity, University of Bedfordshire, Polhill Avenue, Bedford, Bedfordshire, MK41 9EA. Phone: +441234 793237, email: daniel.bailey@beds.ac.uk.

Abstract word count: 200

Main text word count: 4136

Abstract

The objectives of this study were to evaluate the acute effects of interrupting prolonged sitting with an accumulated 2 h of light-intensity walking on postprandial cardiometabolic risk markers. In this randomised crossover trial, 24 participants (twelve males) aged 18-55 years took part in two, 6.5 h conditions: 1) prolonged sitting (SIT) and 2) sitting interrupted hourly with 20 min light-intensity treadmill desk walking at between 1.2-3.5 km/h^{-1} (INT-SIT). Standardized meals were provided at 0 h and 3 h. Blood samples and blood pressure measures were taken hourly. Statistical analyses were completed using linear mixed models. Postprandial incremental area under the curve responses (mmol/L·6.5 h) for glucose (4.52 [3.47, 5.56] and 6.66 [5.62, 7.71] for INT-SIT and SIT, respectively) and triglycerides (1.96 [0.96, 2.96] and 2.71 [1.70, 3.71] mmol/L·6.5 h, for INT-SIT and SIT, respectively) were significantly lower in INT-SIT than SIT. Mean systolic and diastolic blood pressure responses were lower by 3% and 4%, respectively, in INT-SIT than SIT ($P<0.05$). There was no significant condition x sex interaction effect for any outcomes ($P>0.05$). These findings suggest that interrupting sitting with an accumulated 2 h of light-intensity walking acutely improves cardiometabolic risk levels in males and females compared with prolonged sitting.

Keywords: Sedentary bout; sedentary time; physical activity; cardiometabolic risk; cardiorespiratory fitness

Introduction

Elevated postprandial glucose and triglycerides are significant risk factors for cardiovascular disease and Type 2 diabetes (D'Agostino et al., 2004; Einarson, Machado, & Henk Hemels, 2011). Evidence supports the notion that impaired levels of these cardiometabolic risk markers are associated with high amounts of sedentary behaviour (Healy, Matthews, Dunstan, Winkler, & Owen, 2011), which is defined as any waking behaviour characterized by an energy expenditure ≤1.5 metabolic equivalents (METs), while in a sitting, reclining, or lying posture (Tremblay et al., 2017).

Experimental research has reported that prolonged sedentary behaviour leads to an acute impairment in cardiometabolic risk markers (Stephens, Granados, Zderic, Hamilton, & Braun, 2011). This may be particularly relevant to office-based workers who spend >70% of their working hours seated (Clemes, O'Connell, & Edwardson, 2014). Breaking up prolonged sitting with short, frequent bouts of light-intensity walking imparts beneficial postprandial cardiometabolic responses (Bailey & Locke, 2015; Dunstan et al., 2012; Larsen et al., 2014). In light of such evidence, an expert statement on reducing prolonged periods of sedentary work recommended that desk-based employees should initially accumulate a minimum of 2 h/day of light-intensity activity (standing or light walking) during working hours (Buckley et al., 2015). There is currently limited research evaluating the effects of accumulating ≥2 h of light-intensity walking over a single work day on postprandial cardiometabolic risk (Zeigler, Mullane, Crespo, Buman, & Gaesser, 2016; Zeigler, Swan, Bhammar, & Gaesser, 2015) and none of these studies have examined glucose, insulin, or triglyceride responses. Furthermore, there is limited understanding regarding the influence of sex on cardiometabolic responses to interrupting sedentary time (Dempsey et al., 2016a; Dunstan et al., 2012). One study reported a greater suppression in postprandial glucose in females than males with Type 2 diabetes in response to interrupting sitting (Dempsey et al., 2016a), whereas Dunstan et al. (2012) did not observe any difference in postprandial glucose or insulin responses between male and females who were overweight and obese.

The objectives of this study were, therefore, to evaluate the effects of interrupting prolonged sitting with an accumulated 2 h of light-intensity walking during a simulated work day on postprandial cardiometabolic risk marker responses in sedentary male and females. It was hypothesised that sitting interrupted with 2 h of light-intensity walking would lead to beneficial acute postprandial cardiometabolic responses in both males and females compared with prolonged sitting.

Methods

Study overview

This two-way randomised crossover design study was ethically approved by the University of Bedfordshire School of Sport Science and Physical Activity Ethics Review Committee. All study procedures were undertaken at the University of Bedfordshire Sport and Exercise Science Laboratories. Subsequent to a preliminary testing visit, participants completed two experimental conditions: (1) prolonged sitting and (2) sitting interrupted hourly with 20 min light-intensity treadmill desk walking. Each condition was separated by ≥6 days. Order of the experimental conditions was randomised using a simple computer generated randomisation method (www.randomizer.org). Due to the transient changes that occur in glucose metabolism during the female menstrual cycle (Valdes & Elkind-Hirsch, 1991), females were tested in the follicular phase only.

Participants

Twelve male and twelve female participants aged 18-55 years gave informed consent to take part prior to any test procedures. Participants were required to be sedentary for ≥7 h/day. Exclusion criteria were self-reported diabetes, any known blood borne disease, pregnancy, current or recent smoker, allergy or dislike to foods included in the experimental test meals, and any other health issues that would limit the participant's ability to engage in the activity bouts.

Sample size calculations

The primary outcome was postprandial glucose incremental area under the curve (iAUC). Allowing for an intervention effect of 16% change in glucose iAUC, 10% within-group error variance, a within-person correlation of 0.6, 90% power, and an α of 0.05, it was estimated that 22 participants (eleven male and eleven female) would be required for this two-group, two-treatment crossover design. These estimates were based on previous experimental research reporting a significant reduction in postprandial glucose total area under the curve (AUC) in response to interrupting sitting with light-intensity walking (Bailey & Locke, 2015). The study was also powered to detect a main effect of sex based on a difference of 32% change in glucose iAUC between males and females (Dempsey et al., 2016b), 10% within-group error variance, a within-person correlation of 0.6, 95% power, and an α of 0.05

Preliminary measures

Stature and weight were measured using a stadiometer (Harpenden 98.602, Holtain Ltd., Crymych) and electronic weighing scales (Tanita Corp., Tokyo, Japan), respectively. Participants were then familiarised with the Borg Rating of Perceived Exertion (RPE) scale (Borg, 1982) and the Lifespan TR800-DT5 treadmill desk (LifeSpan, Salt Lake City, UT, USA) that was used during the experimental conditions. Participants then walked on the treadmill desk to determine a perceived light-intensity walking speed (RPE of 6-9) and this speed was then used for that respective participant in the relevant experimental condition. The treadmill desk walking speeds selected by the participants ranged between 1.2 and 3.5 km/h^{-1}. Once the appropriate walking speed had been determined, participants walked at this speed for 15 min whilst typing about something meaningful to them on a laptop computer. The purpose of this was to confirm that the desk height and walking speed selected would be comfortable for the walking bouts performed in the relevant experimental condition (Alderman, Olson, & Mattina, 2014).

Experimental protocol

Figure 1 shows the experimental protocol. The 6.5 h experimental conditions were as follows:

(1) Prolonged sitting (SIT): participants remained seated at a desk and were instructed to minimise excessive movement.

(2) Interrupted sitting (INT-SIT): participants interrupted their sitting with 20 min of light-intensity walking on a treadmill desk at 20 min, 80 min, 140 min, 200 min, 260 min, and 320 min. This resulted in an accumulation of 2 h of light-intensity walking, which was based on recommendations for reducing sedentary work in desk-based employees (Buckley et al., 2015).

Participants attended the laboratories at ~08:30 after an overnight fast. Participants were asked to refrain from caffeine and alcohol for 24 h and avoid exercise for 72 h before experimental conditions based on evidence that a single session of exercise may enhance insulin sensitivity for at least the next 48 h (Mikines, Sonne, Farrell, Tronier, & Galbo, 1988). Participants were asked to weigh and record all food and drink consumed for 24 h preceding the first experimental condition and replicate the quantity and timings of eating for the 24 h period prior to the second experimental condition (Bailey et al., 2016). Participants were asked to travel to the laboratories via motorised transport to minimise physical activity prior to the experimental conditions.

Upon arrival, participants sat for a minimum of 10 min and resting blood pressure (BP) was then measured. Body fat% was then estimated using the Tanita BC-418 Segmental Body Composition Analyzer (Tanita Corp., Tokyo, Japan); this occurred during the first experimental condition only. An activPAL device (PAL Technologies, Glasgow, Scotland) was then attached to the participants' left thigh to be worn during the experimental period. A fasting blood sample was then taken immediately before consumption of a standardised breakfast. The 6.5 h experimental condition began upon the first mouthful of the breakfast meal. Breakfast and

lunch were provided at 0 h and 3 h, respectively, during each experimental condition. During conditions, participants were permitted to read, talk, or work on a laptop computer; this included the treadmill desk walking bouts. To ensure participants remained sedentary during sitting periods, they were pushed in a wheelchair by a researcher when visiting the toilet and the food consumption area.

Meals and water consumption

The standardised breakfast and lunch meals each provided 30% of estimated daily energy requirements for each participant. Energy requirements were estimated for each individual based on body mass using the Mifflin equations (Mifflin et al., 1990). A physical activity factor of 1.4 was applied to represent a sedentary day. Breakfast consisted of cornflakes and whole milk providing 57% carbohydrate, 29% fat and 14% protein. Lunch consisted of a chicken sandwich, salted crisps and chocolate providing 47% carbohydrate, 39% fat, 14% protein. The glycaemic index of the breakfast and lunch meals was 87 and 71, respectively, which was calculated using weighted means of the glycaemic index values for the component foods (Wolever & Jenkins, 1986). Participants were asked to consume each meal within 15 min. The time taken to consume each meal during the first experimental condition was recorded and participants were asked to replicate this as closely as possible during their second experimental condition. During the first condition, water was provided *ad libitum* and the total volume consumed was recorded. This quantity was replicated during the second condition by provision of three equal volumes of water at 0, 120 and 240 min.

Blood collection and biochemistry

During experimental conditions, eight capillary finger prick blood samples were collected using a lancet (Haemolance Plus Lancet, Prospect Diagnostics, Dronfield, UK). The first sample was taken in a fasted state followed by subsequent samples at 45, 105, 165, 225, 285, 345 and 390 min into two EDTA-containing microvettes (Microvette CB300 EDTA, Sarstedt Ltd, Leicester, UK). Approximately 600 µL of whole blood was collected at each time point. From

one microvette, 30 µL of whole blood was used to immediately analyse blood glucose concentration using the YSI 2300 STAT plus glucose and lactate analyzer (YSI Inc., Yellow Springs, OH, USA). The remaining whole blood from both microvettes was centrifuged (Heraeus Pico 17 microcentrifuge, Thermo Scientific, Loughborough, UK) at 2000 × *g* for 5 min. Plasma was then extracted and stored at -80 °C for later batch analysis of insulin and triglyceride concentrations. Plasma insulin concentrations were determined using an enzyme linked immunosorbent assay technique (Mercodia, Uppsala Sweden) and plasma triglyceride concentrations were determined spectrophotometrically using the lipase hydrolysis method (GOP-PAP; Randox, Crumlin, Ireland). Samples from each participant were analysed in the same run to eliminate inter-assay variation.

Blood pressure measurements

During experimental conditions, resting brachial BP was measured on the left arm with participants seated in an upright position using an automatic device (Omron M5-I, Omron Matsusaka Co. Ltd., Matsusaka, Japan). To determine baseline values, BP was measured three times with a 2 min rest between each measure and an average of the three readings was taken. Single measures were then taken at 60, 120, 180, 240, 300, 360, and 390 min.

Calculation of outcome variables

For physical activity outcomes, activPAL manufacturer software (ActivPAL^{TM} Professional V7.2.32) was used to classify data into sitting, standing and stepping categories and generate csv event files for each experimental condition. Data was then trimmed based on condition start/end times prior to data extraction using tailored Microsoft Excel 2017 formulas. Light and moderate-intensity stepping was classified as <3 Metabolic Equivalents (METs) and $\geq$3 METs, respectively. Postprandial glucose, insulin, and triglyceride iAUC was calculated for each 6.5 h experimental period using the trapezoidal rule. Mean arterial pressure (MAP) was calculated as: $MAP \cong P_{Dias} + \frac{1}{3}(P_{Sys} - P_{Dias})$.

Statistical analyses

Statistical analyses were performed using SPSS v23.0 (SPSS Inc., Armonk, N.Y., USA). Normality was checked using standard graphical procedures (Grafen & Hails, 2002). Insulin iAUC was non-normally distributed and was log transformed prior to analysis. The data for this variable was then back-transformed to natural units for reporting to provide meaningful information. Linear mixed models were used to assess the main effect of condition and sex and the condition x sex interaction for the cardiometabolic outcomes. Condition and sex were fixed factors and participants were random factors and these models adjusted for potential confounders (age, body fat% and baseline outcome values). For analysis of physical activity outcomes, linear mixed models were used to assess the main effect of condition, with condition as a fixed factor and participants as random factors. These models did not adjust for any confounders. A two-tailed significance level of ≤0.05 was set. Cohens' d effect sizes were calculated to describe the magnitude of differences between conditions; 0.2, 0.5 and 0.8 indicated a small, medium or large effect, respectively (Cohen, 1988). All data are expressed as mean (95% confidence interval [CI]) unless stated otherwise.

Results

Descriptive characteristics of the participants are reported in Table 1. Participants spent significantly less time sitting and significantly higher time in light and moderate-intensity stepping in INT-SIT compared with SIT (Table 2).

Baseline and iAUC values for each cardiometabolic outcome can be seen separately for males and females in Table 3. Baseline concentrations of insulin were significantly higher in INT-SIT than SIT (12.4 [10.4, 14.7] and 9.3 [7.8, 11.0] μU/mL, respectively) and significantly higher in males than females (13.7 [10.8, 17.3] and 8.4 [6.6, 10.6] μU/mL, respectively). There were no significant differences in baseline values between SIT and INT-SIT for glucose (4.39 [4.24, 4.55] and 4.45 [4.30, 4.61] mmol/L, respectively), triglycerides (0.88 [0.67, 1.10] and 0.97 [0.76, 1.19] mmol/L, respectively), systolic BP (119 [114, 123] and 120 [115, 124] mmHg,

234 respectively), and diastolic BP (78 [74, 81] and 78 [75, 81] mmHg, respectively). Males had
235 significantly higher baseline values than females for glucose (4.75 [4.53, 4.96] and 4.10 [3.88,
236 4.31] mmol/L, respectively), triglycerides (1.36 [1.08, 1.63] and 0.50 [0.22, 0.78] mmol/L,
237 respectively), systolic BP (129 [123, 136] and 109 [103, 116] mmHg, respectively), and
238 diastolic BP (84 [80, 89] and 71 [67, 76] mmHg, respectively).
239
240 Figure 2 shows glucose, insulin, triglyceride, and BP responses over time for each condition.
241 There was a significant main effect of condition for glucose iAUC with concentrations being
242 38% lower in INT-SIT compared with SIT (4.52 [3.47, 5.56] and 6.66 [5.62, 7.71] mmol/L·6.5
243 h, respectively); large effect size (d=1.07). The main effect of sex was not significant (6.74
244 [5.19, 8.29] and 4.44 [2.89, 5.99] mmol/L·6.5 h for males and females, respectively) and
245 neither was the condition x sex interaction for glucose iAUC.
246
247 The main effect of condition (138.0 [109.9, 173.4] and 160.7 [127.8, 201.7] μU/mL·6.5 h for
248 INT-SIT and SIT, respectively) and the condition x sex interaction effect for insulin iAUC were
249 not significant. There was a significant main effect of sex for insulin iAUC with females having
250 lower concentrations than males (91.2 [65.3, 127.4] and 242.7 [173.9, 339.1] μU/mL·6.5,
251 respectively).
252
253 There was a significant main effect of condition for triglyceride iAUC with concentrations being
254 32% lower in INT-SIT compared with SIT (1.96 [0.96, 2.96] and 2.71 [1.70, 3.71] mmol/L·6.5
255 h, respectively); medium effect size (d=0.38). There was a significant main effect of sex with
256 females having lower triglyceride iAUC responses than males (-0.60 [-2.13, 0.93] and 5.27
257 [3.74, 6.79] mmol/L·6.5 h, respectively). The condition x sex interaction was not significant.
258
259 There was a significant main effect of condition for mean resting systolic BP, diastolic BP, and
260 MAP. Systolic BP was 3% lower in INT-SIT than SIT (118 [116, 119] and 122 [120, 124]
261 mmHg, respectively; d=1.15), while diastolic BP was 4% lower (74 [73, 76] and 77 [75, 78]

mmHg, respectively; d=0.70) and MAP 2% lower (89 [87, 90] and 91 [90, 93] mmHg, respectively; d=0.91) in INT-SIT than SIT. The effect size for each of these differences was large. There was a significant main effect of sex for each of these variables with females having lower systolic BP (117 [115, 119] and 123 [120, 125] mmHg, respectively), diastolic BP (74 [71, 76] and 77 [75, 80] mmHg, respectively) and MAP (87 [85, 89] and 93 [91, 95] mmHg, respectively) compared with males.

Discussion

The main findings of this study were that interrupting sitting with an accumulated 2 hours of light-intensity treadmill desk walking leads to an acute improvement in postprandial glucose, triglycerides and BP in sedentary males and females.

The total accumulated 2 h volume of light-intensity walking was based on recommendations that desk-based employees should initially accumulate a minimum of 2 h/day of light-intensity activity during working hours to benefit their health (Buckley et al., 2015). There is limited evidence evaluating the cardiometabolic response to accumulating ≥2 h of light activity in a single work day (Buckley, Mellor, Morris, & Joseph, 2014; Hawari, Al-Shayji, Wilson, & Gill, 2016; Thorp et al., 2014; Zeigler et al., 2016; Zeigler et al., 2015). The majority of these studies evaluated responses to standing protocols (Buckley et al., 2014; Hawari et al., 2016; Thorp et al., 2014). Standing continuously for 185 min in an afternoon significantly attenuated postprandial glucose responses by 43% (Buckley et al., 2014), whereas alternating between a sitting and standing posture every 30 min (2 h standing in total) significantly attenuated postprandial glucose by 11% (Thorp et al., 2014). However, accumulating 4 h of standing in prolonged bouts (alternating between sitting and standing every 15 min) or short intermittent bouts (standing for 90 s at a time interspersed with 30 s sitting) did not lead to any significant differences in postprandial glucose, insulin or triglycerides compared with prolonged sitting (Hawari et al., 2016). It is possible that the standing bouts were not long enough in duration in the study by Hawari et al. (2016) to elicit a beneficial response. In the present study, engaging

in shorter light-intensity walking bouts (20 min) was sufficient to significantly attenuate postprandial glucose and triglycerides by 38% and 32%, respectively, potentially due to increased muscular-contraction mediated disposal of these metabolites (Bailey & Locke, 2015). Similar to the current study, engaging in progressively longer treadmill desk walking bouts over the course of the day (from 10 min up to 30 min; total volume of 2.5 h) significantly lowered systolic and diastolic BP compared with prolonged sitting (Zeigler et al., 2016; Zeigler et al., 2015). The study by Zeigler et al. (2015) that was performed in the participants' normal office environment also reported a significant decrease in fatigue following the treadmill desk walking day. These findings suggest that treadmill desk walking may be an effective intervention for reducing cardiometabolic disease risk in office workers.

Although several studies have reported beneficial cardiometabolic responses to accumulating ≥2 h of light activity in a single work day, interrupting sitting with a lower total volume of light activity may also be effective. Several studies report attenuations in glucose when non-overweight, overweight/obese, and dysglycaemic participants engage in light-intensity walking for 2-5 min every 20-30 min (Bailey & Locke, 2015; Bergouignan et al., 2016; Dunstan et al., 2012; Henson et al., 2016; Pulsford, Blackwell, Hillsdon, & Kos, 2017). However, some studies did not observe significant changes in glucose in response to 2 min light-intensity walking every 20 min (Bailey et al., 2016; Hansen, Andersen, Vinther, Pielmeier, & Larsen, 2016). It is difficult to explain the disparity in findings from Bailey et al. (2016) and Hansen et al. (2016) as these studies used similar designs and study samples to other studies (Bailey & Locke, 2015; Pulsford et al., 2017), however, this may be due to differences in the composition of the meals provided during the experimental conditions. It is unknown whether the participants in the studies that reported negligible responses would have benefited from longer duration light-intensity walking bouts and further research is required to elucidate the differential effects of interrupting sitting with varying frequency and duration of physical activity.

Unlike the present study, previous research has reported attenuated insulin responses to interrupting sitting with 2-5 min of light-intensity walking every 20-30 min (Dunstan et al., 2012; Henson et al., 2016; Pulsford et al., 2017).The sample in the current study were in good general health and may have been more insulin sensitive than the participants in the studies by Dunstan et al. (2012) and Henson et al. (2016). This may thus explain the lack of change in insulin in the present study. However, the participants in the study by Pulsford et al. (2017) were of a similar health status to the present study. The use of capillary blood for determination of plasma insulin concentrations in the present study, rather than venous blood as used in previous studies, could therefore partly explain the disparity in findings. Indeed, prior exercise may alter the difference between arterialised and venous insulin sensitivity responses (Edinburgh et al., 2017), which may limit direct comparisons being made between studies.

Research evaluating BP responses to interrupting sitting with light-intensity activity is limited. In addition to the studies by Zeigler et al. (Zeigler et al., 2016; Zeigler et al., 2015) discussed above, Larsen et al. (2014) observed a significant reduction in systolic and diastolic BP in response to 2 min light-intensity walking every 20 min. It is likely that a complex interaction of exercise-induced mechanisms can account for the reduced BP responses, including changes in cardiac output and peripheral vascular resistance that are regulated by thermoregulation, blood volume, sympathetic and afferent nerve activity, and vasoactive substances (MacDonald, 2002). However, there were no differences in MAP in the study by Larsen et al. (2014), which is in contrast to the present study. It is possible that the longer walking bouts in the present study caused more pronounced vascular responses.

In the limited research evaluating triglyceride responses to interrupting sitting with light-intensity activity, 3-5 min of light-intensity walking every 30 min did not result in a significant attenuation compared with prolonged sitting in Type 2 diabetes and dysglycaemic participants (Dempsey et al., 2016a; Henson et al., 2016). This is in contrast to the current study that

demonstrated a significant 32% triglyceride attenuation in the interrupted sitting condition. This might suggest that interrupting sitting with longer bouts of light-intensity walking may be more effective in attenuating the rapid inactivity-induced decrease in lipoprotein lipase activity that occurs in animal models (Bey & Hamilton, 2003). Future research should therefore investigate lipoprotein lipase responses to the experimental protocols in the present study to provide mechanistic explanations. Furthermore, the potential for interrupting sitting with longer bouts of light-intensity walking should be studied as a potential therapeutic intervention in at-risk populations, such as Type 2 diabetes and dysglycaemia.

There was no significant condition x sex interaction effect in the present study for any of the cardiometabolic outcomes, indicating that males and females responded similarly to interrupting sitting. This is in contrast to Dempsey et al. (2016a) who observed a significant condition x sex interaction for the difference in glucose responses between prolonged sitting and interrupting sitting with light-intensity walking (no condition x sex interactions were observed for insulin or triglycerides). The results indicated that the magnitude of attenuation from interrupting sitting was greater in women than in men (Dempsey et al., 2016a). Previous research also suggests that young women have greater protection from adverse macrovascular responses to prolonged sitting, whereas young men exhibit more consistent declines in flow mediated dilation (Vranish et al., 2017). More research is required to establish sex differences in response to interrupting sitting to identify mechanistic explanations of any differences observed and appropriately inform intervention strategies targeting population subgroups.

As elevated postprandial glucose and triglyceride responses are associated with oxidative stress-induced atherogenic changes and increases in cardiometabolic disease risk (O'Keefe & Bell, 2007), the findings of the present study have potential clinical importance. The 3-4 mmHg lower systolic and diastolic BP responses in the current study could be clinically meaningful if they were sustained, which could extrapolate to a reduced risk of stroke and

ischemic heart attacks by 15% and coronary heart disease by 6% (Cook, Cohen, Hebert, Taylor, & Hennekens, 1995). Interrupting sitting with light-intensity treadmill desk walking could be an effective strategy to reduce cardiometabolic disease risk in office workers. Studies are now needed to determine postprandial cardiometabolic responses to longer-term interventions targeting reductions in prolonged sitting.

This study has some limitations that should be considered. Although the purpose of the study was to examine cardiometabolic responses to standardised meals, normal dietary intake is likely to vary in free-living settings with regards to macronutrient composition, glycaemic index, meal size and frequency. Thus, the interaction between interrupting sitting and habitual dietary patterns remains unclear. The controlled laboratory environment in which the conditions took place limits the ability to generalise the findings to free-living settings where habitual behaviours, such as workload and stress, may affect glucose and BP control. The total volume of walking in the interrupted sitting condition amounted to 2 h, which may be difficult for office workers to achieve who are unable to gain access to a treadmill workstation. Furthermore, the feasibility of treadmill desk workstations in the workplace remains to be determined. It is possible that short-term use of a treadmill desk may decrease work productivity and performance (Ojo, Bailey, Chater, & Hewson, 2018) and future research should thus establish the long term effects of these workstations in the workplace. Lastly, as the study sample were in good general health, it may not be appropriate to generalise the findings to clinical populations.

In conclusion, this study demonstrates that interrupting sitting with an accumulated 2 h of light-intensity walking acutely improves postprandial glucose, triglyceride, and BP responses in males and females compared with prolonged sitting. The findings have application to workplace settings in which treadmill desk walking may be an effective approach for reducing sedentary time and cardiometabolic disease risk in office workers.

References

Alderman, B. L., Olson, R. L., & Mattina, D. M. (2014). Cognitive function during low-intensity walking: a test of the treadmill workstation. *J Phys Act Health, 11*(4), 752-758. doi:10.1123/jpah.2012-0097

Bailey, D. P., Broom, D. R., Chrismas, B. C., Taylor, L., Flynn, E., & Hough, J. (2016). Breaking up prolonged sitting time with walking does not affect appetite or gut hormone concentrations but does induce an energy deficit and suppresses postprandial glycaemia in sedentary adults. *Appl Physiol Nutr Metab, 41*(3), 324-331. doi:10.1139/apnm-2015-0462

Bailey, D. P., & Locke, C. D. (2015). Breaking up prolonged sitting with light-intensity walking improves postprandial glycemia, but breaking up sitting with standing does not. *J Sci Med Sport, 18*(3), 294-298. doi:10.1016/j.jsams.2014.03.008

Bergouignan, A., Latouche, C., Heywood, S., Grace, M. S., Reddy-Luthmoodoo, M., Natoli, A. K., . . . Kingwell, B. A. (2016). Frequent interruptions of sedentary time modulates contraction- and insulin-stimulated glucose uptake pathways in muscle: Ancillary analysis from randomized clinical trials. *Sci Rep, 6*, 32044. doi:10.1038/srep32044

Bey, L., & Hamilton, M. T. (2003). Suppression of skeletal muscle lipoprotein lipase activity during physical inactivity: a molecular reason to maintain daily low-intensity activity. *J Physiol, 551*(Pt 2), 673-682. doi:10.1113/jphysiol.2003.045591

Borg, G. A. (1982). Psychophysical bases of perceived exertion. *Med Sci Sports Exerc, 14*(5), 377-381.

Buckley, J. P., Hedge, A., Yates, T., Copeland, R. J., Loosemore, M., Hamer, M., . . . Dunstan, D. W. (2015). The sedentary office: an expert statement on the growing case for change towards better health and productivity. *Br J Sports Med, 49*(21), 1357-1362. doi:10.1136/bjsports-2015-094618

Buckley, J. P., Mellor, D. D., Morris, M., & Joseph, F. (2014). Standing-based office work shows encouraging signs of attenuating post-prandial glycaemic excursion. *Occup Environ Med, 71*(2), 109-111. doi:10.1136/oemed-2013-101823

Clemes, S. A., O'Connell, S. E., & Edwardson, C. L. (2014). Office workers' objectively measured sedentary behavior and physical activity during and outside working hours. *J Occup Environ Med, 56*(3), 298-303. doi:10.1097/JOM.0000000000000101

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed.). Hillsdale, NJ: Erlbaum.

Cook, N. R., Cohen, J., Hebert, P. R., Taylor, J. O., & Hennekens, C. H. (1995). Implications of small reductions in diastolic blood pressure for primary prevention. *Arch Intern Med, 155*(7), 701-709.

D'Agostino, R. B., Jr., Hamman, R. F., Karter, A. J., Mykkanen, L., Wagenknecht, L. E., Haffner, S. M., & Insulin Resistance Atherosclerosis Study, I. (2004). Cardiovascular disease risk factors predict the development of type 2 diabetes: the insulin resistance atherosclerosis study. *Diabetes Care, 27*(9), 2234-2240.

Dempsey, P. C., Larsen, R. N., Sethi, P., Sacre, J. W., Straznicky, N. E., Cohen, N. D., . . . Dunstan, D. W. (2016a). Benefits for Type 2 Diabetes of Interrupting Prolonged Sitting With Brief Bouts of Light Walking or Simple Resistance Activities. *Diabetes Care*. doi:10.2337/dc15-2336

Dempsey, P. C., Larsen, R. N., Sethi, P., Sacre, J. W., Straznicky, N. E., Cohen, N. D., . . . Dunstan, D. W. (2016b). Benefits for Type 2 Diabetes of Interrupting Prolonged Sitting With Brief Bouts of Light Walking or Simple Resistance Activities. *Diabetes Care, 39*(6), 964-972. doi:10.2337/dc15-2336

Dunstan, D. W., Kingwell, B. A., Larsen, R., Healy, G. N., Cerin, E., Hamilton, M. T., . . . Owen, N. (2012). Breaking up prolonged sitting reduces postprandial glucose and insulin responses. *Diabetes Care, 35*(5), 976-983. doi:10.2337/dc11-1931

Edinburgh, R. M., Hengist, A., Smith, H. A., Betts, J. A., Thompson, D., Walhin, J. P., & Gonzalez, J. T. (2017). Prior exercise alters the difference between arterialised and venous glycaemia: implications for blood sampling procedures. *Br J Nutr, 117*(10), 1414-1421. doi:10.1017/S0007114517001362

Einarson, T. R., Machado, M., & Henk Hemels, M. E. (2011). Blood glucose and subsequent cardiovascular disease: update of a meta-analysis. *Curr Med Res Opin, 27*(11), 2155-2163. doi:10.1185/03007995.2011.626760

Grafen, G., & Hails, R. (2002). *Modern statistics for the life sciences* (1st ed.). New York, USA: Oxford University Press.

Hansen, R. K., Andersen, J. B., Vinther, A. S., Pielmeier, U., & Larsen, R. G. (2016). Breaking up Prolonged Sitting does not Alter Postprandial Glycemia in Young, Normal-Weight Men and Women. *Int J Sports Med, 37*(14), 1097-1102. doi:10.1055/s-0042-113466

Hawari, N. S., Al-Shayji, I., Wilson, J., & Gill, J. M. (2016). Frequency of Breaks in Sedentary Time and Postprandial Metabolic Responses. *Med Sci Sports Exerc, 48*(12), 2495-2502. doi:10.1249/MSS.0000000000001034

Healy, G. N., Matthews, C. E., Dunstan, D. W., Winkler, E. A., & Owen, N. (2011). Sedentary time and cardio-metabolic biomarkers in US adults: NHANES 2003-06. *Eur Heart J, 32*(5), 590-597. doi:10.1093/eurheartj/ehq451

Henson, J., Davies, M. J., Bodicoat, D. H., Edwardson, C. L., Gill, J. M., Stensel, D. J., . . . Yates, T. (2016). Breaking Up Prolonged Sitting With Standing or Walking Attenuates the Postprandial Metabolic Response in Postmenopausal Women: A Randomized Acute Study. *Diabetes Care, 39*(1), 130-138. doi:10.2337/dc15-1240

Larsen, R. N., Kingwell, B. A., Sethi, P., Cerin, E., Owen, N., & Dunstan, D. W. (2014). Breaking up prolonged sitting reduces resting blood pressure in overweight/obese adults. *Nutr Metab Cardiovasc Dis, 24*(9), 976-982. doi:10.1016/j.numecd.2014.04.011

MacDonald, J. R. (2002). Potential causes, mechanisms, and implications of post exercise hypotension. *J Hum Hypertens, 16*(4), 225-236. doi:10.1038/sj.jhh.1001377

Mifflin, M. D., St Jeor, S. T., Hill, L. A., Scott, B. J., Daugherty, S. A., & Koh, Y. O. (1990). A new predictive equation for resting energy expenditure in healthy individuals. *Am J Clin Nutr, 51*(2), 241-247.

Mikines, K. J., Sonne, B., Farrell, P. A., Tronier, B., & Galbo, H. (1988). Effect of physical exercise on sensitivity and responsiveness to insulin in humans. *Am J Physiol, 254*(3 Pt 1), E248-259.

O'Keefe, J. H., & Bell, D. S. (2007). Postprandial hyperglycemia/hyperlipidemia (postprandial dysmetabolism) is a cardiovascular risk factor. *Am J Cardiol, 100*(5), 899-904. doi:10.1016/j.amjcard.2007.03.107

Ojo, S., Bailey, D., Chater, A., & Hewson, D. (2018). The Impact of Active Workstations on Workplace Productivity and Performance: A Systematic Review. *Int J Environ Res Public Health, 15*(3), 417.

Pulsford, R. M., Blackwell, J., Hillsdon, M., & Kos, K. (2017). Intermittent walking, but not standing, improves postprandial insulin and glucose relative to sustained sitting: A randomised cross-over study in inactive middle-aged men. *J Sci Med Sport, 20*(3), 278-283. doi:10.1016/j.jsams.2016.08.012

Stephens, B. R., Granados, K., Zderic, T. W., Hamilton, M. T., & Braun, B. (2011). Effects of 1 day of inactivity on insulin action in healthy men and women: interaction with energy intake. *Metabolism, 60*(7), 941-949. doi:10.1016/j.metabol.2010.08.014

Thorp, A. A., Kingwell, B. A., Sethi, P., Hammond, L., Owen, N., & Dunstan, D. W. (2014). Alternating Bouts of Sitting and Standing Attenuates Postprandial Glucose Responses. *Med Sci Sports Exerc, 46*(11), 2053-2061. doi:10.1249/MSS.0000000000000337

Tremblay, M. S., Aubert, S., Barnes, J. D., Saunders, T. J., Carson, V., Latimer-Cheung, A. E., . . . Participants, S. T. C. P. (2017). Sedentary Behavior Research Network (SBRN) - Terminology Consensus Project process and outcome. *Int J Behav Nutr Phys Act, 14*(1), 75. doi:10.1186/s12966-017-0525-8

Valdes, C. T., & Elkind-Hirsch, K. E. (1991). Intravenous glucose tolerance test-derived insulin sensitivity changes during the menstrual cycle. *J Clin Endocrinol Metab, 72*(3), 642-646. doi:10.1210/jcem-72-3-642

Vranish, J. R., Young, B. E., Kaur, J., Patik, J. C., Padilla, J., & Fadel, P. J. (2017). Influence of sex on microvascular and macrovascular responses to prolonged sitting. *Am J Physiol Heart Circ Physiol, 312*(4), H800-H805. doi:10.1152/ajpheart.00823.2016

Wolever, T. M., & Jenkins, D. J. (1986). The use of the glycemic index in predicting the blood glucose response to mixed meals. *Am J Clin Nutr, 43*(1), 167-172.

Zeigler, Z. S., Mullane, S. L., Crespo, N. C., Buman, M. P., & Gaesser, G. A. (2016). Effects of Standing and Light-Intensity Activity on Ambulatory Blood Pressure. *Med Sci Sports Exerc, 48*(2), 175-181. doi:10.1249/MSS.0000000000000754

Zeigler, Z. S., Swan, P. D., Bhammar, D. M., & Gaesser, G. A. (2015). Walking Workstation Use Reduces Ambulatory Blood Pressure in Adults With Prehypertension. *J Phys Act Health, 12 Suppl 1*, S119-127. doi:10.1123/jpah.2013-0487

Table 1 Descriptive participant characteristics (mean ± SD)

	Males	Females
Age (years)	32.0 ± 10.5	39.5 ± 10.3
Height (cm)	176.7 ± 5.5	166.3 ± 5.1
Weight (kg)	83.4 ± 15.9	68.8 ± 16.2
Body mass index (kg/m^2)	26.6 ± 4.5	24.8 ± 5.1
Body fat%	22.5 ± 5.0	29.8 ± 7.6
Sitting time (h/day)	9.4 ± 2.4	9.2 ± 2.4
Physical activity (MET-min/week)	1823 ± 1658	1618 ± 1182

Table 2 Physical activity during the experimental conditions.

	Prolonged sitting		Interrupted sitting		P value for main effect of condition
Sitting (min)	377.8	(372.2, 383.3)	250.7	(238.8, 262.7)	<0.001
Standing (min)	11.0	(5.4, 16.5)	18.8	(7.6, 29.9)	0.247
Light-intensity stepping (min)	0.9	(0.6, 1.1)	35.3	(18, 52.6)	<0.001
Moderate-intensity stepping (min)	0.4	(0.3, 0.5)	85.2	(67.1, 103.2)	<0.001
Total stepping time (min)	1.3	(0.9, 1.6)	120.5	(117.7, 123.3)	<0.001
Light-intensity steps (*n*)	17	(12, 22)	1045	(539, 1550)	<0.001
Moderate-intensity steps (*n*)	19	(13, 25)	3734	(2920, 4549)	<0.001
Total steps (*n*)	36	(26, 45)	4779	(4423, 5134)	<0.001

Table 3 Biochemical values for each condition

	Prolonged sitting		Interrupted sitting		P value for main effect of condition	P value for main effect of sex	P value for condition x sex interaction
	Males	Females	Males	Females			
Baseline blood glucose (mmol/L)	4.69 (4.45, 4.92)	4.09 (3.86, 4.33)	4.81 (4.57, 5.04)	4.10 (3.86, 4.33)	0.404	**0.001**	0.436
Baseline plasma insulin (μU/mL)	11.9 (9.2, 15.4)	7.2 (5.6, 9.3)	15.7 (12.2, 20.4)	9.7 (7.5, 12.6)	**0.002**	**0.009**	0.869
Baseline triglycerides (mmol/L)	1.23 (0.90, 1.55)	0.54 (0.22, 0.87)	1.49 (1.16, 1.81)	0.46 (0.14, 0.79)	0.479	**<0.001**	0.187
Baseline systolic blood pressure (mmHg)	129 (123, 136)	108 (102, 115)	129 (122, 136)	110 (103, 117)	0.651	**<0.001**	0.609
Baseline diastolic blood pressure (mmHg)	84 (79, 89)	71 (66, 76)	84 (79, 89)	71 (67, 76)	0.818	**0.001**	0.959
Blood glucose iAUC (mmol/L·6.5 h)	8.19 (6.51, 9.86)	5.14 (3.41, 6.87)	5.29 (3.50, 7.07)	3.75 (2.02, 5.47)	**0.001**	0.074	0.198
Plasma insulin iAUC (μU/mL·6.5 h)	266.7 (189.1, 375.4)	96.8 (67.5, 138.6)	221.3 (154.2, 317.6)	86.1 (61.1, 121.3)	0.110	**0.001**	0.665
Triglycerides iAUC (mmol/L·6.5 h)	5.66 (4.11, 7.21)	-0.25 (-1.82)	4.88 (3.27, 6.48)	-0.95 (-2.54, 0.63)	**0.022**	**<0.001**	0.895
Mean systolic blood pressure (mmHg)	124 (121, 127)	119 (116, 122)	121 (118, 124)	115 (112, 117)	**0.010**	**0.003**	0.765
Mean diastolic blood pressure (mmHg)	79 (76, 81)	74 (72, 77)	76 (74, 79)	73 (70, 75)	**0.016**	**0.049**	0.636
Mean arterial pressure (mmHg)	94 (92, 97)	89 (86, 91)	92 (89, 94)	86 (83, 88)	**0.011**	**0.004**	0.768

Data presented as mean (95% CI)

Statistically significant differences highlighted in bold

iAUC, incremental area under the curve

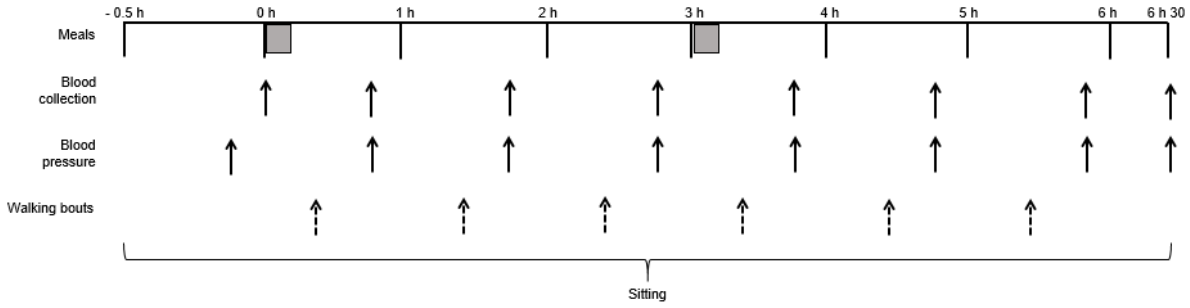

Figure 1 Schematic of experimental protocol

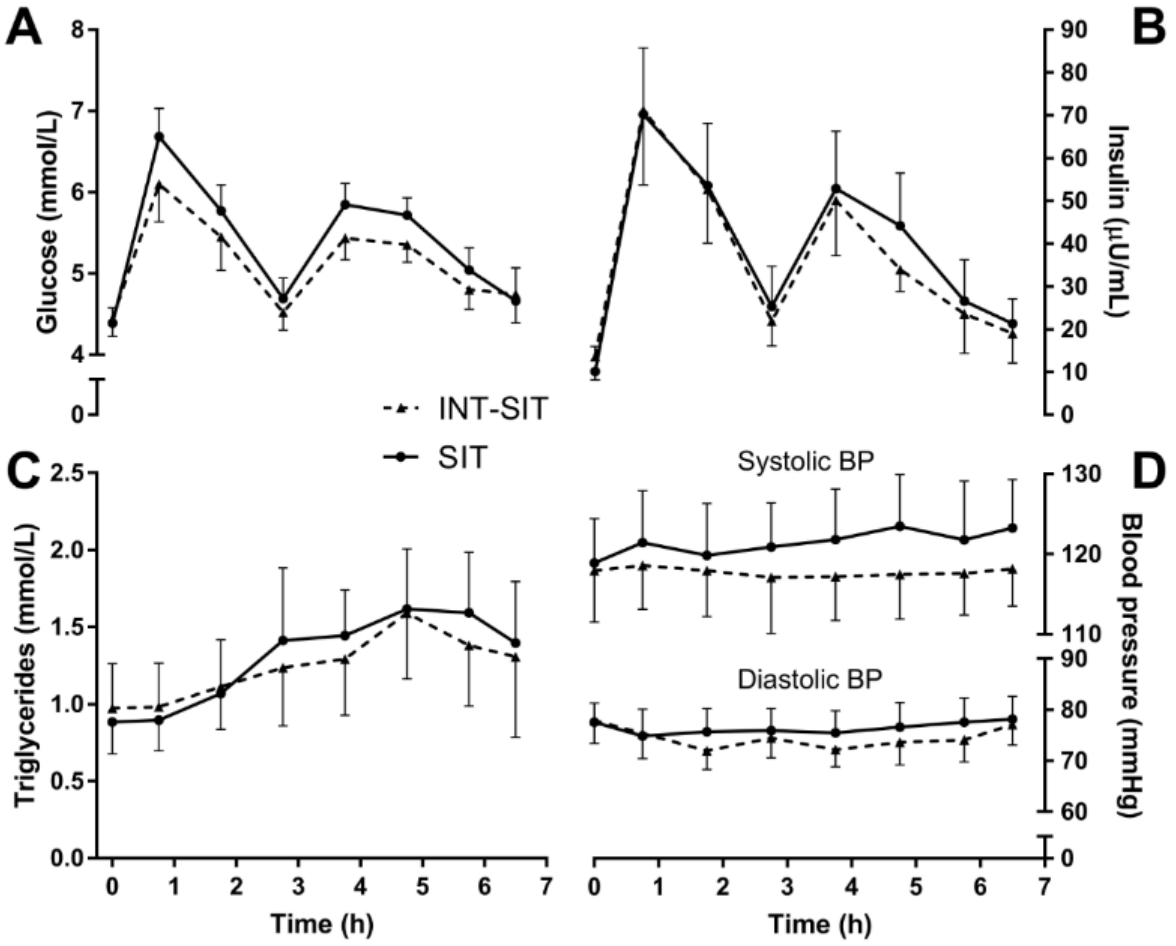

Figure 2 Changes in glucose (A), insulin (B), triglycerides (C), and blood pressure during the prolonged sitting (SIT) and interrupted sitting (INT-SIT) conditions. Data are mean and 95% confidence interval. Some error bars have been omitted for clarity.