Alternating Bouts of Sitting and Standing Attenuate Postprandial Glucose Responses

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ABSTRACT

THORP, A. A., B. A. KINGWELL, P. SETHI, L. HAMMOND, N. OWEN, and D. W. DUNSTAN. Alternating Bouts of Sitting and Standing Attenuate Postprandial Glucose Responses. *Med. Sci. Sports Exerc.*, Vol. 46, No. 11, pp. 2053–2061, 2014. **Purpose**: This study aimed to examine whether reductions in sitting time through alternating 30-min bouts of sitting and standing can reduce postprandial glucose, insulin, and triglyceride responses. **Methods**: Twenty-three overweight/obese sedentary office workers (17 males and six females; mean ± SD: age, 48.2 ± 7.9 yr; body mass index, 29.6 ± 4.0 $kg \cdot m^{-2}$) undertook two short-term (5 d) experimental conditions in an equal, randomized (1:1) order. In a simulated office environment, participants performed typical occupational tasks for 8 $h \cdot d^{-1}$ while in a 1) seated work posture (*control condition*) or 2) interchanging between a seated and standing work posture every 30 min using an electric, height-adjustable workstation (*intervention condition*). Fasting and postprandial blood samples after a mixed test drink were collected hourly for 4 h on days 1 and 5 of each condition to assess serum insulin, plasma glucose, and triglycerides. Dietary intake ($kJ \cdot d^{-1}$) and physical activity were standardized during each condition. The trial was registered with the Australian New Zealand Clinical Trials Registry (ACTRN12611000632998). **Results**: After adjustment for time (days 1 and 5), incremental area under the analyte time curve differed significantly between conditions for plasma glucose ($P = 0.007$) but not for serum insulin or plasma triglycerides. Adjusted mean glucose incremental area under the analyte time curve was lowered by 11.1% after the intervention condition (6.38 $mM \cdot h^{-1}$ (confidence interval, 5.04–7.71)) relative to the control condition (7.18 $mM \cdot h^{-1}$ (confidence interval, 5.85–8.52)). No temporal changes (days 1 vs 5) between conditions were observed. **Conclusions**: Alternating standing and sitting in 30-min bouts results in modest beneficial effects on postprandial glucose responses in overweight/obese office workers. **Key Words:** OCCUPATIONAL SITTING TIME, SEDENTARY BEHAVIOR, CARDIOMETABOLIC RISK, OFFICE WORKERS, SIT–STAND WORKSTATION

Limiting time spent in sedentary behaviors is now considered a distinct public health consideration, which is additional to the importance of meeting physical activity and health guidelines (15). Recently, evidence has emerged, indicating that the pattern in which sedentary time is accumulated may be important (18,20) for reducing risk of type 2 diabetes and other chronic diseases. Observational studies have demonstrated that breaks in sedentary time (such as standing up from a seated position or ambulating) can be beneficially associated with several cardiometabolic biomarkers (body mass index (BMI), waist circumference, serum triglycerides, and 2-h plasma glucose) after controlling for the role of total sedentary time and moderate- to vigorous-intensity physical activity (MVPA) (18). Recent findings from short-term (1 d) laboratory studies in older overweight (8) adults and young healthy (28) adults also demonstrate significant benefits on postprandial glucose and insulin concentrations through intermittently breaking up prolonged sitting with short-duration bouts of treadmill walking.

For working adults, time spent sitting in the workplace can be the single greatest contributor to overall sedentary time. In particular, office workers may spend 75% of their workday sedentary, with much of this time accumulated in prolonged (>30 min) bouts (35). Recent studies have shown that replacing sitting with bouts of standing through the use of height-adjustable workstations is a feasible and practical approach for reducing workplace sitting time (1,19). However, concomitant improvements in cardiometabolic biomarkers have not been observed yet possibly because of the relatively healthy populations examined and the small-scale nature of the intervention trials reported to date.

In a randomized, controlled, laboratory-based trial, we examined the short-term (5 d) effects of reducing workplace

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sitting time through increased standing on postprandial glucose and lipid responses in overweight/obese, but otherwise healthy, sedentary office workers. We hypothesized that changes in postprandial glucose and lipid responses resulting from repeated days of prolonged sitting would be attenuated by incorporating intermittent bouts of standing using an electric, height-adjustable desk during the workday.

METHODS

Participants. Adults age 35–65 yr with a BMI >25 $kg \cdot m^{-2}$ and employed full time in a predominantly sedentary (deskbound) occupation were recruited from the general community through local newspaper articles, electronic advertisements on free volunteer websites, and study flyers posted on public bulletin boards. Participants were excluded if they were pregnant, a smoker, had clinically diagnosed diabetes mellitus, non-English speaking, taking glucose- and/or lipid-lowering medication, employed in a nonsedentary occupation (<4 $h \cdot d^{-1}$ sitting at work), regularly engaged in high levels of MVPA (as defined by the US federal physical activity guidelines, >300 $min \cdot wk^{-1}$) (37), or had a musculoskeletal injury or other health issues that significantly impaired ambulation.

Participants were screened for eligibility via a telephone-administered interview with those who met the inclusion criteria invited to attend a familiarization session. One protocol deviation was permitted for a participant undertaking nonpaid (computer based) work. At the familiarization session, baseline anthropometric measurements were obtained and participants were familiarized with the laboratory's office setting, which included basic office equipment (telephone, computer, and internet) and an electric, height-adjustable desk (model 1600 × 800 mm; Linak, Australia). All participants provided written informed consent, and all received financial compensation for their time after the study.

Study design. The study was performed in a controlled laboratory setting at the Baker IDI Heart and Diabetes Institute in Melbourne, Australia. The protocol was approved by the Alfred Hospital Human Research Ethics Committee and was followed in accordance with the principles of the Declaration of Helsinki. The trial is registered with the Australian New Zealand Clinical Trials Registry (ACTRN12611000632998). The study was initially approved for males only. However, because of the low recruitment rate at the midway point of the study, the protocol was amended to also include females.

Participants underwent two 5-d experimental conditions in a randomized (1:1) order. The prolonged sitting at work (control) condition required participants to perform their usual work tasks in a deskbound (seated) work posture continuously for 8 $h \cdot d^{-1}$ with ambulatory movement restricted to brief interruptions for the toilet only. The prolonged sitting interrupted with standing breaks at work (intervention) condition required participants to perform their usual work tasks while systematically interchanging between a seated and standing posture every 30-min for 8 $h \cdot d^{-1}$ (total of 4-h deskbound and 4-h standing). Sit-to-stand transitions were facilitated through the use of an electric, height-adjustable workstation. Light ambulatory movement was permitted within the confines of the laboratory during the intermittent periods of standing only.

Each experimental condition was performed for five consecutive workdays (Monday to Friday) with a minimum of 7-d washout period in between to eliminate any potential carry-over effects (median, 7 d; range, 7–35 d; 61% had a 7-d washout period) (Fig. 1). To minimize hormonal influences on insulin sensitivity (10), two females with regular menstruation undertook each condition during the follicular phase of their menstrual cycle (determined by the date of onset of their last menstruation).

Study protocol. During the 48-h run-in phase before each experimental condition, participants were asked to record all food and beverage intake and refrain from engaging in structured MVPA (i.e., no physical activity beyond activities of daily living). Participants arrived at the laboratory between 0700 and 0930 h each day after an overnight fast of ≥10 h (no food or drink except water) to commence their 8-h laboratory-based workday.

On the morning of day 1 and day 5 (assessment day) of each experimental condition, participants had their weight

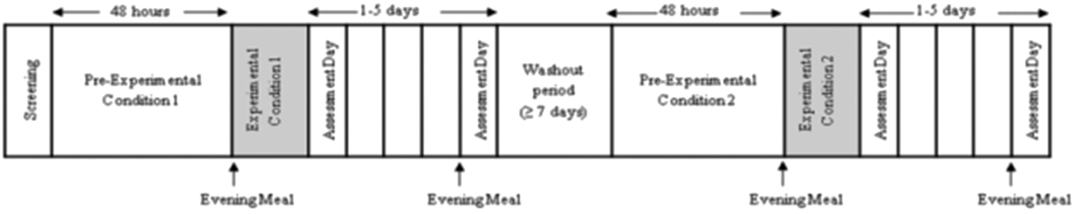

FIGURE 1—Study design. ***Pre-experimental conditions.*** **In the 48-h run-in period, participants were instructed to avoid alcohol, caffeine, and MVPA and to weigh and record all food and beverage intake consumed.** ***Experimental conditions.*** **The randomly assigned orders were 1) prolonged sitting at work (control condition), involving 8-h deskbound work without ambulatory movement or 2) prolonged sitting interrupted with standing breaks at work (intervention condition), involving interchanging between a seated and standing work posture every 30 min (total, 4-h standing + 4-h sitting at work). Each condition was completed over five consecutive workdays (Monday to Friday). Participants were provided with energy-balanced meals (breakfast, lunch, and snacks) during each 8-h laboratory-based workday and were instructed to weigh and record evening meals (if not provided) and to avoid MVPA outside the laboratory.** ***Assessment day.*** **Fasting and postprandial hourly blood was collected (total 4-h) was collected. A mixed test drink was provided.** ***Pre-assessment day evening meal.*** **A prepackaged meal designed to provide 30% of estimated energy intake (based on age, sex, BMI, and sedentary activity level) and macronutrient profile of 12%–15% protein, 30%–33% fat, and 53%–55% CHO was consumed at around 1900 h.** ***Washout period.*** **This period lasted for a minimum of 7 d. Participants were permitted to return to habitual diet and activity patterns.**

and height (day 1 only) measured to the nearest 0.1 kg and 0.1 cm, respectively, while wearing light clothing and no shoes using a portable digital scale set with an adjustable-height rod (Charder Medical MS-3400 Digital, 300 kg × 100 g; Charder Electronic Co. Ltd., Taichung, Taiwan). Height and weight were used to calculate BMI ($kg \cdot m^{-2}$). Waist circumference was measured to the nearest 0.1 cm in the horizontal plane at the narrowest point of the torso, in duplicate.

Fasting venous blood samples (30 mL) were collected via cannulation from the antecubital vein for the analysis of serum insulin, plasma glucose, plasma triglycerides, and plasma cholesterol (total HDL and LDL cholesterol). A standardized 200-mL mixed test drink providing 3195 kJ energy, 75 g CHO (100% corn maltodextrin powder; Natural Health Supplements, Australia), and 50 g fat (Calogen; Nutricia Australia Pty. Ltd., New South Wales, Australia) was administered after fasting blood collection. The specific nutritional components of the mixed test drink have been described elsewhere (8). Briefly, the fat content of the mixed drink provided 60% of the total energy and was composed of 5 g saturated fat, 30.4 g monounsaturated fat, and 14.3 g polyunsaturated fat. Participants consumed the mixed test drink within 10 min (followed by 200 mL of water) before commencing the 8-h workday. Postprandial venous blood samples (15 mL) were collected thereafter at 60, 120, 180, and 240 min. During the blood collection phase on day 1, participants consumed water *ad libitum*; research staff recorded the volume ingested every 60 min and replicated the pattern of water consumption on day 5. A lunch meal was provided at the end of the 4-h blood collection phase.

With the exception of day 5 when participants left the laboratory after the blood collection phase (total, 4 h of work), participants remained working in the laboratory for a total of 8 h each day. After each workday, participants were instructed to consume an early evening meal (1900 h) and to avoid participating in structured MVPA.

Standardization of diet and physical activity. To minimize diet-induced variability in participants' metabolic profile during each experimental condition, standardized daytime meals (breakfast, lunch, and snacks) developed by a registered nutritionist were prepared daily. The meals provided 70% of each participant's daily estimated energy intake (based on an individual's age, gender, and a habitual sedentary activity level) and had a macronutrient profile consistent with a western diet (53%–55% CHO, 12%–15% protein, 30%–33% fat) (6,36). Participants were instructed to abstain from consuming alcohol and caffeine in the 48 h before each assessment day to prevent any potential effects on glucose metabolism. A standardized evening meal that contributed 30% of participants' daily estimated energy intake and had a comparable macronutrient profile with that of daytime meals was also provided (at 1900 h) before each assessment day to minimize fluctuations in participants' fasting metabolic profile the following morning; all other evening meals consumed during the experimental conditions were weighed and recorded in a food diary by the participants.

To monitor daily activity levels and postural allocation during the study, participants wore a triaxial accelerometer (ActiGraph model GTM-3 plus; ActiGraph Corp., Pensacola, FL) and an activPAL^3 triaxial physical activity monitor (PAL Technologies Ltd., Glasgow, Scotland) from the start of the run-in phase to the end of each experimental condition (total, 7 d). Participants wore the activPAL monitor midline on the anterior aspect of the right thigh at all times and the accelerometer on the right hip along the ancillary waistline during waking hours, only removing the devices briefly for water-based activities (i.e., shower, bath). During the washout period between experimental conditions, participants resumed their habitual diet and physical activity patterns.

Analytical methods. All blood samples were centrifuged immediately at 1500*g* for 15 min at 4°C and sent to an off-site testing laboratory (Alfred Hospital Pathology) for analysis except for serum insulin samples, which were stored at −80°C for batch analysis after the study. All blood samples were assessed on an Archicentre ci6200 instrument (Abbott Diagnostics, Lake Forest, IL). Plasma glucose levels were measured by a spectrophotometric hexokinase method; plasma triglycerides, by a glycerol phosphate oxidase method; serum insulin, by a chemiluminescent microparticle immunoassay; total cholesterol, by a standard enzymatic method; and HDL cholesterol, via an accelerator-selective detergent. LDL cholesterol was calculated using the Friedewald formula (13).

Randomization and sample size. To eliminate bias, the order in which participants undertook the two experimental conditions was determined from a computer-generated, block-randomized sequence with a balanced treatment allocation ratio of 1:1 (http://www.randomization.com, accessed April 4, 2010). On the basis of a previous study (8), a sample size of 24 patients was estimated to provide 80% power to show a significant change in glucose incremental area under the analyte time curve (iAUC) of 10% (SD, 16%), insulin iAUC of 12% (SD, 20%), and triglyceride iAUC of 34% (SD, 54%) between conditions on the basis of a two-tailed probability of 0.05.

Calculations and statistical analyses. iAUC was calculated using the trapezium rule during the 4-h postprandial period for glucose, insulin, and triglycerides using GraphPad Prism version 6. The ratio between insulin iAUC (pM) and glucose iAUC (mM) was calculated to provide an integrated assessment of the sensitivity of pancreatic β-cells to secrete insulin in response to glucose (index of β-cell function) (24).

Dietary intake was assessed using computerized software (FoodWorks, 2009) to determine mean energy intake ($kJ \cdot d^{-1}$) and macronutrient content (CHO, protein, or fat ($g \cdot d^{-1}$)). Daily activity was determined from accelerometer data recorded in 10-s epochs using standardized cut points for time spent sedentary (<100 cpm) (17) in light-intensity activity (100–1951 cpm) (12) and in MVPA (≥1952 cpm) (12). Protocol adherence during each experimental condition was determined from activPAL monitor data recorded in 15-s epochs during each 8-h workday. Accelerometer and activPAL monitor data were analyzed using SAS 9.3.1.

Paired *t*-tests were used to assess differences in physical activity and dietary parameters before and during each condition. Separate mixed models adjusting for age, sex, time, and order effects were used to examine between-condition differences in weight, waist circumference, baseline plasma glucose, serum insulin, plasma triglycerides, physical activity, and diet. Sex interaction tests were only performed when the overall condition effect for the outcome measure was statistically significant. Temporal changes between conditions (day 1 vs day 5) were also assessed by including a condition–time interaction term. Linear mixed models with a single random effect (participant) were used to evaluate the differential effects of the experimental conditions (adjusted for time effects) on glucose and triglycerides iAUC and the ratio between insulin iAUC (pM) and glucose iAUC (mM). To account for nonparametric data, insulin iAUC was assessed using a multilevel latent model (generalized linear latent and mixed models). Linear mixed and generalized linear latent and mixed models also tested for differences in temporal changes between conditions. Models were adjusted for within-subject (condition, time, and order) and between-subject covariates (baseline predrink values for the outcome of interest, sex, age, waist circumference, and dietary intake during the condition ($kJ \cdot d^{-1}$)). All statistical analyses were performed using Stata 12.0 for Windows (StataCorp LP) using a probability level of 0.05. Data are reported as marginal mean ± SEM or marginal mean (95% confidence interval (CI)) in the text and tables, unless otherwise indicated.

RESULTS

Between August 29, 2011, and May 3, 2013, a total of 187 potential participants were assessed for study eligibility (Fig. 2). Twenty-six met the inclusion criteria, attended a

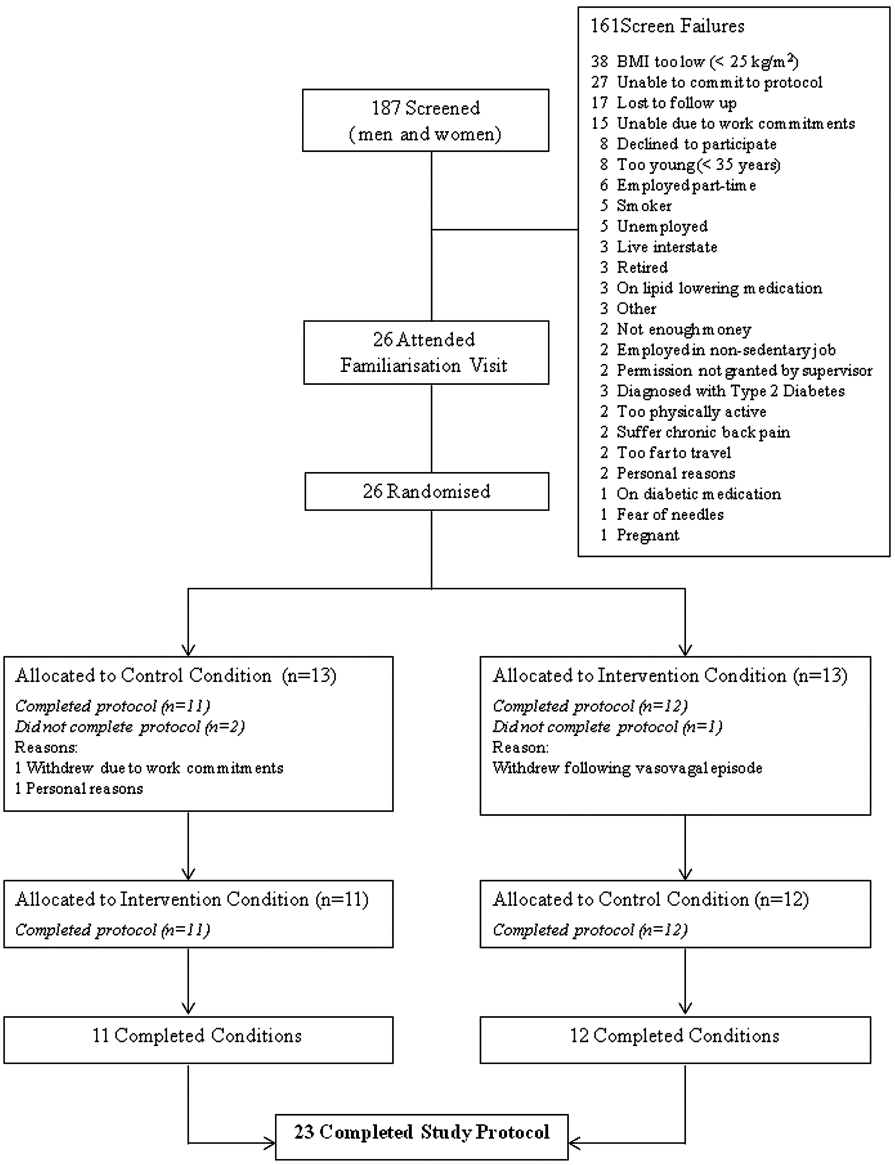

FIGURE 2—Trial CONSORT diagram.

familiarization visit, and were randomly assigned to an order to complete the experimental conditions. Three of those randomized withdrew their consent shortly after enrollment in the trial. The baseline characteristics of the participants who withdrew did not differ significantly from the characteristics of those who completed the trial (data not shown). Complete data for study outcomes were available for 23 participants (17 males and six females).

Biochemical, anthropometric, and sociodemographic characteristics of participants at baseline are presented in Table 1. Briefly, study participants were predominately male, overweight, Caucasian, married, and employed in an office-based role. With the exception of marital status, where the percentage of those married was higher for men than that for women (100% vs 67%, $P < 0.01$), there was no significant sex differences in participant characteristics at baseline (all $P > 0.13$) (data not shown). Two females underwent testing during the follicular phase of their menstrual cycle (mean, 28-d washout period; range, 21–35 d); the remaining four had ceased menstruating.

There was a small albeit significant difference in dietary intake between experimental conditions. With the exception of CHO intake ($g \cdot d^{-1}$), participants consumed a greater amount of energy (mean ± SEM, 11,705 ± 210 vs 11,391 ± 210 $kJ \cdot d^{-1}$; $P = 0.01$), fat (102.1 ± 1.9 vs 95.7 ± 1.9 $g \cdot d^{-1}$, $P > 0.001$), and protein (103.9 ± 2.5 vs 99.5 ± 2.5 $g \cdot d^{-1}$, $P = 0.01$) each day during the intervention condition compared with that during the control condition. Participants' habitual daily energy intake was similar between the run-in phases (control, 10,279 ± 532 $kJ \cdot d^{-1}$, vs intervention, 9923 ± 532 $kJ \cdot d^{-1}$; $P = 0.50$). However, the run-in diets were lower in CHO ($P \leq 0.001$) and energy ($P = 0.008$, intervention condition only) compared with those during the conditions.

TABLE 1. Characteristics of study participants.

	All (n = 23)
Male, n (%)	73.9 (17)
Age (yr)	48.2 ± 8
BMI ($kg \cdot m^{-2}$)	29.6 ± 4.1
Obese (%)[a]	34.8
Waist circumference (cm)	
Males	99.9 ± 10.5
Females	100.4 ± 11.3
Fasting glucose (mM)	5.08 ± 0.46
Fasting insulin (pM)	71.70 ± 39.38
Triglycerides (mM)	1.49 ± 0.57
Total cholesterol (mM	5.15 ± 0.69
LDL cholesterol (mM)	3.33 ± 0.65
HDL cholesterol (mM)	1.13 ± 0.26
Self-reported workplace sitting ($h \cdot d^{-1}$)	6.6 ± 1.2
Self-reported MVPA (%)	
0–75 $min \cdot wk^{-1}$	47.8
75–150 $min \cdot wk^{-1}$	21.7
150–300 $min \cdot wk^{-1}$	30.4
Ethnicity (%)	
Caucasian	87.0
Indian	8.7
Asian	4.3
Married (%)	91.3
Occupation (%)	
Office worker	73.9
Self-employed[b]	17.4
Student/other[c,d]	8.7

Data are presented as mean ± SD or as proportion (%).
[a]Obese, defined as BMI ≥30 $kg \cdot m^{-2}$.
[b]Self-employed, defined as working for own company full time in a deskbound occupation.
[c]Student, defined as adult undertaking paid postgraduate study full time.
[d]Other, defined as adult undertaking nonpaid, computer-based work (>8 $h \cdot d^{-1}$).

According to accelerometer data, participants engaged in a modest amount of daily MVPA. However, the duration of activity was not significantly different between the run-in phases (control, 27.8 ± 5.3 $min \cdot d^{-1}$, vs intervention, 26.0 ± 5.4 $min \cdot d^{-1}$; $P = 0.79$) or experimental conditions (control, 20.5 ± 2.8 $min \cdot d^{-1}$, vs intervention, 21.0 2.8 $min \cdot d^{-1}$; $P = 0.84$). Similarly, there was no difference in time spent in MVPA before and during each experimental condition (both, $P > 0.21$). As predicted, participants' mean daily sedentary time increased and light-intensity activity time decreased significantly during both experimental conditions compared with those during the run-in phases (both, $P < 0.001$).

Protocol compliance during the experimental conditions was high (97%–98%). According to activPAL monitor data recorded during the control condition, on average, participants spent (mean ± SEM) 468.1 ± 1.3 min sitting, 3.2 ± 0.4 min stepping, and 7.9 ± 0.8 min standing during an 8-h workday. During the intervention condition, the average time spent sitting was 232.0 ± 1.4 min, 5.6 ± 0.4 min for stepping, and 242.5 ± 1.5 min for standing during an 8-h workday.

Fasting plasma glucose, triglycerides, and serum insulin concentrations and weight, waist circumference and ratio of iAUC insulin to iAUC glucose were not significantly different between the two conditions when adjusting for time (days 1 and 5) (Table 2) (all, $P > 0.09$).

Overall condition effects and temporal changes between conditions for plasma glucose, serum insulin, and plasma triglyceride concentrations over the 4-h postprandial period are presented in Figure 3. There was a significant effect of condition (in favor of the intervention condition) on plasma glucose concentrations ($P = 0.007$) but not on serum insulin or plasma triglycerides. Adjusted mean glucose iAUC was lowered by 11.1% after the prolonged sitting interrupted with standing breaks condition (6.38 $mM \cdot h^{-1}$ (CI, 5.04–7.71)) relative to the prolonged sitting condition (7.18 $mM \cdot h^{-1}$ (CI, 5.85–8.52)). There was a nonsignificant sex–condition interaction effect ($P = 0.063$), indicating that the mean percent change in glucose iAUC between conditions was similar in male and female participants.

As shown in Figure 3, there was no significant time × condition interaction effect observed for plasma glucose, serum insulin, or plasma triglyceride iAUC. This suggests that the beneficial effect of the intervention condition on plasma glucose concentrations was similar at days 1 and 5.

DISCUSSION

This is the first study to use a simulated office environment to examine the short-term (5 d) effects of reducing workplace sitting time through systematic bouts of standing on postprandial glucose and lipid responses in overweight, sedentary office workers. Our results show that the introduction of 30-min bouts of standing (using an electric, height-adjustable

TABLE 2. Condition and temporal effects of experimental conditions on biochemical and anthropometric characteristics of study participants.

	Prolonged Sitting at Work Condition			Prolonged Sitting Interrupted with Standing Breaks Condition			
	Assessment Day 1	Assessment Day 5	*P* Value	Assessment Day 1	Assessment Day 5	*P* Value	Condition Effect
Weight (kg)[b]	87.0 ± 2.7	87.2 ± 2.7	0.15	86.8 ± 2.7	87.0 ± 2.7	0.22	0.09
Waist circumference (cm)[b]							
Male	99.8 ± 2.7	100.0 ± 2.7	0.01	99.8 ± 2.7	99.9 ± 2.7	0.57	0.93
Female	100.9 ± 3.3	101.3 ± 3.3	0.33	101.5 ± 3.3	101.9 ± 3.3	0.51	0.54
Fasting glucose (mM)[b]	5.10 ± 0.09	5.00 ± 0.09	0.003	5.11 ± 0.09	5.00 ± 0.09	0.5	0.92
Fasting insulin (pM)[b]	72.07 ± 7.70	72.56 ± 7.76	0.65	76.07 ± 8.13	76.59 ± 8.19	0.99	0.19
Fasting triglycerides (mM)[b]	1.44 ± 0.16	1.68 ± 0.16	0.01	1.50 ± 0.16	1.74 ± 0.16	0.08	0.45
iAUC insulin: iAUC glucose[a,c]	8.52 ± 0.85	8.5 ± 0.84	0.80	8.39 ± 0.84	8.33 ± 0.85	0.48	0.41

Data are presented as marginal means ± SEM.
P value represents significance of temporal changes (day 1 vs day 5) within condition.
[a]Index of β-cell function.
[b]Model adjusted for age, sex, order, and time.
[c]Treated as a main outcome; model adjusted for waist circumference, age, energy intake, sex, order, and time.

desk) can significantly attenuate the postprandial glucose response related to uninterrupted sitting during a typical workday. No such attenuations were observed for postprandial insulin or triglycerides.

Our findings extend the recent experimental evidence that breaking up prolonged sitting with walking bouts acutely improves postprandial glucose metabolism (8,28) by providing novel insights into the specific effects of intermittent standing. To date, only one other study has investigated the acute effects of intermittent standing bouts on glucose and lipid metabolism under laboratory conditions (26). The 2-d study involving 15 healthy normolipidemic males found no postcondition improvement in postprandial glucose, insulin, and triglyceride levels after 1 d of prolonged sitting with a 45-min standing bout (without movement) every hour for 6 h (total of 4.5 h standing) compared with that after prolonged sitting only. In the current study, a modest albeit significant 11% reduction in glucose iAUC during the prolonged sitting with standing breaks condition was observed. Differences in study population and design may have contributed to the disparate findings because our study included overweight, middle-age sedentary adults who were permitted to engage in spontaneous light ambulation during standing bouts as opposed to young, healthy males who were required to stand in a fixed position (26).

The magnitude of change in glucose iAUC was less than reported from interrupting prolonged sitting with 2-min walking breaks every 20 (8) or 30 min (28). However, the promotion of longer, less frequent standing breaks at work using a height-adjustable desk may be more amenable to application in the workplace and therefore have population-health relevance as a sustainable intervention. The protocol investigated is particularly pertinent because most adults spend the majority of the workday sitting (35), and this sitting time frequently coexists with the postprandial state. The significance of our findings should be interpreted in the context of observations that postprandial glucose elevation is associated with cardiovascular disease risk (5,31), and there is increasing evidence that even borderline high postprandial glycemia (4.4–7.8 mM) can contribute to the development of atherosclerosis and subsequent CHD events (22).

In our study, we observed no difference in insulin iAUC or the ratio of insulin iAUC to glucose iAUC during the experimental conditions. This contrasts with recent findings showing that 1 d of prolonged sitting led to a reduction (by 39%) in whole-body insulin action compared with that in upright light-intensity activity (33) in healthy, active, young adults. The absence of a condition effect on measures of insulin sensitivity may be partly explained by the diet provided during the experimental conditions. In the current study, standardized daytime meals (and some evening meals) that matched participants' low energy demands during the prolonged sitting at work condition were provided during each condition to separate the effects of the condition on glucose metabolism from the effects of a positive energy balance. This is because it has previously been shown that impaired insulin action during prolonged sitting is potentiated by an energy surplus (33). It is plausible that the energy-balanced diet provided to participants during their workday (8 $h \cdot d^{-1}$) coupled with an unexpected lower daily energy intake (-300 $kJ \cdot d^{-1}$) during the prolonged sitting condition compared with that provided during prolonged sitting with standing breaks condition may have mitigated potential detrimental effects on insulin action during the unbroken sitting condition.

The exact mechanisms through which standing bouts (with some light ambulation) may exert beneficial effects on glucose metabolism remain unclear. The absence of changes in postprandial insulin sensitivity in our study suggests that either we were underpowered to detect a significant condition effect or that the benefit may be mediated through pathways that are distinct from insulin. Localized muscle contraction can stimulate glucose uptake by skeletal muscle cells independent of plasma insulin levels (23,30) possibly because of a separate pool of glucose transporters that are accessible only during contractile activity (4,7). Human EMG studies show that the gastrocnemius (calf) muscle is constantly active during standing whereas the vastus lateralis (quadriceps) muscle, related to whole-body insulin sensitivity (21), is quiescent; only during ambulation are both muscles recruited (2). Sustained contractile activity in the gastrocnemius during prolonged periods of standing may help promote recruitment of GLUT-4 glucose transporters to the plasma membrane (14) to facilitate muscle glucose uptake (25,29).

Animal studies have identified that local contractile activity in postural skeletal muscles during standing and periods of

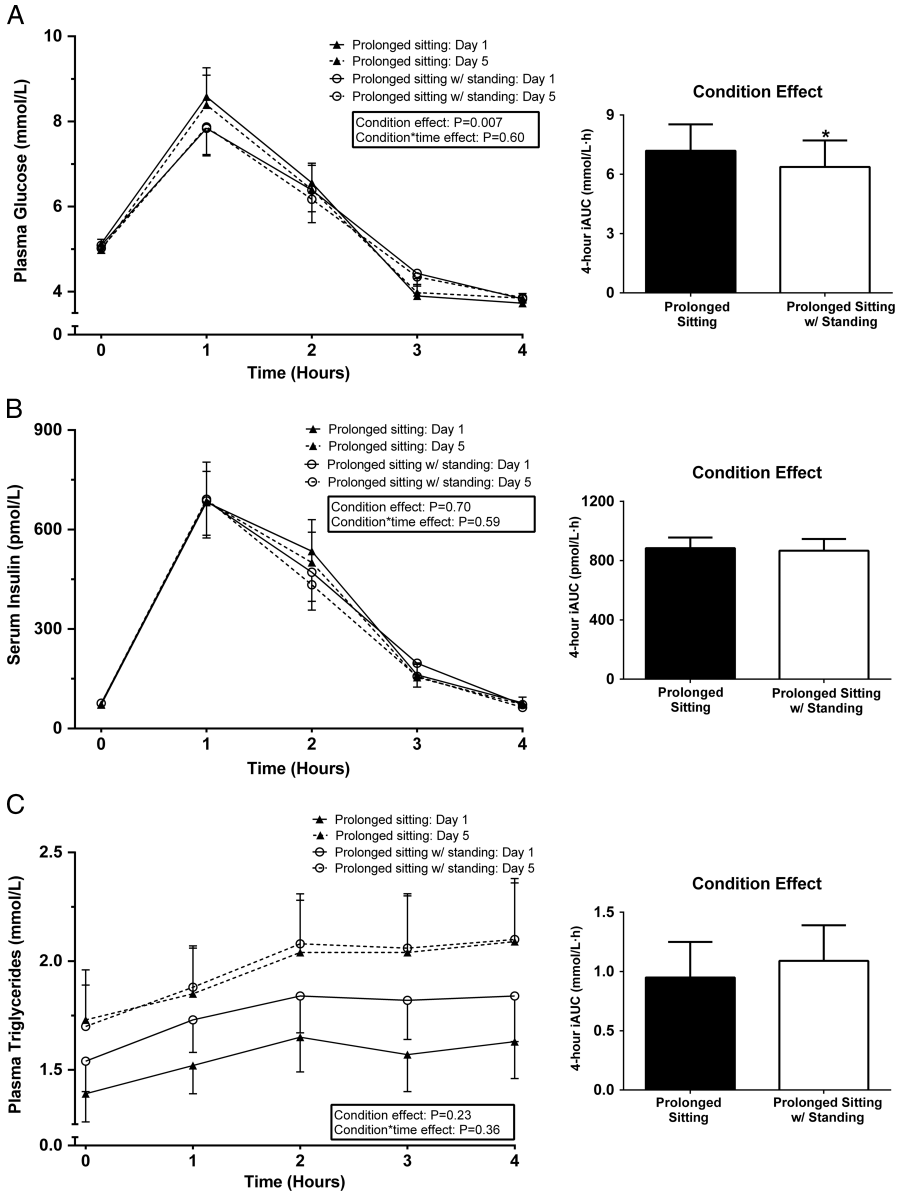

FIGURE 3—Fasting and postprandial plasma glucose (A), serum insulin (B), and plasma triglyceride (C) concentrations measured on assessment days (days 1 and 5) during the prolonged sitting at work condition (*black triangle*) and prolonged sitting interrupted with standing breaks at work condition (*white circle*). Data in analyte time curves are presented as mean ± SEM. Condition effects (4-h iAUC) adjusted for time (days 1 and 5) data are presented as marginal means ± 95% CI (adjusted for condition, time, condition order, baseline predrink values for the outcome of interest, sex, age, waist circumference, and dietary intake during the condition ($kJ \cdot d^{-1}$)). *Significantly different from prolonged sitting at work condition (*black triangle*), $P = 0.007$.

intermittent low-intensity ambulation may play an important role in lipid metabolism (3,16). We observed no difference in plasma triglyceride iAUC between conditions, supporting an earlier study that showed no effect of experimentally induced standing bouts over a 6-h period on postprandial serum triacylglycerol, inactive monomeric lipoprotein lipase protein, and apolipoprotein levels (26). It is plausible that the absence of a condition effect was related to standing not being a sufficient stimulus to enhance lipoprotein lipase activity (11) and the duration of the postprandial phase (4 h) being too brief to detect changes in triglyceride metabolism (27). As previously shown (34), the high monounsaturated fat composition (60%) of the mixed test drink used in the current study may also explain the relatively controlled postprandial triglyceride response observed during each experimental condition.

This is the first study performed under controlled laboratory conditions to assess the cumulative effect of prolonged sitting. The only other study to date to explore the cardiometabolic effects of repeated days of prolonged sitting was performed for 4 d under free-living conditions (9). The absence of any temporal changes during conditions in the current study may be explained by the study not being powered to detect changes from days 1 to 5. Other factors that may have

obscured any temporal effect is the relatively normal metabolic profile of participants at the commencement of the study and participants continuing to engage in a modest amount of MVPA before and throughout each condition (approximately 20 $min \cdot d^{-1}$), which may have attenuated any cumulative deterioration in glucose and lipid metabolism.

A major strength of our study is that it is the first to explore the health effects of standing breaks in office workers. These are adults who are likely to be the most susceptible to the health risks associated with prolonged sitting (38). Our study is also the second intervention trial to date (8) to investigate the acute effect of prolonged sitting in an overweight, middle-age adult cohort at heightened risk for diabetes and cardiovascular disease; other studies have typically focused on young, healthy, physically active adults. Additional strengths include controlling for participants' dietary intake and physical activity before and during the study, which enabled us to differentiate the effect of the experimental conditions on postprandial glucose and lipid responses from that of MVPA or a positive energy balance. A notable limitation of our study design is the small number of females who were recruited. It is recognized that intervention studies investigating the effect of imposed sedentary behavior (including bed rest studies) on cardiometabolic outcomes have predominately been performed in males (32) and future studies should include females to examine potential sex-specific effects. The decision to perform hourly blood measures may have compromised the accuracy with which we captured peak glucose and insulin concentrations, and the inclusion of additional time points (30, 45, and 90 min) earlier in the postprandial phase would have provided a more comprehensive iAUC profile.

In conclusion, introducing intermittent standing bouts across the workday results in modest beneficial effects on postprandial glucose responses in overweight/obese office workers at increased risk of diabetes and cardiovascular disease.

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The authors declare no conflict of interest.

The results of the present study do not constitute endorsement by the American College of Sports Medicine.

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