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Breaking Up Evening Sitting with Resistance Activity Improves Postprandial Glycemic Response: A Randomized Crossover Study

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ABSTRACT

GALE, J. T., D. L. WEI, J. J. HASZARD, R. C. BROWN, R. W. TAYLOR, and M. C. PEDDIE. Breaking Up Evening Sitting with Resistance Activity Improves Postprandial Glycemic Response: A Randomized Crossover Study. *Med. Sci. Sports Exerc.*, Vol. 55, No. 8, pp. 1471–1480, 2023. **Introduction:** Interrupting sedentary time during the day reduces postprandial glycemia (a risk factor for cardiometabolic disease). However, it is not known if benefits exist for postprandial glucose, insulin and triglyceride responses in the evening, and if these benefits differ by body mass index (BMI) category. **Methods:** In a randomized crossover study, 30 participants (25.4 ± 5.4 yr old; BMI 18.5–24.9: n = 10, BMI 25–29.9: n = 10, BMI ≥30: n = 10) completed two intervention arms, beginning at ~1700 h: prolonged sitting for 4 h, and sitting with regular activity breaks of 3 min of resistance exercises every 30 min. Plasma glucose, insulin, and triglyceride concentrations were measured in response to two meals fed at baseline and 120 min. Four-hour incremental area under the curve was compared between interventions. Moderation by BMI status was explored. **Results:** Overall, when compared with prolonged sitting, regular activity breaks lowered plasma glucose and insulin incremental area under the curve by 31.5% (95% confidence interval = −49.3% to −13.8%) and 26.6% (−39.6% to −9.9%), respectively. No significant differences were found for plasma triglyceride area under the curve. Interactions between BMI status and intervention was not statistically significant. **Conclusions:** Interventions that interrupt sedentary time in the evening may improve cardiometabolic health by some magnitude in all participants regardless of bodyweight. **Key Words:** SEDENTARY BEHAVIORS, ACTIVITY BREAKS, POSTPRANDIAL GLYCEMIA, INSULINEMIA, INSULIN RESISTANCE

Sedentary behaviors have become an inherent part of modern life as changes in building design, transport options, technological advancements, occupational demands, and digital entertainment encourage people to sit more and move less (1,2). Observational evidence indicates that higher levels of sedentary behavior in the form of total daily sitting time is associated with an increased risk of incident type 2 diabetes and cardiovascular disease, independent of physical activity levels (3). Furthermore, when compared with those in the lowest category of sedentary time, those in the highest category exhibit a 22%, 15%, and 13% increased risk of mortality from all causes, cardiovascular disease, and some cancers, respectively (4).

Findings from large observational studies indicate that people who accumulate accelerometer measured sedentary time in longer, uninterrupted bouts have an increased risk of cardiovascular disease (5), incident cancer (6), and all-cause mortality (6,7) regardless of total sedentary time. For example, women with the most prolonged accumulation pattern of sedentary time had a 54% increased risk of incident cardiovascular disease (95% confidence interval [CI] = 1.17 to 2.02, P = 0.003) when compared with women with the most interrupted accumulation pattern (5). These findings are consistent with data from cross-sectional studies that indicate individuals who accumulate sedentary time in longer bouts have a higher waist circumference, body mass index (BMI), and fasting glucose and triglyceride concentrations than individuals with similar total sedentary time (8–10).

There is a growing body of evidence indicating that the association between the pattern of sedentary time accumulation

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Submitted for publication September 2022.
Accepted for publication March 2023.
Supplemental digital content is available for this article. Direct URL citations appear in the printed text and are provided in the HTML and PDF versions of this article on the journal's Web site (www.acsm-msse.org).

0195-9131/23/5508-1471/0
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DOI: 10.1249/MSS.0000000000003166

and health outcomes may be explained, at least in part, by the effect of sedentary time on postprandial metabolism. The results of acute laboratory studies indicate that regularly interrupting prolonged sitting (every 20–30 min) with short bouts of activity (<6 min) attenuates postprandial glycemia and insulinemia by 13% to 42% over the day in healthy adults (11–16), those who are overweight or have obesity (17–21), and those who have type 2 diabetes (22–24). Furthermore, those who are less metabolically healthy, such as those with a greater body mass or decreased insulin sensitivity, might experience the greatest benefit (i.e., largest magnitude reduction) in glucose and insulin responses from performing regular activity breaks (25). Indeed, activity break–induced improvements in postprandial glycemia appear to be of greater magnitude and more consistent in those with type 2 diabetes (23) and obesity (11,17,19). However, no studies appear to have compared people from different BMI categories within the same study.

The majority of studies investigating the effects of regularly interrupting sedentary behavior on postprandial metabolism have commenced in the morning, with many aiming to imitate a working day (22,26–28). However, after the advent of streaming services and the normalization of "binge watching," long and uninterrupted periods of sedentary time are potentially more common during the evening. Indeed, recent evidence has highlighted that office workers (29), retired people (30), and those with type 2 diabetes (31) accumulate the longest period of prolonged, uninterrupted sitting in the evening. In addition, there is evidence that the average adult consumes almost half their daily energy intake during the evening (32) and that insulin sensitivity is diminished in the evening compared with the morning (33). The accumulation of these factors likely promotes an elevated postprandial glucose response. Accordingly, regular activity breaks have the potential to meaningfully affect glycemic control over the evening, but to date, little research has been conducted in this area.

A single randomized crossover trial has assessed the effect of interrupting prolonged sitting with simple resistance exercise in the evening (34). Although novel in its design, the study by Climie et al. (34) was small (n = 9), focused exclusively on overweight/obese participants, and the authors themselves highlight the need for "further evidence of efficacy" before considering the development of public health interventions in this area (34). To date, no study has investigated the effect of performing regular activity breaks in the evening in healthy weight participants. Therefore, the primary aim of this study was to determine the effect of performing regular activity breaks during the evening, compared with prolonged sitting on postprandial glucose, insulin, and triglyceride responses in a group of healthy adults. The secondary aim was to explore the potential of BMI to modify this effect.

RESEARCH DESIGN AND METHODS

Study design. This randomized crossover trial was conducted in Dunedin, New Zealand, between April and October 2021. Participants completed two, 4-h laboratory-based intervention sessions in the evening, beginning between 1700 and 1730 h. The prolonged sitting intervention involved sitting, uninterrupted for 4 h. The regular activity breaks intervention was identical to prolonged sitting; however, participants interrupted prolonged sitting with 3 min of resistance exercises every 30 min. The intervention timeline is outlined in Supplemental Figure 1 (see Supplemental Digital Content, http://links.lww.com/MSS/C828). This study was approved by the University of Otago Ethics Committee (Health; H20/161, December 2020) and was prospectively registered with the Australian New Zealand Clinical Trials Registry (ANZCTR) No. ACTRN12621000250831.

Participants. A sample size of 30 participants was estimated to provide 80% power to the 5% significance level to detect a difference of 0.4 SD in either total or incremental glucose area under the curve (AUC) (34). We chose to power on a 0.4 SD effect because that would be considered a small to moderate effect, a study of this size was feasible to undertake, and other studies (34) have found an effect of a similar magnitude. A total of 30 participants from three BMI categories (n = 10 healthy weight [BMI 18.5 to 24.9 kg·m^{-2}], n = 10 overweight [BMI 25 to 29.9 kg·m^{-2}], and n = 10 and obese [BMI ≥30 kg·m^{-2}]) were recruited through the distribution of e-mail invitations to the wider University of Otago Campus (Dunedin, New Zealand) between April and September 2021. Eligible participants were 18–40 yr of age, nonsmokers, able to speak and understand English, not taking medication or supplements that are known to affect glucose or triglyceride metabolism, without allergies or intolerances to dairy or gluten (because these components were present in the test meals), and self-reported habitual sedentary time of >5 h·d^{-1} at work or at home and >2 h in the evening. Participants were asked not to participate if they had been advised by a medical professional to avoid physical activity. Furthermore, participants were asked to obtain medical clearance from their general practitioner to participate in the study if their responses to the Physical Activity Readiness Questionnaire indicated that participating in physical activity may not be medically appropriate. All participants provided written informed consent.

Screening and eligibility. To confirm eligibility and enrolment in the study, participants attended an introductory session at the research clinic (Mellor Laboratories, University of Otago, Dunedin, New Zealand). Weight and height were measured in duplicate following standardized protocols. Blood pressure was measured using an automated sphygmomanometer (OMRON HEM-907; Omron Healthcare, Kyoto, Japan) and an appropriately sized cuff. Participants were excluded from the study if their systolic or diastolic blood pressure was above 140 and 90 mm Hg, respectively. Intervention day protocols were then discussed with the participant. During the discussion, participants watched the activity breaks video and underwent supervised practice of the required simple resistance exercises to ensure they could be compliant with the prescribed activity. At the end of the session, participants were fitted with an ActiGraph GT3X+ accelerometer (ActiGraph, Pensacola, FL) and instructed to wear the device 24 h·d^{-1} on

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their nondominant wrist for seven consecutive days, to provide an estimate of habitual physical activity patterns. A wear time diary was provided for participants to record non–wear times, bedtimes, and physical activity performed when not wearing the accelerometer (e.g., contact sport or swimming). Participants were also asked to record activities that are known to be inaccurately identified by the accelerometer such as yoga, Pilates, cycling on a stationary bike, and some resistance-based exercises.

Randomization. Participants were randomized to complete the two interventions in one of two possible orders (Fig. 1), stratified by weight status. The randomization sequence was generated before participant recruitment by MCP using Stata software (version 16; StataCorp, College Station, TX) and concealed electronically. The afternoon before each participant beginning their first intervention session, the next sequential randomization sequence was revealed and assigned. Participants were informed of which intervention they were completing first upon arrival at their first intervention session.

Preintervention standardization protocols. The day before each intervention session, participants were asked to collect a standardized breakfast (cereal, milk, yoghurt and juice), morning tea (caramel slice), lunch (chicken noodle soup, cheese, ciabatta, and margarine), to be consumed the next day (before arriving at the clinic). Each food was individually weighed and packaged for each participant to ensure that these meals together provided 56% of each participant's estimated energy requirement (determined using the Schofield equation, participant weight, and a physical activity factor of 1.5). The macronutrient composition across the three meals was 57% carbohydrate (mean = 138.1 g, SD = 26.0), 15% protein (mean = 34.4 g, SD = 6.5), and 28% fat (mean = 30.0 g, SD = 5.6). Absolute energy and macronutrient content of the meal is reported in Supplemental Table 1 (see Supplemental Digital Content, http://links.lww.com/MSS/C828). An additional muesli bar as a standard portion providing 708 kJ energy, 21.9 g carbohydrate, 2.9 g of protein, and 7.6 g fat was provided as an optional snack to all participants. The option taken before the first intervention was required to be replicated before the second intervention session. Participants were asked to consume all food provided before 1400 h on the day of the intervention session. Additionally, participants were

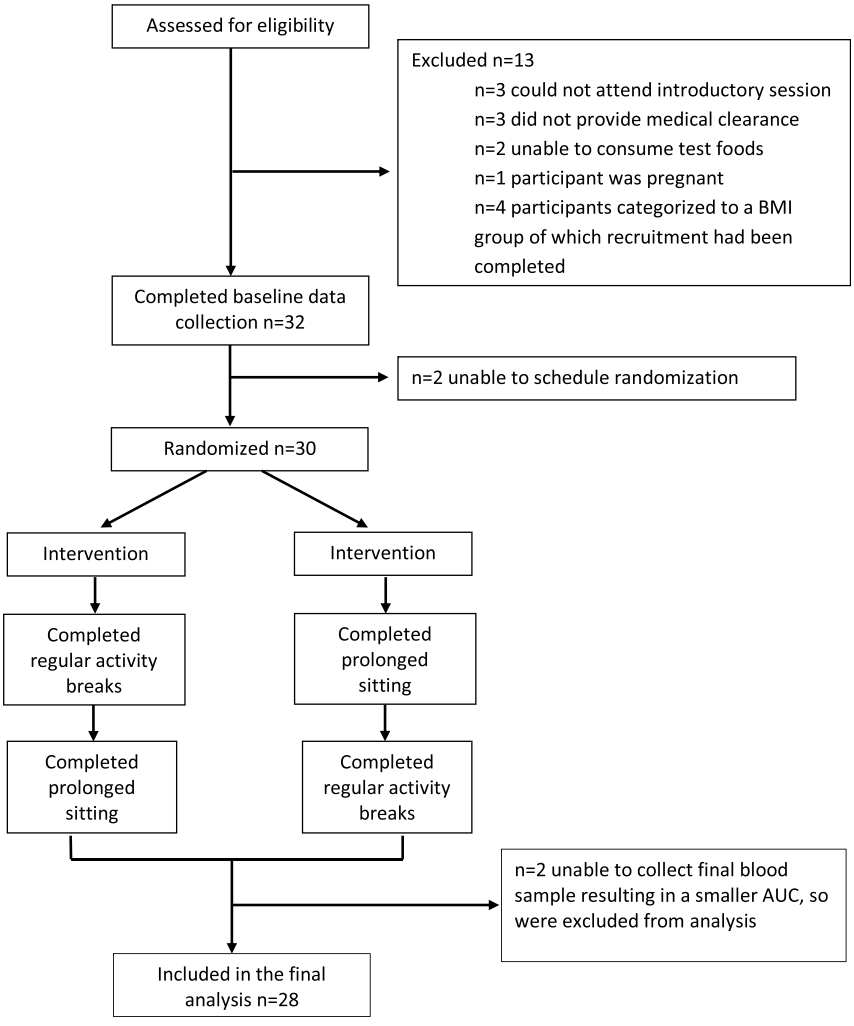

FIGURE 1—Study recruitment flow chart.

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asked to record the timing of meals and replicate this on the day of their second intervention session. In the 24 h before each intervention session, participants were asked to avoid all moderate-to-vigorous physical activity. Participants self-reported compliance with standardization protocols, and this was confirmed verbally at the beginning of each intervention session.

Intervention protocol. Each participant completed two 4-h intervention sessions, in the evening, separated by a minimum of 6 d (median = 6 d, interquartile range = 6 to 13 d) to account for any carryover effect of the first intervention. In the prolonged sitting intervention, participants arrived at the clinic between 1700 and 1730 h. Participants remained seated for the duration of the session, only getting up to use the bathroom when required. Bathroom breaks were recorded and repeated during the next session to account for any additional activity. While seated, participants were able to read, watch television, or work on a portable device.

The regular activity breaks intervention was identical to the prolonged sitting intervention except participants interrupted sitting with 3 min of simple resistance exercises (consisting of chair squats, calf raises, and standing knee raises with straight leg hip extensions) every 30 min for the duration of the session. Each 3-min interruption involved performing each of the three exercises for 20 s and then repeating for a total of three rounds (adapted from Dempsey et al. [23]). Participants performed the exercises in time with a video, which was displayed on a large television screen.

As a mode of exercise, simple resistance exercises were used as the activity break in this study because they require little to no equipment and can be done on the spot. Simple resistance exercises thus have the potential to be more widely accepted and practical as a means of breaking up prolonged sitting in a free-living environment.

Test meals. Participants consumed two standardized test meals during the on-site intervention session. All meals were commercially available, but each component was individually portioned in the lab to provide the prescribed amount of macronutrients. Dinner (beef curry, rice, naan, and margarine) was given at baseline and dessert (boysenberry slice) was given 2 h later, which provided 34% and 10% of each participant's estimated daily energy requirement, respectively. Together, the test meals had a macronutrient profile of 59% carbohydrate (mean = 114.8 g, SD = 21.3), 15% protein (mean = 26.9 g, SD = 5.0), and 26% fat (mean = 23.4 g, SD = 4.3) (see Supplemental Table 1, Supplemental Digital Content, Absolute energy, carbohydrate, protein, and fat provided from the standardized pre-intervention meals and test meals, http://links.lww.com/MSS/C828). Participants were asked to consume each meal within 15 min. Water was provided *ad libitum* during the first intervention session and matched during the second intervention session.

Blood collection protocol. Upon arrival at the clinic, a cannula was inserted into a vein in the antecubital fossa (or any accessible vein in the forearm). At least 15 min later, a baseline blood sample was collected. Blood samples of approximately 4 mL were drawn hourly from the cannula using a syringe, with additional samples collected 30 and 45 min after consumption of the standardized meals (resulting in a total of nine samples). Samples were immediately transferred to EDTA-containing vacutainers and stored on ice. Within 1 h of collection, samples were centrifuged at 3500 rpm for 10 min and stored at −80°C for later analysis.

Analytical methods. Plasma glucose concentrations were determined using the hexokinase enzymatic method, and plasma triglyceride concentrations were determined using the glycerol oxidase enzymatic method. Both of which used a Cobas C 311 analyzer (Roche Diagnostics, Mannheim, Germany). Plasma insulin concentrations were determined using electrochemiluminescence methods on a Cobas e 411 analyzer (Roche Diagnostics). All samples from each participant were analyzed in the same run. Calibrators and kits for plasma glucose, insulin, and triglyceride analysis were supplied by Roche Diagnostics. Intraassay coefficients of variation were 4.3% for glucose, 2.0% for insulin, and 4.3% for triglyceride.

Habitual physical activity data processing. Self-reported sleep and wake times from participant wear time diaries were manually entered into ActiLife (ActiLife version 6.13.4) to constrain the Cole–Kripke algorithm (35) that was used to determine time spent asleep. Time-stamped activity data from ActiGraph accelerometers were downloaded using ActiLife software, saved in 15-s epochs, and imported into Stata (Version 12.1; StataCorp LLC, College Station, TX). The duration and the intensity of activity performed during self-reported non–wear time (e.g., swimming) were identified and manually overwritten in Stata. Cut points were used to categorize awake wear time into sedentary time (<2860 counts per minute) and total physical activity (≥2861 counts per minute) (36). Valid wear time was defined as wear time ≥10 h during awake hours.

Statistical analysis. The primary outcomes for this study were total AUC and incremental AUC (iAUC) for glucose, with insulin and triglyceride as secondary outcomes. Total AUC values for glucose, insulin, and triglyceride concentrations were calculated using concentrations from the nine samples collected over each 4-h intervention period using the *integ* command in Stata. This calculation fits a cubic spline curve through the nine time points and calculates the area under this curve. iAUC was calculated for glucose and insulin by subtracting the area from the baseline concentration over the 4-h period from the total AUC. Some participants had a triglyceride response that dropped below their baseline concentration for most of the 4 h, resulting in no incremental response above baseline. Therefore, the distribution of triglyceride iAUC became truncated (making it inappropriate to use in a regression model), so to provide estimates relative to baseline, we instead used a regression model with AUC as the outcome and adjusted for baseline triglyceride level (i.e., the concentration of triglycerides from the blood sample taken when the participants arrived in the laboratory) as a covariate. When samples were missing due to cannula malfunction (n = 12, 2.2%), the AUC was calculated without the missing time points. Insulin AUC and iAUC were log-transformed to correct for positive skew

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and results presented as percent differences. To allow comparison of the effects, all main results were also reported as mean percent differences, and the results for insulin AUC and iAUC were also transformed to their absolute units by multiplying the results by the geometric mean of the prolonged sitting condition. These are reported in the text.

Mean differences, 95% CI, and P values between intervention conditions were estimated using a mixed effects regression model with participant as a random effect and adjusted for randomized order. To assess moderation by BMI status, an interaction term between the moderator and the intervention was included in the regression model. As the sample was not powered to detect statistically significant interactions, moderation was explored by stratifying the regression models by the moderators and reporting the estimated effect size and 95% CI for each group.

The inclusion of two participants (one in the overweight BMI group and one in the obese BMI group) who were missing assessments at 240 min (and therefore had AUC assessed from 180 min) did not have an appreciable effect on any of the results (see Supplemental Table 2, Supplemental Digital Content, Sensitivity analysis estimating effects in 30 adult participants and by BMI category, including two participants who only had AUC assessed to 180 min., http://links.lww.com/MSS/C828); therefore, the primary results are presented with the 28 participants with AUC calculated from the full 240 min.

All statistical analyses were undertaken in Stata 17.0 (StataCorp, TX). Residuals of models were plotted and visually assessed for homoskedasticity and normality. $P < 0.05$ was considered statistically significant.

RESULTS

Participant characteristics. Characteristics of the participants are reported in Table 1. Thirty participants across three BMI categories participated in this study. Participants ranged in age from 19 to 39 yr, were mostly female, of New Zealand European ethnicity, and with some level of tertiary education. Based on the 7 d of accelerometry collected before the intervention sessions, participants, on average, spent 7 h 45 min asleep, 10 h 30 min engaged in sedentary behavior, and 4 h 50 min engaged in total physical activity per day.

Effect on postprandial metabolism. To illustrate average postprandial responses, mean plasma glucose, insulin, and triglyceride concentrations for the whole sample and by BMI status are displayed for each intervention in Figure 2. For those in the healthy weight BMI group, mean plasma glucose concentrations peaked at 45 min after dinner. For those in the overweight and obese BMI groups, mean plasma glucose concentrations peaked at 60 min after dinner during the prolonged sitting intervention and peaked at 45 min after dinner during the activity breaks intervention. A smaller peak was observed 45 min after dessert for all BMI groups in both interventions. In the obese group, the initial peaks in insulin (after dinner) were more than twice (118.1 pmol·L^{-1} in prolonged sitting, 101.6 pmol·L^{-1} in regular activity breaks) those observed in the healthy BMI group (47.9 pmol·L^{-1} in prolonged sitting, 46.8 pmol·L^{-1} in regular activity breaks). Mean triglyceride concentrations peaked 60 min after dinner during the activity breaks intervention and 45 min after dinner during the prolonged sitting intervention, in all BMI groups.

Across the whole sample, when compared with prolonged sitting, regular activity breaks significantly lowered postprandial plasma glucose AUC by 7.4% (95% CI = 3.3% to 11.4%, $P < 0.001$) and iAUC by 31.5% (95% CI = 13.8% to 49.3%, $P = 0.001$). Postprandial insulin AUC was lowered by 17.9% (95% CI = 5.1% to 29.0%, $P = 0.008$) and iAUC by 26.2% (95% CI = 9.9% to 36.9%, $P = 0.003$) (Table 2). These results transformed into absolute units were 2200 pmol·L^{-1} per 240 min (95% CI = 627 to 3564 pmol·L^{-1} per 240 min) and 2474 pmol·L^{-1} per 240 min (95% CI = 935 to 3739 pmol·L^{-1} per 240 min), respectively. When compared with prolonged sitting, regular activity breaks increased plasma triglyceride AUC by 5.9% (95% CI = −3.1% to 14.8%) and adjusted

TABLE 1. Baseline participant characteristics ($n = 30$).[a]

	All	Healthy Weight ($n = 10$)	Overweight ($n = 10$)	Obese ($n = 10$)
Age, yr	25.4 (5.4)	23.5 (4.2)	25.8 (5.8)	26.8 (5.8)
Gender, n (%)				
Male	8 (27)	4 (40)	1 (10)	3 (30)
Female	22 (73)	6 (60)	9 (90)	7 (70)
Anthropometric measures				
Weight, kg	83.3 (19.9)	69.3 (11.0)	74.4 (7.3)	106.1 (14.7)
Height, cm	169.4 (10.6)	174.1 (12.1)	163.3 (6.9)	170.7 (9.9)
BMI,[b] kg·m^{-2}	29.1 (6.6)	22.7 (1.5)	27.8 (1.2)	36.6 (5.5)
Blood pressure, mm Hg				
Systolic	121.3 (8.3)	120.8 (10.0)	119.3 (6.0)	124.0 (8.4)
Diastolic	74.8 (8.8)	70.4 (8.6)	74.0 (8.5)	80.0 (7.2)
Baseline activity,[c] min·d^{-1}				
Sleep	466.4 (75.5)	460.7 (65.7)	481.1 (80.6)	456.6 (85.7)
Sedentary time	634.0 (87.9)	621.9 (81.1)	621.2 (106.9)	661.6 (73.4)
Total physical activity[d]	289.2 (80.0)	292.5 (79.0)	308.7 (81.6)	263.9 (81.9)
Non–wear time	51.9 (56.4)	65.0 (73.4)	33.4 (24.6)	57.8 (60.8)

[a]Values reported as mean (SD), unless otherwise stated.
[b]BMI categories are defined as follows: healthy weight = BMI 18.5 to 24.9 kg·m^{-2}, overweight = BMI 25 to 29.9 kg·m^{-2}, and obese = BMI ≥30 kg·m^{-2}.
[c]$n = 29$ as one participant did not complete baseline actigraphy.
[d]Total physical activity reported because of difficulties accurately differentiating MVPA using wrist-worn actigraphy cut points.

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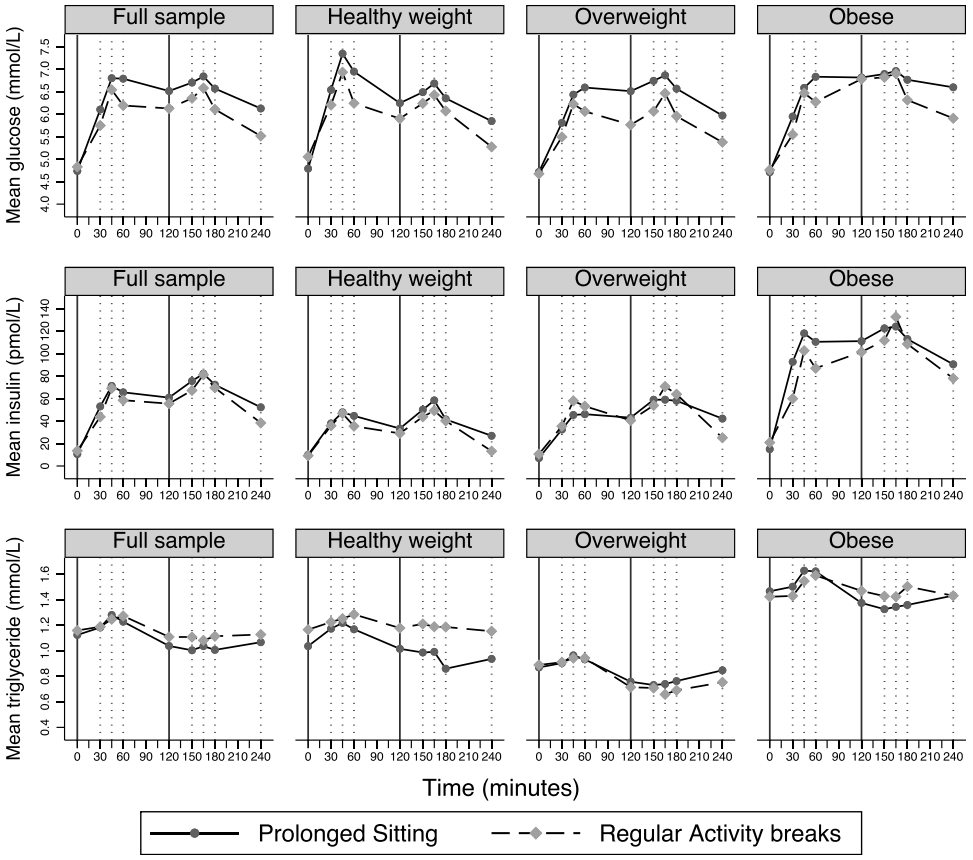

FIGURE 2—Mean glucose, insulin, and triglyceride levels for prolonged sitting and activity breaks conditions, for all participants and by BMI category. *Dashed vertical lines* indicate blood collection time points. *Solid vertical lines* indicate timing of test meal consumption.

AUC by 2.9% (95% CI = −3.5% to 9.7%); however, neither of these differences were statistically significant ($P = 0.196$ and 0.359, respectively). The distribution of glucose and insulin concentration AUC and iAUC and triglyceride concentration AUC by intervention is reported in Supplemental Figure 2 (see Supplemental Digital Content, http://links.lww.com/MSS/C828).

The interaction between BMI and intervention was not statistically significant for any outcome (glucose AUC $P = 0.958$; glucose iAUC $P = 0.724$; insulin AUC $P = 0.517$; insulin iAUC $P = 0.589$; triglyceride AUC $P = 0.209$; triglyceride AUC adjusted for baseline $P = 0.344$). On average, when compared with prolonged sitting, regular activity breaks reduced plasma glucose iAUC by 42.9% in the healthy weight BMI group, 32.1% in the overweight BMI group, and 20.6% in the obese BMI group (iAUC results are focused on in the text as they account for differences in baseline concentrations between groups; however, both iAUC and AUC results are presented in Table 2). When compared with prolonged sitting, regular activity breaks resulted in reductions of 32.7% in plasma insulin iAUC for those in the healthy weight BMI group, 29.4% for those in the overweight BMI group, and 14.5% for those in the obese BMI group. For triglyceride baseline adjusted AUC, when compared with prolonged sitting, regular activity breaks reduced baseline adjusted AUC by 3.6% for those in the overweight BMI group but increased baseline adjusted AUC by 4.1% for those in the healthy weight BMI group and 6.1% for those in the obese BMI group.

DISCUSSION

Results from this study indicate that interrupting periods of prolonged sitting by regularly performing resistance exercise breaks in the evening reduces postprandial glucose and insulin response in the overall study population by 32% and 26%, respectively. The current study is the first study to investigate the effects of performing regular activity breaks in the evening to include healthy weight participants. However, despite differences in participants, the 33% resistance exercise activity break–induced reduction in postprandial glucose iAUC by Climie et al. (34) was similar in magnitude to the 32% reduction observed in the current study. Taken together, these two studies provide robust evidence supporting the idea that interrupting prolonged sitting in the evening has the potential to provide meaningful cardiometabolic health benefits.

As with other studies performed during the day, the biological mechanism that accounts for these results is likely to involve an increase in contraction stimulated skeletal muscle glucose uptake, independent of insulin (37). Indeed, findings from Bergouignan et al. (38) indicate that acute interruptions

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TABLE 2. Effect of activity breaks on 4-h plasma glucose, insulin, and triglyceride AUC and iAUC response compared with prolonged sitting in a group of 28 adult participants and by BMI category.[a]

AUC	Prolonged Sitting	Activity Breaks	Mean Difference (95% CI)[b]
Glucose AUC, mmol·L^{-1} per 240 min	**Mean (SD)**	**Mean (SD)**	**mmol·L^{-1} per 240 min**
All	1533 (178)	1420 (144)	−113 (−174 to −51)
Normal weight	1516 (223)	1414 (162)	−102 (−230 to 27)
Overweight	1493 (162)	1369 (137)	−124 (−237 to −10)
Obese	1591 (137)	1478 (121)	−114 (−172 to −55)
Insulin AUC, pmol·L^{-1} per 240 min	**Geometric Mean (95% CI)**	**Geometric Mean (95% CI)**	**%**
All	12290 (9863 to 15315)	10089 (7632 to 13338)	−17.9 (−29.0 to −5.1)
Normal weight	8353 (6598 to 10576)	6328 (4144 to 9661)	−24.3 (−40.8 to −3.1)
Overweight	10540 (8102 to 13713)	8418 (5713 to 12403)	−20.1 (−27.8 to 2.5)
Obese	22009 (14959 to 32380)	20306 (13911 to 29640)	−7.7 (−27.6 to 17.6)
Triglycerides AUC, mmol·L^{-1} per 240 min	**Mean (SD)**	**Mean (SD)**	**mmol·L^{-1} per 240 min**
All	262 (96)	278 (112)	15.5 (−8.0 to 38.9)
Normal weight	248 (88)	290 (130)	42.2 (−12.4 to 96.7)
Overweight	196 (48)	193 (34)	−3.0 (−30.9 to 24.9)
Obese	345 (85)	349 (91)	4.3 (−14.1 to 22.7)
iAUC			
Glucose iAUC, mmol·L^{-1} per 240 min	**Mean (SD)**	**Mean (SD)**	**mmol·L^{-1} per 240 min**
All	400 (178)	274 (164)	−126 (−197 to −55)
Normal weight	380 (233)	217 (163)	−163 (−310 to −16)
Overweight	364 (167)	247 (166)	−117 (−243 to 9)
Obese	457 (108)	363 (139)	−94 (−167 to −21)
Insulin iAUC, pmol·L^{-1} per 240 min	**Geometric Mean (95% CI)**	**Geometric Mean (95% CI)**	**%**
All	9443 (7151 to 12469)	6968 (4926 to 9858)	−26.2 (−39.6 to −9.9)
Normal weight	5566 (3569 to 8680)	3747 (2013 to 6973)	−32.7 (−55.2 to 1.1)
Overweight	8851 (6647 to 11785)	6244 (4079 to 9560)	−29.4 (−46.8 to −16.5)
Obese	18126 (11663 to 28171)	15495 (9948 to 24135)	−14.5 (−36.5 to 15.1)
AUC adjusted for baseline[c]			
Triglycerides AUC, mmol·L^{-1} per 240 min	**Baseline Mean (SD)**	**Baseline Mean (SD)**	**Mean Difference (95% CI) Triglycerides AUC Adjusted for Baseline, mmol·L^{-1} per 240 min**
All	1.12 (0.39)	1.14 (0.40)	8.1 (−9.2 to 25.4)
Normal weight	1.04 (0.34)	1.17 (0.49)	12.0 (−19.8 to 43.8)
Overweight	0.86 (0.18)	0.88 (0.19)	−7.0 (−18.3 to 4.3)
Obese	1.46 (0.37)	1.39 (0.31)	21.4 (−7.9 to 50.7)

[a]Definition of BMI categories: healthy weight, 18.5 to 24.9 kg·m^{-2} (n = 10); overweight, 25 to 29.9 kg·m^{-2} (n = 9); and obese, >30 kg·m^{-2} (n = 9).
[b]Mean difference, 95% CI, and P values estimated using a mixed effects regression model adjusted for randomized order with participant as a random effect. Insulin AUC and iAUC were log-transformed and effect sizes presented as percent difference.
[c]Triglyceride AUC showed that some participants had a response that dropped below their baseline level (therefore having iAUC = 0: n = 6 in activity condition, n = 1 in sitting condition). These negative responses are not captured by iAUC and the distribution becomes truncated, so instead an analysis of AUC that adjusted for baseline level was undertaken.

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to prolonged sitting with physical activity (2 min light-intensity walking every 20 min for 6 h) stimulated glucose uptake along the contraction-mediated pathway in skeletal muscle (collected via *vastus lateralis* muscle biopsy) in preference to the insulin-mediated pathway.

The results of the current study also add weight to a small but growing body of evidence, which indicates that interrupting sitting with short bouts of simple resistance exercise (11,21–23) attenuates both postprandial glucose and insulin responses in a magnitude that is similar to the reductions seen with walking activity breaks (11,23). Two of these studies were performed in participants with type 2 diabetes (22,23). However, the two studies performed in healthy adults (11,21) show reductions in postprandial insulin iAUC that are incredibly consistent with the findings of the current study (24%–26%). Interestingly neither of these studies (11,21) found statistically significant reductions in glucose iAUC, although the magnitude of the observed reductions was likely to be clinically important (8% to 22%, respectively). This disparity in statistical significance between these two studies (11,21) and the current one is possibly attributable to the larger sample size of the current study. However, this disparity could also be attributed to any combination of methodological differences including time of day, exercise intensity, duration of postprandial measurement period, and demographic difference in the study populations.

In the current study, clinically meaningful reductions in postprandial glucose and insulin responses were observed across all BMI categories, indicating that healthy adults across the BMI spectrum could benefit from interrupting prolonged sitting in the evening with regular short bouts of resistance exercises. However, the magnitude of the effect appears to differ by BMI category. To the best of our knowledge, this is the first study to assess the effect of interruptions to prolonged sitting with resistance exercises on postprandial cardiometabolic markers by BMI status within a single study population. Although this analysis is purely exploratory in nature, given the sample size that would be required to be adequately powered to detect interaction effects (n = 120), the results indicate that the effects of regular activity breaks may differ across different weight category groups. Regular activity break–induced reductions in postprandial glucose and relative reductions in

postprandial insulin were largest in participants in the healthy weight BMI group. However, although the relative difference in insulin response was smallest in the obese group (relative differences are reported because the insulin data were log-transformed to correct for skewed residuals), when you visually inspect the geometric means, it does appear that absolute changes in insulin appear to be similar in the overweight and obese groups, both of which are larger in magnitude to the absolute reductions in insulin iAUC observed in the healthy weight group. Absolute reductions in insulin concentrations are likely to be clinically more important than relative reductions. Furthermore, an interesting (but not unexpected) finding of the current study was the markedly larger insulin response to the initial test meal in the obese BMI group. Not only did participants in the obese BMI group display slightly higher baseline insulin levels, the increase in insulin concentrations in response to the first test meal was approximately twice that observed in the other two groups, possibly indicating some degree of insulin resistance. It is not possible to untangle the effect of insulin sensitivity from BMI in the current study. Therefore, future studies should investigate how insulin resistance and body composition may modify the effect of regular activity breaks independently from BMI.

This study has some limitations to consider. The sample size of the present study makes it the largest study to date to use resistance exercise to break up prolonged sitting, was appropriate for the primary objective (to determine the difference in total AUC and iAUC for glucose between interventions), and facilitated the detection of what we believe are clinically meaningful activity-induced reductions in postprandial responses across BMI categories. However, powering the study on the interaction between BMI and the effect of regular activity breaks would have required a sample size four times greater (39,40), which was deemed unfeasible. Future studies of this size or smaller should consider reporting their results by BMI category to facilitate future subgroup meta-analysis. As the sample was mostly female, the results may be less generalizable to males. However, to date, there is little evidence to suggest differences in resistance exercise activity break–induced reductions in postprandial metabolism between healthy males and females. Classifying physical activity by intensity was limited because of difficulties accurately differentiating between moderate- to vigorous-intensity and light-intensity physical activity using existing wrist-worn accelerometry cut points. Future validation of cut points for wrist-worn accelerometry is needed. Additionally, we cannot exclude the possibility that the small differences in habitual 24 h activity measured between BMI categories may have been contributing to some of the differences we observed in glucose and insulin responses. As with all laboratory studies, the highly controlled setting is unlikely to reflect sitting behavior in a free-living setting, and thus further research is required to develop behavior change strategies that enable the investigation of longer-term health effects of performing regular activity breaks in the evening in a free-living environment.

We had participants sit uninterrupted for 4 h (except to use the bathroom as required), which could be deemed unrealistic. However, a 4-h period is equivalent to approximately only four episodes of most popular TV shows or two feature films, and globally, the average Netflix watch time is estimated to be approximately is 3.2 $h \cdot d^{-1}$ per subscriber (41). Furthermore, Keown et al. (29) noted that office workers accumulated mean prolonged sedentary bouts of 130 min (SD = 156 min) during non–work hours. This indicates that participants were engaged in prolonged sitting bouts of 2 h 10 min on average, whereas some individuals' prolonged sitting bouts were more than 4 h (29). Therefore, the duration of the prolonged sitting intervention in the current study may reflect sedentary time accumulation patterns of some adults in a real-life setting.

The feasibility of performing activity breaks at the frequency (every 30 min) and duration (3 min) used in the current study should be the focus of future field-based studies. However, it should be noted that although other modes of activity break have been found, in a laboratory environment, to be effective in shorter durations, the vast majority of studies that use resistance exercise have used the same protocol as was used here (21–23,42). Additionally, a small number of studies have investigated the effects of different frequencies of activity breaks (12,22,31), but the most consistent effects are still seen when activity breaks are performed every 30 min. Further research in a laboratory environment may be warranted to identify the ideal combination(s) of frequency and duration of activity breaks in the evening before moving to field-based research. Overall, these findings suggest that interventions that interrupt nonoccupational sedentary behaviors in the evening have the potential to improve cardiometabolic health across categories of BMI status. The evening is a time when periods of prolonged sitting, high caloric intake, and reduced insulin action occur simultaneously. Populations who engage in such behaviors may benefit from interrupting their evening sedentary time with resistance exercises. Streaming services could consider implementing scheduled regular activity break videos or prompts into their applications to encourage viewers to interrupt periods of prolonged sitting.

This research was funded by The Health Research Council of New Zealand. J. T. G. was supported by the Department of Human Nutrition Doctoral Scholarship, University of Otago.

Parts of this study were presented in abstract form at the 21st Annual Meeting of The International Society of Behavioral Nutrition and Physical Activity, Phoenix, Arizona, May 18–21, 2022.

Guarantor Statement. Peddie, M. C. is the guarantor of this work and, as such, had full access to all the data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis.

The authors declare no conflicts of interest. The results of the study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation. The results of the present study do not constitute endorsement by the American College of Sports Medicine.

Conceptualization: M. P., J. H., R. B., and R. T.; methodology: J. H. and M. P.; formal analysis: J. G. and J. H.; investigation: M. P., J. H., and J. G.; resources: M. P.; data curation: J.H.; writing—original draft preparation: J. G.; writing—review and editing: J. G., D. W., J. H., R. B., R. T., and M. P.; supervision: J. H. and M. P.; project administration: J. G.; funding acquisition: M. P. All authors have read and agreed to the published version of the manuscript.

Data described in the manuscript will be made available upon reasonable request to the corresponding author.

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