Title:

Intermittent Standing Does Not Acutely Improve Postprandial Metabolism in University Students

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Abstract

Height-adjustable workstations offer a practical strategy to reduce sedentary behaviour in student populations, but the effect of standing intervals on young adults' metabolic health remains uncertain. This study investigated the acute impact of breaking up sitting time with intermittent standing on postprandial metabolic responses in university students. Using a randomised, cross-over design, 23 participants (13 females, 10 males; age, 24 ± 5 years; BMI, 23.2 ± 3.1 kg/m^2) completed two trials: 2 hours of uninterrupted sitting (SIT); and 2 hours alternating between sitting and standing every 30 minutes (STAND). During this period, participants underwent an oral glucose tolerance test, with [glucose] and [insulin] measured. *Ad libitum* food intake post intervention was also measured. No significant effects between trials nor trial × time interaction was found for [glucose] or [insulin] (all $p > 0.05$). The postprandial iAUC did not differ for [glucose] ($p = 0.824$; SIT: 222 ± 83 mmol/L; STAND: 225 ± 90 mmol/L) or [insulin] ($p = 0.269$; SIT: 17507 ± 9738 pmol/L; STAND: 15649 ± 10181 pmol/L). There were no differences in energy or macronutrient intake between trials. These findings indicate that interrupting sitting with 30-minute standing intervals does not improve postprandial metabolic responses in young, normal-weight adults.

Keywords: sitting, standing desk, sedentary behaviour, blood glucose, insulin, young adults

Introduction

Sedentary behaviour is defined as any nonsleeping activity with an energy expenditure ≤1.5 metabolic equivalents (METs) and in a postural condition of sitting, reclining or lying down (Tremblay et al., 2017). Countries across Europe have witnessed increasing sedentary behaviour over the twenty-first century (López-Valenciano et al., 2020), which has been associated with an elevated risk of cardiovascular disease (Stamatakis et al., 2011), type II diabetes (Hu et al., 2003), and obesity (Banks et al., 2011). Changes in various facets of contemporary living have undoubtedly played a major role, from the widespread adoption of motorised transportation to the rise in office-based occupations and increased leisure time spent on electronic devices (Owen et al., 2011). Public health guidelines from the World Health Organization (WHO) have responded to this trend by underscoring the importance of minimising sedentary time (WHO, 2020). This emphasis stems from the independent negative association between sedentary behaviour and metabolic health (Healy et al., 2008). Indeed, metabolic dysfunction, encompassing conditions such as insulin resistance, dyslipidaemia, and hypertension, typically serves as a foundational factor in the development of chronic conditions (Grundy et al., 2004), which are known to develop from young adulthood (Berenson et al., 1998). There is an association even in adolescence between higher sedentary behaviour and an increased risk of having three or more of the following: high triglycerides, high fasting glucose, high waist circumference, high blood pressure, and low HDL cholesterol (Mark & Janssen, 2008). Therefore, developing strategies to reduce sedentary behaviour in young adults assumes paramount importance, serving not only as a measure to safeguard their present metabolic health but also as a method to prevent the accrual of adverse effects that could precipitate substantial health challenges in later life.

University students represent an expanding young demographic who engage in alarming amounts of sedentary behaviour. A meta-analysis conducted in 2018 concluded that time spent sedentary

had increased in students over the past 10 years to approximately 7.3 hours per day, which may be higher than levels observed in the general young adult population (Castro et al., 2020). Although students also engage in high levels of physical activity (Peterson et al., 2018), this does not appear to negate adverse changes in metabolic health (Farrahi et al., 2022). Between 29% and 64% of students may have at least one metabolic risk factor, such as elevated blood pressure or abdominal obesity (Dalleck & Kjelland, 2012; Silva et al., 2014; Yahia et al., 2017), and so strategies must be developed to reduce sedentary time in university student populations.

A crucial component of metabolic health is glycaemic control, as effectively managing glucose exposure helps prevent hyperglycaemia and insulin resistance, thereby reducing the risk of cardiovascular disease and diabetes (Jyotsna et al., 2023). One way to assess glycaemic control is through the postprandial glycaemic response. Breaking up prolonged sitting is independently associated with improved postprandial glycaemia, and thus might be an effective strategy to enhance metabolic health (Healy et al., 2008). Experimental studies have demonstrated that incorporating walking breaks to interrupt prolonged sitting can lower postprandial plasma glucose and insulin concentrations (Dunstan et al., 2012; Peddie et al., 2013). Alternatively, breaking up sitting time with intervals of standing at a height-adjustable workstation may provide a more convenient and popular solution to mitigate sedentary behaviour in students by allowing them to continue engaging in academic activities (Castro et al., 2021). This is especially pertinent given that time spent studying may contribute the largest proportion of their sedentary behaviour (Rouse & Biddle, 2010). Interrupting sitting with 2-minute standing breaks every 20 minutes does not appear to improve postprandial metabolic responses (Bailey et al., 2015; Brocklebank et al., 2017; Pulsford et al., 2017; Kerr et al., 2017). However, accumulating 10 – 30 minutes of standing per hour has been shown to reduce postprandial glycaemia in middle-aged adults who are healthy (Benatti et al., 2017), overweight/obese (Crespo et al., 2016), and highly sedentary (Thorp et al., 2014).

Studies investigating standing interventions with young adults have yielded conflicting results. Whilst some findings have demonstrated positive effects (Butler et al., 2018; Crawford et al., 2020; Dobashi et al., 2021), others have reported no discernible impact on metabolic health (Altenburg et al., 2019; Kono et al., 2023; Miyashita et al., 2013; Peddie et al., 2021). The question persists regarding the adequacy of standing as a sufficiently intense activity to positively affect postprandial metabolism in students, who are typically young adults and may experience lower metabolic demands of standing due to greater energy efficiency (Grevendonk et al., 2021). Additionally, there is a notable gap in the literature regarding the impact of standing desks on eating behaviours, with only two studies conducted to date (Josaphat et al., 2020; Metz et al., 2023). This is significant because any potential benefits of standing desks for metabolic health could be undermined if changes in activity levels lead to compensatory eating behaviours.

Therefore, the present study aimed to bridge this gap by investigating not only the effects of standing desks on postprandial metabolism, but also on food consumption as a secondary outcome. The primary aim was to examine the immediate effects of interspersing sitting time with intermittent standing on the postprandial metabolic response in university students. It was hypothesised that interrupting 2 hours of sitting with two 30-minute standing periods would attenuate the postprandial increase in blood glucose and plasma insulin concentrations compared to continuous sitting. A secondary aim was to determine if standing breaks influence *ad libitum* energy intake compared to prolonged sitting, thereby providing a dual focus on the implications of standing desks for metabolic health management. The findings of this study carry practical significance by informing decisions about the integration of standing desks into university spaces. Such interventions have gained popularity among students (Benzo et al., 2016; Jerome et al., 2017), heightening the relevance of this research to current educational environments.

Methods

Participants and study design

Twenty-three students (13 females, 10 males) were recruited from an English university in the East Midlands. All participants were free of any known metabolic or cardiovascular diseases. A randomised, cross-over design was employed, with participants completing a familiarisation session and two experimental trials. Ethical approval was obtained from the Nottingham Trent University School of Science and Technology Invasive Ethics Committee (application ID: 1831856). Before commencing the study, all participants were thoroughly informed about the experimental procedure, provided written informed consent, and completed a health screening questionnaire.

Familiarisation session

Participants attended a familiarisation session where they were fully acquainted with all procedures, including the use of the standing desk, the *ad libitum* meal, the glucose solution, and fingertip blood sampling. Demographic information was recorded, and participants' height, body mass, waist and hip circumferences were measured to calculate BMI and waist-to-hip ratio. The International Physical Activity Questionnaire – short form (IPAQ-SF) was used to assess levels of physical activity and sedentary behaviour (Craig et al., 2003). Additionally, the Three-Factor Eating Questionnaire (TFEQ; Stunkard & Messick, 1985) was administered to evaluate dietary restraint (21 items), disinhibition (16 items), and susceptibility to hunger (14 items) (Josaphat et al., 2020).

Experimental trials

Participants attended two separate visits to complete the experimental trials in a randomised order: uninterrupted sitting (SIT); and sitting with intermittent standing breaks (STAND) (**Figure 1**). The intervention order was randomised using an online blocked randomisation tool

(https://www.sealedenvelope.com/simple-randomiser/v1/lists) and visits were separated by at least 7 days. To minimise the influence of oestrogen fluctuations on insulin sensitivity (Yeung et al., 2010), experimental trials were avoided during the late follicular phase. Female participants were required to undergo ovulation testing (One Step Ovulation Rapid Test Cassette, Home Health UK Ltd, Bushey, England) on the day before each experimental trial to confirm they were not in this phase (Williams et al., 2020). During the week before the first trial, participants kept a 7-day food and physical activity diary, which they used to replicate their eating and exercise behaviour in the week before the second trial. Participants were instructed to abstain from alcohol and strenuous exercise, as well as maintain their usual caffeine intake, for 24 hours prior to each trial. They consumed a commercially available ready meal on the evenings (after 5pm) before the trials, after which they were required to fast. Participants arrived at the laboratory via motorised transport for 9:00 AM in an overnight fasted state. Adherence to pre-testing conditions was confirmed verbally with all participants prior to commencement of the trials.

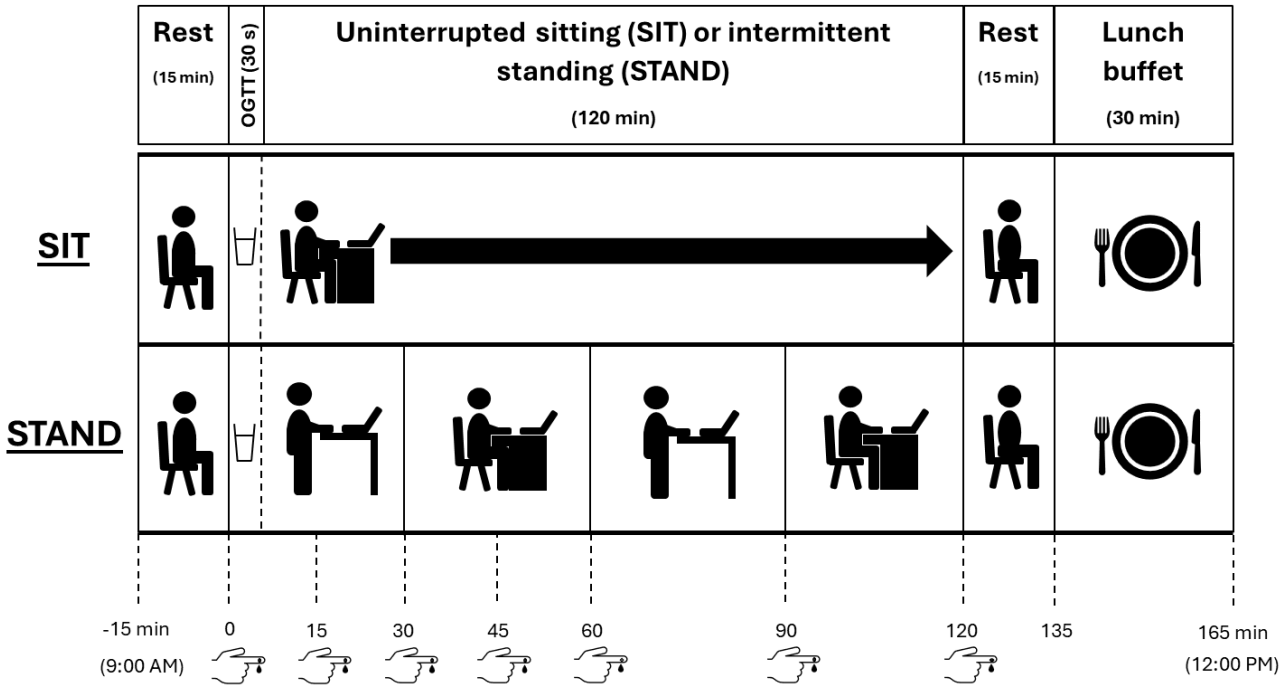


Figure 1 Schematic overview of the protocol.

Participants were given the opportunity to use the restroom before they then entered a small individual booth. Whilst participants were not instructed to remain still when standing, their movements were limited by the booth. Participants initially remained seated for 15 minutes and then a resting fingertip-capillary blood sample was collected.

Next, participants commenced the oral glucose tolerance test (OGTT), consuming a 75 g glucose drink (from 82.4 g of 100% dextrose monohydrate powder; MyProtein Ltd, Cheshire, UK) dissolved in 250 mL of water, with an additional 50 mL of water used to rinse the cup to ensure all the glucose was consumed (Clayton et al., 2018). Fingertip-capillary blood samples were collected after consumption every 15 minutes for the first hour and every 30 minutes for the second hour (**Figure 1**). Participants were allowed to engage in university-related and non-university-related activities throughout the 2-hour period (e.g., reading, writing, studying, watching films, internet browsing, using social media).

An *ad libitum* lunch buffet was provided 15 minutes after the 2-hour period of intermittent standing or uninterrupted sitting, featuring a variety of cold, ready-to-eat foods in quantities exceeding expected consumption (Clayton et al., 2015). The lunch buffet consisted of cereal bars, biscuits, chocolate, crisps, fruit, yoghurts, cooked meat, jam, cheese, mayonnaise, tomato ketchup, butter, bread, and bottled water (Tesco, Toton, UK). Each participant was seated in an isolated laboratory booth with no interaction with the investigators. They were allotted 30 minutes to eat and were instructed to eat until they felt “comfortably full and satisfied” (Clayton et al., 2015). Food intake was determined by weighing the food before and after consumption, with macronutrient content sourced from the manufacturer’s values.

Sample analysis

All blood sample procedures began with collecting into a 20 µL capillary tube, which was analysed immediately for blood glucose concentration using an automated analyser (Biosen C-line Sport; EKF Diagnostics, Barleben, Germany). A further 250 µL was collected in K2 EDTA-

coated microvettes (Sarstedt, Nümbrecht, Germany) and the plasma was separated by centrifugation (10 min; 3000 rpm; 4°C; Thermo Scientific Megafuge 8R, Thermo Fisher Scientific, Massachusetts, USA). The supernatant was harvested into microtubes (Eppendorf, Hamburg, Germany) and stored at -20°C before being transferred to -80°C for storage until later analysis of plasma insulin concentration using enzyme-linked immunosorbent assays (CV: 4.5%; Insulin ELISA, Mercodia, Uppsala, Sweden). Samples that produced an absorbance reading below the lowest standard (16.62 pmol/L) (n = 3) were reported as having a concentration of 16.62 pmol/L, equivalent to the lowest standard. A similar protocol for processing and storing fingertip-capillary blood samples for plasma insulin analysis has been used in a related study (Dey et al., 2024).

Fingertip blood sampling: rationale and validity considerations

Fingertip-capillary sampling was selected over antecubital-venous sampling for its practicality and suitability within the study design. The OGTT required precise blood collection timings, and transitions between sitting and standing at the height-adjustable workstation risked delays. Venepuncture, being more time-intensive, was less practical than fingertip sampling, which enabled faster and less disruptive collections. Also, venepuncture posed challenges such as the heightened risk of fainting during the standing samples, and the need for participants to exit their booths, introducing unintended movement variability.

The degree of random error is comparable between fingertip-capillary and antecubital-venous blood sampling, with between-day reproducibility of fingertip-capillary-derived insulin measurements falling within clinically acceptable limits (Green et al., 2014). Deming regression analysis also reveals no evidence of systematic or proportional bias between the two methods for insulin concentrations at the levels measured in the present study (Green et al., 2014). However, the wide limits of agreement suggest considerable variability between methods, with fingertip-capillary sampling yielding lower mean insulin concentrations (Green et al., 2014). This is potentially due to additional sources of variability such as tissue fluid dilution. In the present

study, investigators took care to gently milk participants' fingers during sampling to avoid excessive pressure and minimise contamination with interstitial fluid. Larger blood volumes were only collected for insulin analysis when participants bled sufficiently without requiring excessive manipulation of the fingertip. These sampling procedures meant that insulin data were available for only 10 participants.

Sample size

A priori power analysis using G*Power 3.1 (Faul et al., 2007) indicated that 22 participants were required to detect a medium effect size (f = 0.25) with an alpha level of 0.05 and power of 0.90 for a repeated-measures ANOVA trial × time interaction. This analysis focused on the main outcome measures of postprandial blood glucose and plasma insulin concentrations, including two groups and seven repeated measures. The assumptions for the analysis included a correlation of 0.5 between repeated measures, as used in a previous related study (Dunstan et al., 2012), and a nonsphericity correction factor (ε) of 1. Post-hoc sample size and power analysis were also conducted using G*Power 3.1 (Faul et al., 2007) to assess the achieved statistical power and required sample size for detecting significant effects based on the observed data.

Statistical analysis

Analyses were conducted using SPSS version 29.0 (SPSS Inc., Chicago, USA). A two-way (trial × time) repeated-measures ANOVA compared within and between-trial condition differences in postprandial blood glucose and plasma insulin concentrations. Total area under the curve (AUC) and positive incremental area under the curve (iAUC) for blood glucose and plasma insulin concentrations were calculated for each trial using GraphPad Prism 8 (GraphPad Software Inc., California, USA). Paired samples *t*-tests compared between-trial condition differences in AUC and iAUC values, as well as macronutrient energy intake. Significance was set at $p < 0.05$. Effect sizes for repeated-measures ANOVA results were calculated using partial eta squared (η^2_p), and

for paired samples *t*-tests, Cohen's *d* was used. Results are reported as mean ± SD unless otherwise specified.

Results

Table 1 Characteristics of all participants (13 females, 10 males) and participants with insulin data (2 females, 8 males). Mean ± SD.

Characteristic	All Participants (n = 23)	Participants with Insulin Data (n = 10)
Age, y	24 ± 5	24 ± 4
Height, m	1.69 ± 0.11	1.75 ± 0.08
Body mass, kg	67.5 ± 16.0	77.9 ± 14.8
BMI, kg/m^2	23.2 ± 3.1	25.3 ± 3.0
Waist circumference, cm	75.1 ± 8.2	80.4 ± 6.5
Hip circumference, cm	97.9 ± 8.7	102.6 ± 8.6
Waist-to-hip ratio	0.77 ± 0.04	0.78 ± 0.05
IPAQ-SF		
Total physical activity, METs min/week	3257 ± 2957	3733 ± 2797
Moderate-to-vigorous intensity physical activity, min/week	350 ± 362	391 ± 242
Total sitting time, h/day	7.7 ± 3.8	5.3 ± 2.7
TFEQ		
Dietary restraint	9.0 ± 5.9	9.1 ± 5.5
Dietary disinhibition	5.6 ± 3.2	5.8 ± 5.7
Hunger	5.4 ± 3.2	6.5 ± 2.9

Blood glucose

Characteristics of the participants are reported in **Table 1**. **Figure 2** shows the blood glucose response over time during the two trials. No significant effects were observed for trial (p = 0.068, η^2_p = 0.14) or the trial × time interaction (p = 0.418, η^2_p = 0.04). As shown in **Figure 3**, there was no significant difference in glucose AUC (p = 0.113, d = 0.35) between SIT (726 ± 112 mmol/L per 2 h) and STAND (751 ± 89 mmol/L per 2 h), nor in glucose iAUC (p = 0.824, d = 0.05) between SIT (222 ± 83 mmol/L per 2 h) and STAND (225 ± 90 mmol/L per 2 h). A post-hoc power analysis based on the observed effect size revealed that the achieved power for detecting differences in glucose

AUC between trials was 0.362, indicating limited statistical power with the current sample size (n = 23).

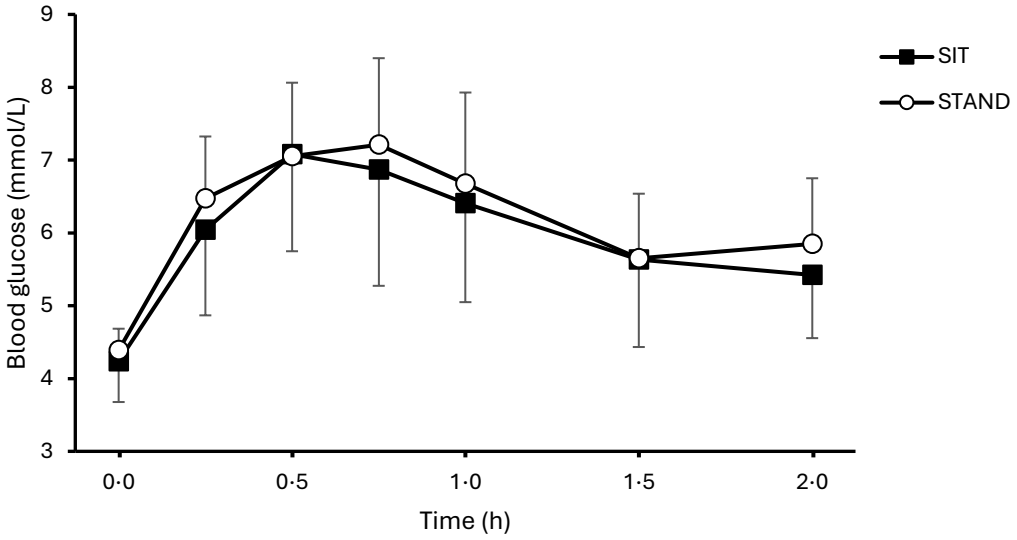


Figure 2 Two-hour postprandial blood glucose concentrations during both experimental trials.

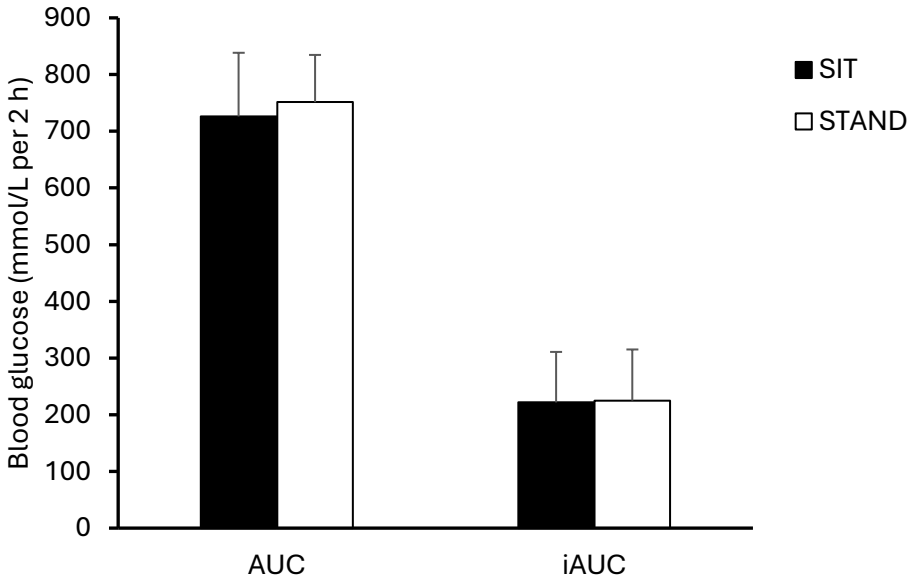


Figure 3 Postprandial blood glucose area under the curve (AUC) and positive incremental area under the curve (iAUC) for the two trial conditions.

Plasma insulin (n = 10)

There were no significant effects of trial ($p = 0.401$, $\eta^2_p = 0.08$) nor trial × time interaction ($p = 0.576$, $\eta^2_p = 0.05$) for plasma insulin concentrations (**Figure 4**). As shown in **Figure 5**, there were no significant differences in insulin AUC ($p = 0.299$, $d = 0.35$) between SIT (20788 ± 10508 pmol/L per 2 h) and STAND (18933 ± 10447 pmol/L per 2 h), nor in insulin iAUC ($p = 0.269$, $d = 0.37$) between SIT (17507 ± 9738 pmol/L per 2 h) and STAND (15649 ± 10181 pmol/L per 2 h). A post-hoc analysis for insulin AUC and iAUC revealed an achieved power of 0.168 and 0.182 respectively for detecting differences between trials, demonstrating that the sample size (n = 10) was underpowered.

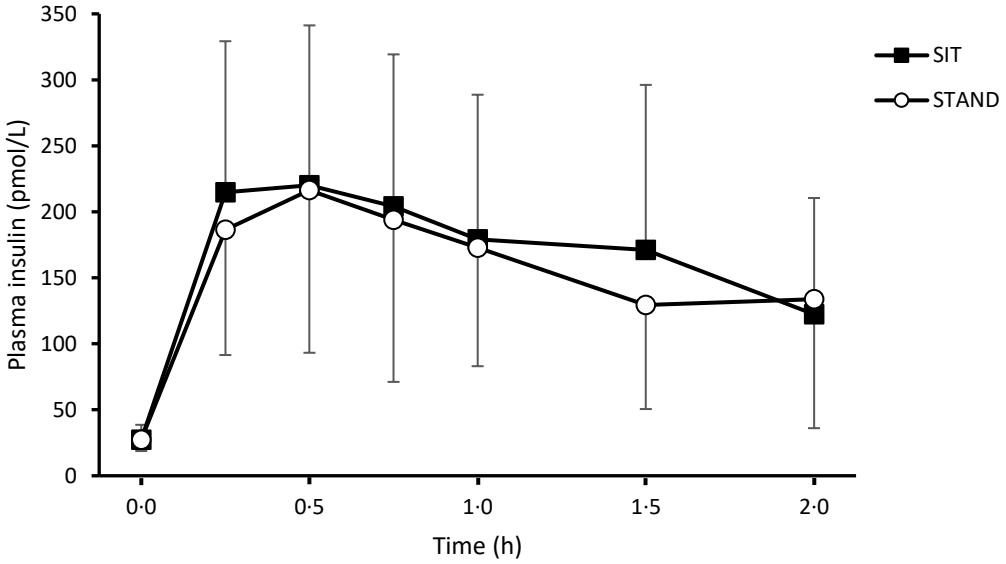


Figure 4 Two-hour postprandial plasma insulin concentrations during both experimental trials.

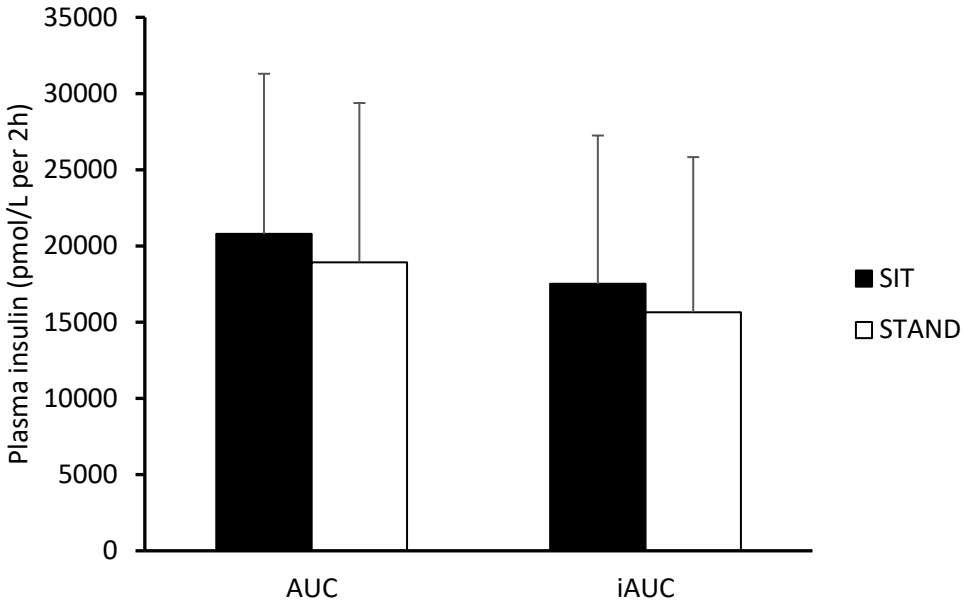


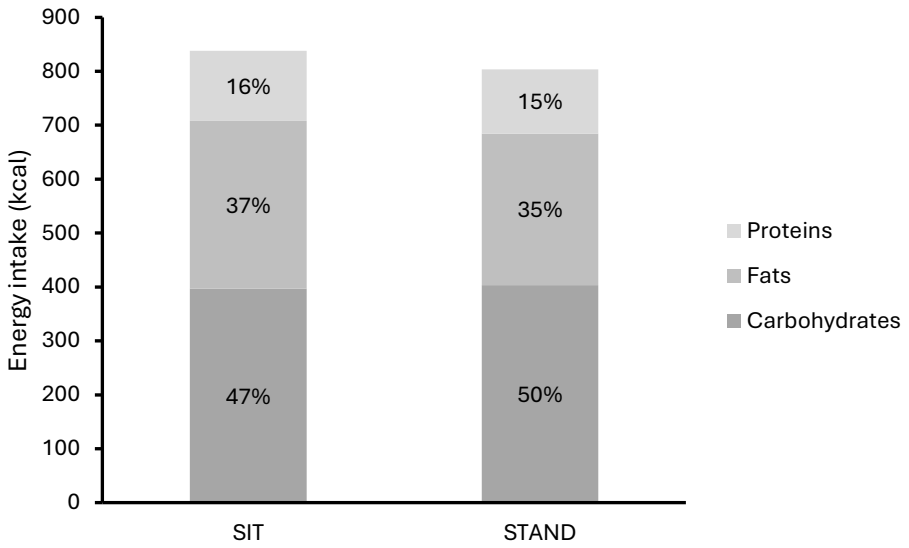
Figure 5 Postprandial plasma insulin area under the curve (AUC) and positive incremental area under the curve (iAUC) for the two trial conditions.

Eating behaviour

There were no significant differences ($p \geq 0.232$) in total *ad libitum* energy intake and macronutrient intake between the two experimental trials (**Table 2**). Macronutrient consumption as a percentage of total energy intake were similar between trials (**Figure 6**).

Table 2 Energy intake and macronutrient consumption between trials. Data are presented as mean ± SD.

	SIT	STAND	*p* value	Cohen's *d*
Energy intake, kcal	853 ± 333	820 ± 333	0.447	0.16
Protein intake, g	33 ± 17	30 ± 16	0.252	0.25
Fat intake, g	35 ± 22	31 ± 21	0.232	0.26
Carbohydrate intake, g	99 ± 44	101 ± 41	0.779	0.06



303

304 **Figure 6** Macronutrient consumption as a percentage of total energy intake during *ad libitum*
305 buffet. Data are presented as mean.

306

307 **Discussion**

308 The present study aimed to examine the acute effects of intermittent standing compared to
309 uninterrupted sitting on the postprandial glucose and insulin responses in university students. It
310 was hypothesised that two 30-minute standing periods would attenuate the postprandial
311 increase in blood glucose and plasma insulin concentrations compared to continuous sitting
312 over the 2-hour experimental period. Contrary to this hypothesis, the main finding was that
313 breaking up sitting time with 30-minute intervals of standing does not influence postprandial
314 metabolism in young, normal-weight adults. Additionally, a secondary aim was to determine
315 whether standing breaks affect energy intake compared to prolonged sitting. The results revealed
316 that two 30-minute standing intervals over 2 hours does not change total *ad libitum* energy intake
317 or macronutrient consumption compared with 2 hours of uninterrupted sitting.

318 The plasma insulin results align with existing literature, indicating that standing breaks do not
319 significantly influence postprandial insulin responses (Benatti et al., 2017; Hawari et al., 2016;
320 Miyashita et al., 2013; Peddie et al., 2021; Pulsford et al., 2017; Thorp et al., 2014). Excess
321 exposure to insulin might be a key factor in the development of insulin resistance and its

associated metabolic diseases (Cao et al., 2010); however, the present study provides further evidence that standing intervals alone are insufficient to reduce postprandial insulin concentrations. Alternatively, breaking up prolonged sitting with short bouts of light or moderate-intensity activity has been shown to be effective in reducing postprandial insulin responses (Dunstan et al., 2012; Peddie et al., 2013). This suggests that more intense activities than standing may be necessary to decrease insulin exposure.

Elevated postprandial glycaemia is also a risk factor for chronic metabolic diseases, even in healthy and non-diabetic adults, due to the associated increase in oxidative stress and inflammation (Blaak et al., 2012). A similar study with a comparable participant sample (age, 24 ± 3 years; BMI, 26.5 ± 4.3 kg/m^2) found that standing for 2 minutes every 20 minutes over 5 hours (6 minutes of standing per hour; 4 sit/stand transitions per hour) had no influence on glucose AUC compared to 5 hours of uninterrupted sitting (Bailey & Locke, 2015). The present study explored a variation in the frequency and duration of standing breaks, but similarly found that 30 minutes per hour of standing with 2 sit/stand transitions per hour also does not blunt the postprandial glucose response in young, normal-weight adults. Taken together, these findings suggest that standing breaks are ineffective in increasing glucose uptake in this demographic. The results differ from a study by Dobashi et al. (2021) in university students, which found that 20 minutes per hour of standing with 2 sit/stand transitions per hour significantly reduced glucose AUC compared to 2 hours of continuous sitting. However, the study included trials that were conducted at lunchtime, without standardised breakfasts, and participants selected their meals from a commercial menu, introducing dietary variability. In contrast, the present study used an overnight fast followed by a morning OGTT, ensuring a uniform glucose load and minimising variability in baseline glucose levels. This controlled approach enhances the reliability of the findings, indicating that standing breaks do not acutely affect postprandial glycaemia in university students.

The same frequency and duration of standing per hour as the present study reduced glucose iAUC by 11% in a sample of sedentary middle-aged adults (Thorp et al., 2014). Differences in the study population might have contributed to the disparate findings because the present study included normal-weight, young and physically active students as opposed to overweight, middle-aged sedentary office workers. Standing might cause more pronounced effects on the glucose metabolism of middle-aged adults because their baseline glucose regulation is less efficient due to the reduction in insulin sensitivity with age (DeFronzo, 1979). Indeed, ageing diminishes the insulin response to glucose intake due to factors such as decreased muscle mass, physical fitness, and β-cell function (Chang & Halter, 2003). In addition, standing induces muscle contractions due to the activation of the gastrocnemius muscle to control anterior-posterior balance (Borg et al., 2007) and other leg muscles involved in postural adjustments (Gao et al., 2017), which may lower blood glucose concentrations through non-insulin dependent glucose uptake. However, the duration and size of gastrocnemius muscle activity during standing is greater in aged compared to young individuals (Dos Anjos et al., 2017). Therefore, contraction-mediated glucose uptake during standing may not be sufficient to increase glucose clearance in young, normal-weight adults.

The results suggest that standing is not an intense enough stimulus to blunt the postprandial glucose response in students, indicating that a more intense stimulus, such as walking breaks, may be necessary. Compared to uninterrupted sitting, light-intensity walking for 2 minutes every 20 minutes reduced 5-hour glucose AUC by 16% (Bailey & Loche, 2015), whilst moderate-intensity walking for 1 minute 40 seconds every 30 minutes reduced 9-hour glucose iAUC by 39% (Peddie et al., 2013) in young adults. However, standing breaks offer a convenient alternative to walking breaks because height-adjustable workstations allow students to seamlessly continue their university work. Pedal desks might overcome this limitation (Han et al., 2018), so future research should focus on assessing their impact on the postprandial glucose response in young adults, as well as their practicality in a university setting and influence on work productivity.

To our knowledge, this study is only the third to explore the impact of standing desks on energy intake. This is important because any potential effect of standing desks on metabolic health could be confounded by compensatory changes in eating behaviour. The results revealed that total *ad libitum* energy intake and macronutrient intake were not significantly different following two hours of intermittent standing compared to uninterrupted sitting. These findings align with previous research, indicating that standing desks do not affect subsequent energy and macronutrient consumption (Josaphat et al., 2020; Metz et al., 2023). Specifically, engaging in cognitive tasks for 75 minutes using a standing desk did not alter subsequent energy intake compared to performing the same cognitive tasks when seated (Josaphat et al., 2020). A similar study used a 45-minute cognitive task and reported comparable results (Metz et al., 2023). Both studies involved young, normal-weight adults. These consistent findings suggest that standing desks do not influence dietary behaviour in the short term. Thus, any effects of standing desks on metabolic health are not confounded by changes in food consumption. Further, the absence of compensatory eating behaviour implies that standing desks could be beneficial for weight management, assuming that they increase energy expenditure compared to sitting, as this was not assessed in the present study.

This study has several limitations that should be acknowledged. First, participants were instructed to refrain from strenuous exercise 24 hours prior to trial days. Whilst participants are more likely to comply with a 24-hour exercise restriction compared to longer durations, insulin sensitivity may still be enhanced if acute moderate-intensity exercise was performed within 48 hours before the trials (Mikines et al., 1988). Another limitation is that although female participants performed an ovulation test to confirm they were not in the late follicular phase, the specific phase of their menstrual cycle was not verified. Insulin sensitivity may be higher during the follicular phase compared to the luteal phase and should therefore be controlled in future studies (Yeung et al., 2010). Further, the study did not instruct participants to remain still during standing periods, as intermittent leg movements naturally occur when standing. Whilst this might

399 have led to variability in how standing time was spent, the very small booths used for the study
400 limited large movements, minimising any potential effect. It is also noteworthy that the acute
401 two-hour intervention does not address the potential cumulative or long-term benefits of
402 intermittent standing. Future studies should explore the sustained impact of such interventions
403 over weeks or months to better understand their practical and health-related significance.

404 The study's generalisability and sample size limitations must be also acknowledged. The small
405 sample size reduces the likelihood that the cohort is representative of the broader university
406 population. Participants were normal-weight and physically active, limiting the applicability of
407 the findings to students at higher metabolic risk, such as those who are overweight or not meeting
408 exercise guidelines for health. Future studies should recruit more diverse populations to better
409 understand the effects of standing interventions in individuals most likely to benefit.
410 Furthermore, the study was underpowered to detect potentially meaningful differences in
411 glucose and insulin AUC and iAUC. A post-hoc sample size calculation for glucose and insulin
412 AUC indicated that 88 participants would be required to detect the measured effect size (d = 0.35)
413 with 90% power at an alpha level of 0.05. The small sample size for insulin outcomes (n = 10)
414 indeed highlights a key limitation. Larger cohorts are needed in future research to confirm these
415 findings and reliably detect small effect sizes.

416 Despite these limitations, the study has several strengths. Standing intervals of 30 minutes were
417 employed, which might offer a more sustainable intervention compared to continuous standing
418 periods used in other studies (Crawford et al., 2020; Kono et al., 2023; Peddie et al., 2021). This
419 approach acknowledges the need for practical standing durations that can be adhered to without
420 significant disruption and discomfort. In addition, standardising the evening meal before trials
421 minimised dietary effects on the postprandial metabolic response. The study may have been
422 strengthened further by measuring postprandial triglyceride concentrations due to their

association with endothelial function and cardiovascular disease risk (Jagla & Schrezenmeir, 2001).

In conclusion, interrupting sitting time with standing did not acutely affect postprandial metabolic responses or energy intake in university students. These findings suggest that substituting sitting time with standing may not be sufficient to reduce cardiometabolic disease risk in young, normal-weight adults. Future research should explore the nuances of how breaking up sitting time with different types and durations of physical activities, including those performed at a pedal desk, contribute to the metabolic health of university students.

Disclosure of interest

The authors report no conflict of interest.

Data availability statement

The data that support the findings of this study are available from the corresponding author, R. M. J., upon reasonable request.

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663 **Table 1** Characteristics of all participants (13 females, 10 males) and participants with insulin

664 data (2 females, 8 males). Mean ± SD.

Characteristic	All Participants (n = 23)	Participants with Insulin Data (n = 10)
Age, y	24 ± 5	24 ± 4
Height, m	1.69 ± 0.11	1.75 ± 0.08
Body mass, kg	67.5 ± 16.0	77.9 ± 14.8
BMI, kg/m^2	23.2 ± 3.1	25.3 ± 3.0
Waist circumference, cm	75.1 ± 8.2	80.4 ± 6.5
Hip circumference, cm	97.9 ± 8.7	102.6 ± 8.6
Waist-to-hip ratio	0.77 ± 0.04	0.78 ± 0.05
IPAQ-SF		
Total physical activity, METs min/week	3257 ± 2957	3733 ± 2797
Moderate-to-vigorous intensity physical activity, min/week	350 ± 362	391 ± 242
Total sitting time, h/day	7.7 ± 3.8	5.3 ± 2.7
TFEQ		
Dietary restraint	9.0 ± 5.9	9.1 ± 5.5
Dietary disinhibition	5.6 ± 3.2	5.8 ± 5.7
Hunger	5.4 ± 3.2	6.5 ± 2.9

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Table 2 Energy intake and macronutrient consumption between trials. Data are presented as mean ± SD.

	SIT	STAND	*p* value	Cohen's *d*
Energy intake, kcal	853 ± 333	820 ± 333	0.447	0.16
Protein intake, g	33 ± 17	30 ± 16	0.252	0.25
Fat intake, g	35 ± 22	31 ± 21	0.232	0.26
Carbohydrate intake, g	99 ± 44	101 ± 41	0.779	0.06

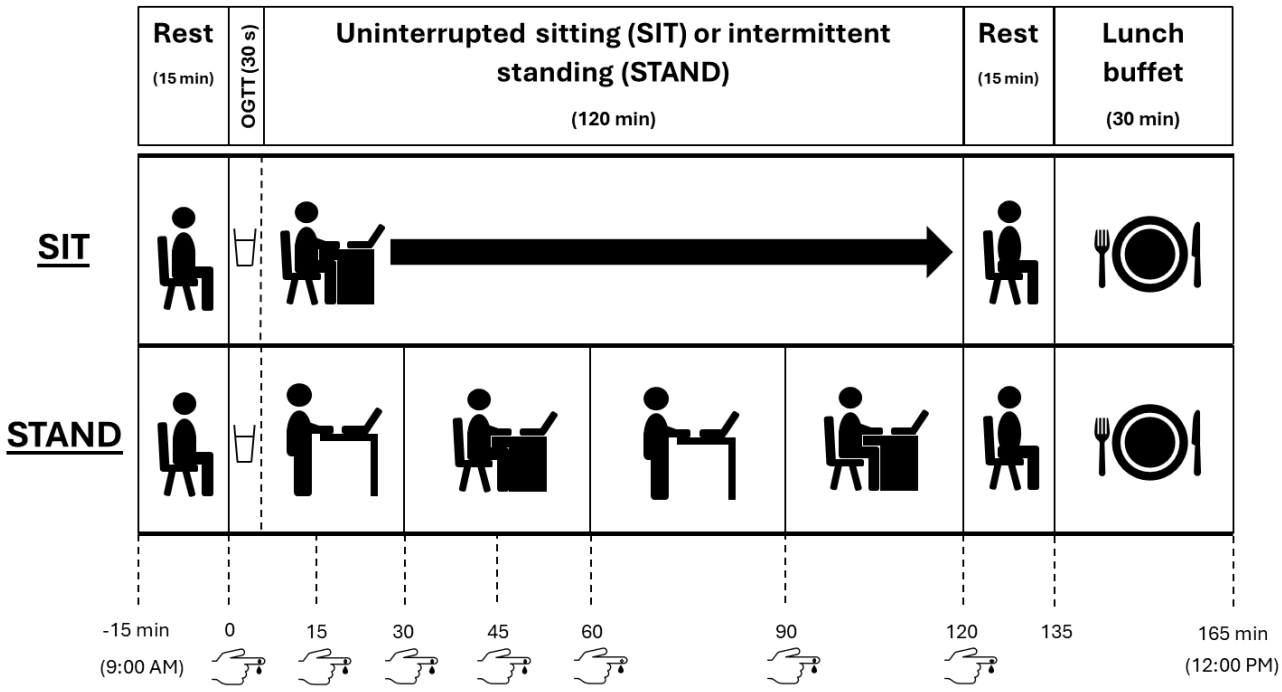


Figure 1 Schematic overview of the protocol.

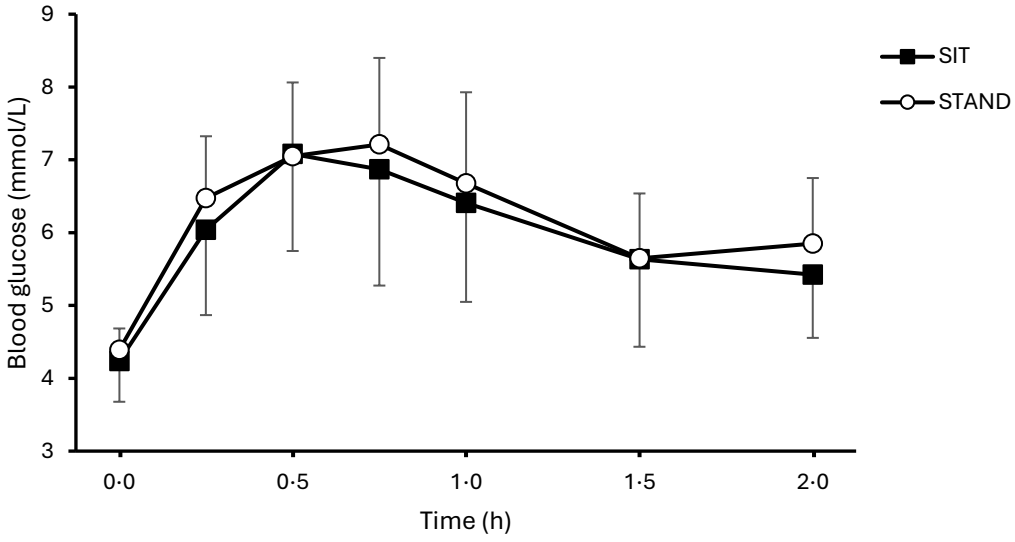


Figure 2 Two-hour postprandial blood glucose concentrations during both experimental trials.

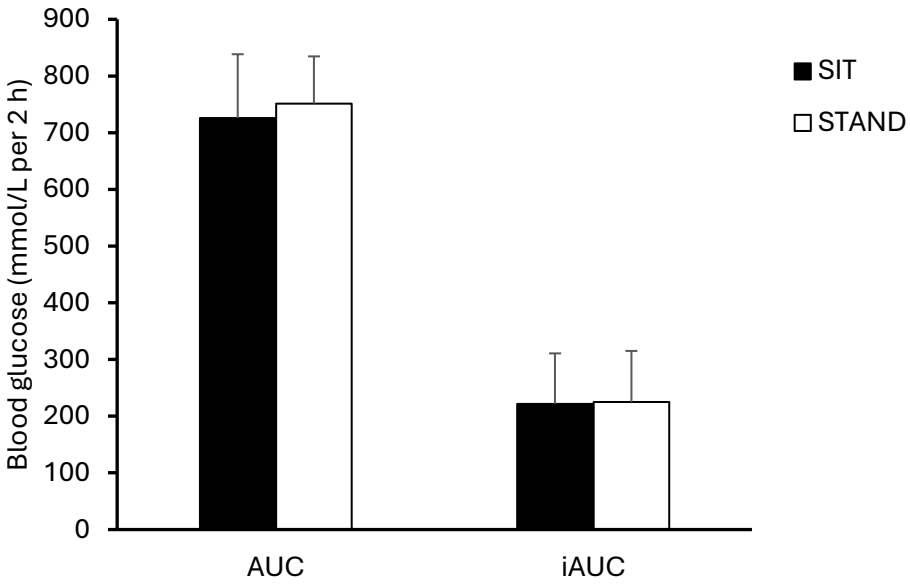


Figure 3 Postprandial blood glucose area under the curve (AUC) and positive incremental area under the curve (iAUC) for the two trial conditions.

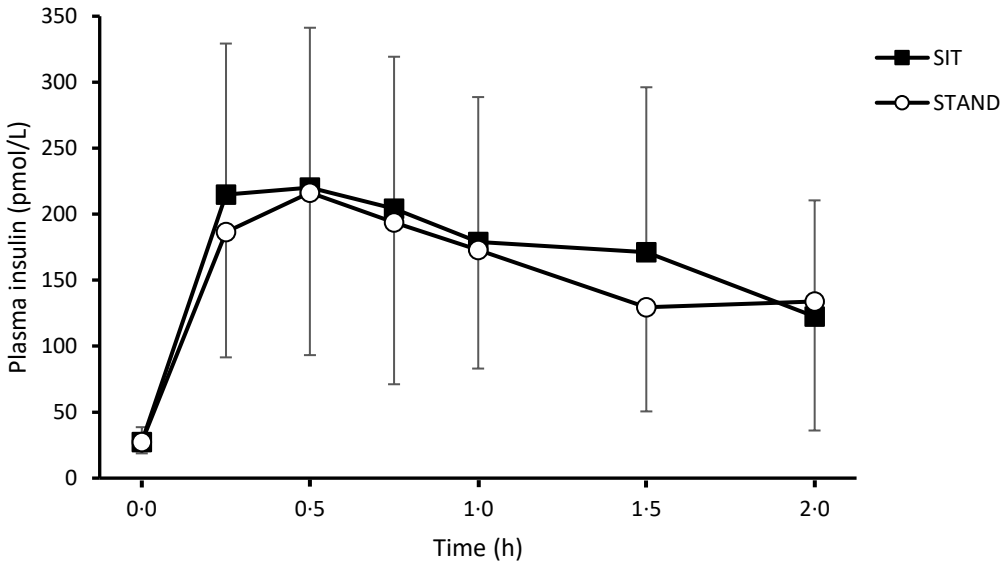
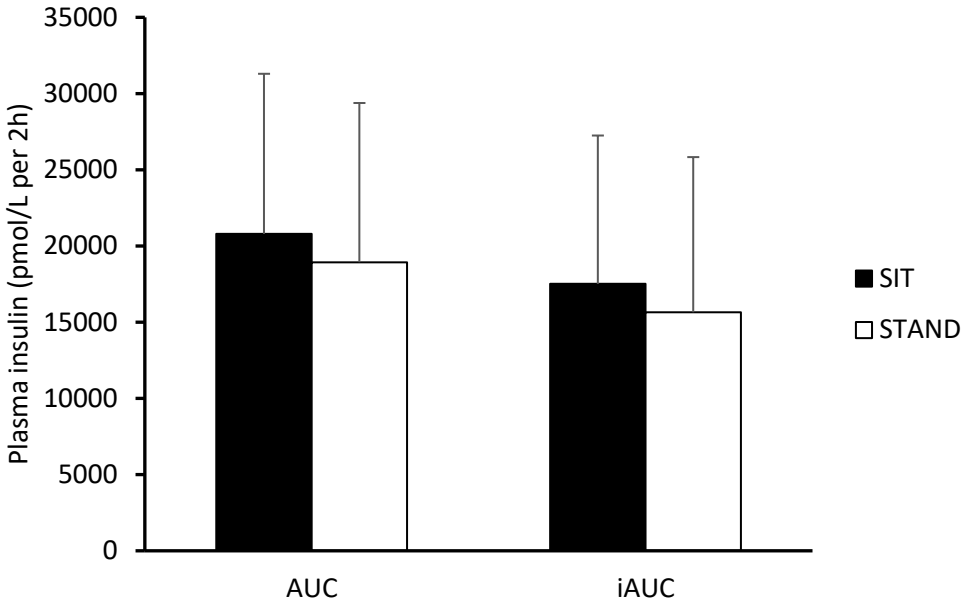


Figure 4 Two-hour postprandial plasma insulin concentrations during both experimental trials.



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762 **Figure 5** Postprandial plasma insulin area under the curve (AUC) and positive incremental area
763 under the curve (iAUC) for the two trial conditions.

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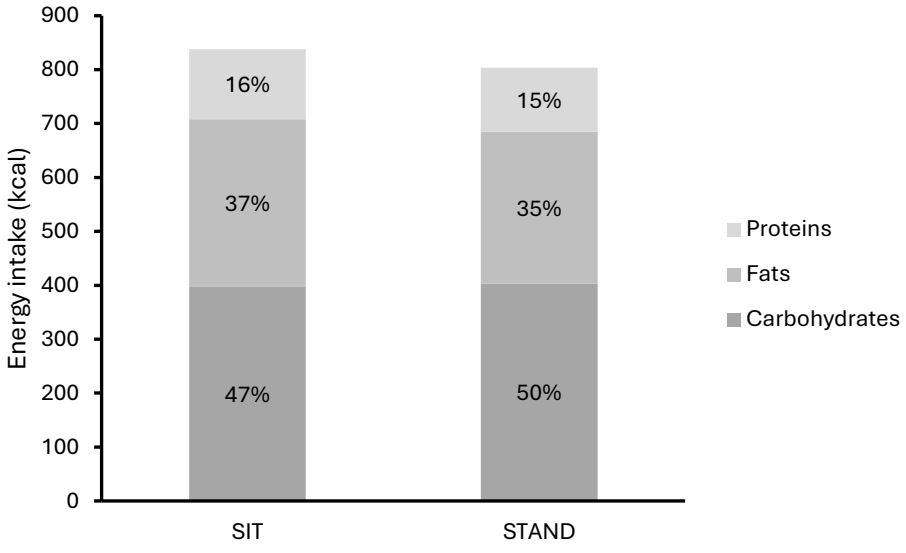

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767 **Figure 6** Macronutrient consumption as a percentage of total energy intake during *ad libitum*
768 buffet. Data are presented as mean.

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774 **Figure 1** Schematic overview of the protocol.

775 **Figure 2** Two-hour postprandial blood glucose concentrations during both experimental trials.

776 **Figure 3** Postprandial blood glucose area under the curve (AUC) and positive incremental area
777 under the curve (iAUC) for the two trial conditions.

778 **Figure 4** Two-hour postprandial plasma insulin concentrations during both experimental trials.

779 **Figure 5** Postprandial plasma insulin area under the curve (AUC) and positive incremental area
780 under the curve (iAUC) for the two trial conditions.

781 **Figure 6** Macronutrient consumption as a percentage of total energy intake during *ad libitum*
782 buffet. Data are presented as mean.

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