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ARTICLE

Exercise snacks performed in real-world settings reduce postprandial hyperglycaemia and glycaemic variability in individuals living with type 2 diabetes: a randomised crossover study

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Abstract

Aims/hypothesis Using a randomised, crossover design, we investigated whether exercise snacks could improve indices of glucose regulation assessed by continuous glucose monitoring, compared with an equivalent no-exercise control period in people living with non-insulin-treated type 2 diabetes.

Methods Previously inactive participants with well-controlled type 2 diabetes (n=31; 21 female participants, ten male participants; approximately 58 years old, BMI approximately 31 kg/m^2, HbA_{1c} approximately 48 mmol/mol [6.6%]) completed two experimental conditions in a randomised, counterbalanced order in the real world under a standardised diet. During the exercise snacks condition (ES), participants completed four 1 min bouts of vigorous bodyweight exercise on two consecutive days, guided by instructional videos sent via email. The control condition (CON) involved two consecutive days of no exercise. Participants wore a continuous glucose monitor and a Fitbit watch to record glycaemic responses and heart rate, respectively. The primary outcome was mean glucose during each 48 h condition. Secondary outcomes included 2 h postprandial glucose responses after standardised meals and markers of glycaemic variability.

Results The difference in mean glucose between ES and CON did not reach statistical significance (between-condition difference −0.2 mmol/l; 95% CI −0.4, 0.0; p=0.07). However, small but statistically significant improvements in standard deviation (−0.1 mmol/l; 95% CI −0.2, −0.1; p<0.001), coefficient of variation (−1%; 95% CI −2, 0; p=0.007), mean amplitude of glycaemic excursions (−0.3 mmol/l; 95% CI −0.5, 0.0; p=0.04) and time in tight range (3%; 95% CI 0, 6; p=0.04) were seen under the ES condition compared with CON. The 2 h postprandial glucose average, peak, area under the curve and incremental area under the curve were also significantly lower after breakfast and dinner during the ES condition compared with CON (all p<0.05).

Conclusions/interpretation Bodyweight exercise snacks totalling 4 min of vigorous activity per day led to small, yet statistically significant improvements in indices of glycaemic variability and postprandial hyperglycaemia in insufficiently active individuals living with well-controlled type 2 diabetes.

Trial registration ClinicalTrials.gov NCT06382246

Keywords At home · Bodyweight exercise · Continuous glucose monitoring · Glycaemic regulation · Mean glucose

Abbreviations

CGM	Continuous glucose monitoring
CON	Control (no exercise)
CV	Coefficient of variation
ES	Exercise snack condition
HR	Heart rate
MAGE	Mean amplitude of glycaemic excursions
RPE	Rating of perceived exertion
SD	Standard deviation
TAR	Time above range
TBR	Time below range
TIR	Time in range
TITR	Time in tight range
VILPA	Vigorous intermittent lifestyle physical activity

Extended author information available on the last page of the article

Research in context

What is already known about this subject?

- An acute session of high-intensity interval exercise can improve indices of glucose regulation in people with type 2 diabetes
- Interrupting sedentary time throughout the day with short activity breaks can also improve glucose regulation in people with type 2 diabetes

What is the key question?

- Can exercise snacks, performed as four 1 min bouts of daily vigorous bodyweight exercise, improve indices of glucose regulation measured using continuous glucose monitoring in people living with non-insulin treated type 2 diabetes?

What are the new findings?

- Under controlled dietary conditions, a total of 4 min of daily vigorous bodyweight exercise snacks performed across the day in the real world reduced glycaemic variability and improved postprandial hyperglycaemia in insufficiently active individuals living with type 2 diabetes

How might this impact on clinical practice in the foreseeable future?

- Daily exercise snacks may be a feasible, time-efficient exercise strategy to enhance glucose management for individuals living with type 2 diabetes, particularly for those who are unable or unwilling to allocate distinct blocks of time during the day for a longer exercise session

Introduction

A single session of moderate-to-vigorous aerobic exercise can improve glucose regulation during and for up to 48 h after the session [1, 2]. Meta-analysis shows that short-term exercise interventions in people with type 2 diabetes reduce mean 24 h glucose, glycaemic variability and time spent in hyperglycaemia as measured by continuous glucose monitoring (CGM) compared with a non-exercise control condition [3]. A single session of high-intensity interval exercise involving repeated 1 min efforts has also been shown to reduce postprandial hyperglycaemia in people with type 2 diabetes measured by CGM [4]. In contrast, when individuals with type 2 diabetes completed 50 min of continuous walking, there were no differences in postprandial hyperglycaemia, glycaemic variability or 24 h mean glucose compared with a non-exercise control condition [5]. Other studies have shown that high-intensity interval exercise may have greater impacts compared with moderate-intensity continuous exercise on immediate post-exercise glucose regulation [6], postprandial hyperglycaemia [7] and 24 h mean glucose [8]. These data collectively suggest that higher exercise intensity may lead to greater acute glycaemic improvements.

'Exercise snacks' are brief bouts of vigorous activity (≤1 min) performed sporadically throughout the day [9–12]. Common examples include stair climbing and bodyweight exercises. The strategy enables small amounts of vigorous exercise during daily living while also breaking up prolonged periods of sedentary time, potentially having dual benefits on glucose regulation [1, 13]. Previous laboratory-based studies have demonstrated acute effects after various exercise snack interventions, including lower insulin and lower mean and postprandial glucose metrics [8, 14–17]. Despite the potential utility of this approach to improve glucose regulation in people living with type 2 diabetes, this possibility has not been studied.

The purpose of this randomised crossover study was to determine the acute impact of exercise snacks (ES condition) compared with a no-exercise control condition (CON) on CGM-derived parameters of glucose regulation in people living with non-insulin-treated type 2 diabetes. Each condition lasted 48 h, and was performed in the real world under controlled dietary conditions. The primary outcome was the difference in mean glucose between ES and CON. Secondary outcomes comprised: (1) 2 h postprandial glycaemia assessed via glucose average, peak, standard deviation (SD), area under the curve (AUC) and incremental AUC (iAUC); (2) glycaemic variability assessed by the coefficient of variation (CV), SD and the mean amplitude of glycaemic excursions (MAGE); and (3) time in range (TIR), time in tight range (TITR), time above range (TAR) and time below range (TBR), all averaged across the two condition days. We hypothesised that

Table 1 Participant baseline characteristics and familiarisation data

Characteristic or measurement	Value
N	31
Female	21 (68)
Age, years	58±11
Time since type 2 diabetes diagnosis, years	
1	2 (7)
1–2	9 (29)
3–5	6 (19)
6–10	4 (13)
>10	10 (32)
Cardiometabolic health markers	
HbA_{1c}, mmol/mol	48±8
HbA_{1c},%	6.6±0.7
Systolic blood pressure, mmHg	127±17
Diastolic blood pressure, mmHg	77±10
ES familiarisation	
Polar peak HR, bpm	133±18
Polar % age-predicted maximal HR, %	82±9
Session RPE, arbitrary units	6±1
Glucose-lowering medications (*n*)	
None	5
Monotherapy (metformin or GLP-1RA only)	13
Dual therapy (metformin plus one other agent)	8
Triple therapy (metformin plus two other agents)	5

Data are presented as means ± SD for continuous variables and *n* (%) for categorical variables, unless otherwise specified, and are based on *n*=31 unless otherwise specified. HR data (recorded from Polar chest strap) are based on *n*=28 and RPE data are based on *n*=24

GLP-1RA, glucagon-like peptide-1 receptor agonist

ES would improve glycaemic regulation compared with the no-exercise condition.

Methods

Participants and sample size

This randomised crossover trial was conducted at McMaster University (Hamilton, Ontario, Canada) and the University of British Columbia – Okanagan (Kelowna, British Columbia, Canada) between April 2024 and April 2025. Participants were recruited from these two cities through a third-party recruitment service (Wayturn, Mariefred, Sweden), supplemented by posters, community events or online advertisements, or through word of mouth or previous study participation. Using an effect size of 0.6, calculated based on the mean glucose data presented in the study by van Dijk et al [16], a sample size of 24 participants was found to be required for a two-tailed paired-samples *t* test with power = 0.8 and α=0.05 (G*Power version 3.1.9.7). This study was pre-registered (ClinicalTrials.gov: NCT06382246) with a target enrolment of *n*=30 to account for potential dropouts and missing CGM data. Individuals of all sex and gender orientations were welcome to participate, but the study was not designed or powered to assess sex or gender differences. The main eligibility criteria included: age 30–75 years, diagnosed with type 2 diabetes, not on insulin therapy, taking three or fewer glucose-lowering medications, HbA_{1c} ≤69 mmol/mol (≤8.5%), and currently performing <150 min per week of aerobic exercise based on the Godin–Shephard

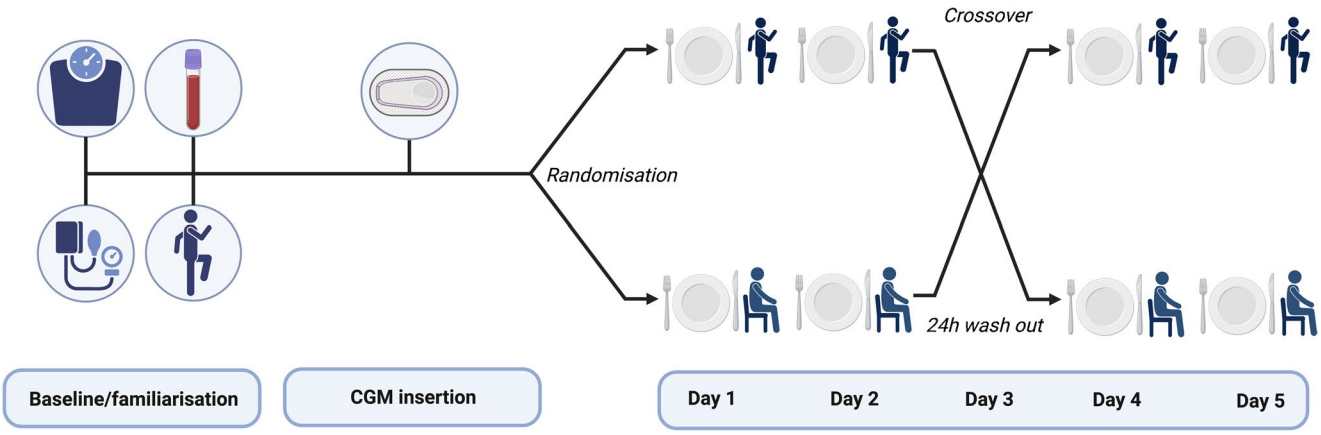


Fig. 1 Study design schematic. The baseline testing and familiarisation visit comprised the following measurements or procedures: anthropometric measurements (body mass, height, waist circumference), blood pressure measured using an automated cuff, a fasted venous blood sample, and one or two exercise snacks for familiarisation. The FreeStyle Libre 2 CGM device was inserted prior to the start of the first condition. Days 1 and 2 represent the first 48 h condition (exercise snacks or control); day 3 was the 24 h washout period between conditions; days 4 and 5 represent the alternate 48 h condition. The plate and cutlery icon represents the standardised, individualised diet that was provided to participants to consume on days 1, 2, 4 and 5. The high-knees icon represents the exercise snacks condition, whereas the seated icon represents the non-exercise control condition. One person did not complete the 24 h washout period between the two 48 h conditions due to a personal scheduling constraint. Created in BioRender. Little, J. (2026) https://BioRender.com/tnxqyta

leisure-time physical activity questionnaire [17]. Full inclusion and exclusion criteria are available in electronic supplementary material (ESM) Table 1. The study was approved by the Hamilton Integrated Research Ethics Board (16834) and the University of British Columbia Clinical Research Ethics Board (H21-03417). Participants who completed this study also subsequently participated in a 12-week remotely delivered exercise snacks intervention as part of a larger feasibility RCT (ClinicalTrials.gov: NCT06407245).

Study protocol

Screening and baseline testing Individuals who were interested in participating completed a remote screening phone call to review the eligibility criteria and consent form. Individuals who were preliminarily deemed eligible were invited to an in-person baseline testing visit at their respective study site. They were asked to report to the laboratory after a fast of ≥8 h, and were recommended to refrain from taking glucose-lowering medication before baseline testing. Participants provided signed informed consent before baseline testing measurements were collected; these comprised anthropometric measurements (body mass, height, waist circumference), blood pressure and a fasted venous blood sample. Participants were also familiarised with exercise snacks, whereby one or two exercise snacks were completed in the lab under the supervision of a study researcher while heart rate (HR) was recorded via a chest strap (Polar, Kempele, Finland). A session rating of perceived exertion (RPE) [18] was collected after completion of these familiarisation exercise snacks. Baseline participant characteristics and familiarisation data are presented in Table 1.

Study conditions Each participant completed a 48 h ES condition and a 48 h CON condition in a randomised, counterbalanced order with a 24 h washout period while consuming a standardised diet in a real-world setting. The two conditions were studied over a total of 5 days. Figure 1 shows the study design schematic. Participants were asked to insert the CGM device (FreeStyle Libre 2 Sensor; Abbott Laboratories, Chicago, IL, USA) on the back of their upper arm or were assisted with device installation by a study researcher the day prior to the start of the first condition. Days 1–2 involved the first condition (ES or CON) during which participants were provided with a standardised and individualised diet to consume for 48 h. Day 3 was a washout day during which participants were allowed to return to their typical dietary patterns for 24 h. Days 4–5 involved the alternate condition (ES or CON), during which participants were again provided with an identical diet to consume for 48 h. Participants were asked to refrain from any additional structured exercise including leisure-time walking and moderate-to-vigorous physical activity between days 1 and 5, which was confirmed using a thigh-worn activPAL4 accelerometer (PAL Technologies, Glasgow, UK) that was applied prior to the study. The condition order (ES first or CON first, counterbalanced) was determined via concealed envelope randomisation, with the envelopes being opened by a study researcher after baseline measurements were collected. The randomisation sequence was stratified by site using variable permuted block size and was generated by a researcher who was not directly involved in data collection. Participants were instructed to replicate details of their food and beverage consumption patterns across conditions, including time of consumption, volume of beverages consumed other than water, and any partial meal or snack consumption. They were also asked to refrain from alcohol consumption during the two 48 h conditions. Participants were given a logbook to record details to aid in the replication process. The total daily energy provided to participants was based on calculations performed using the Harris–Benedict equation [19], multiplied by a small activity factor (1.2). The total daily energy intake provided in the meal plans was 8285±1448 kJ (1980±346 kcal), with all participants successfully replicating diets across the two conditions based on their logbooks. The daily amounts of carbohydrates, fats and protein provided were 252±46 g, 58±16 g and 113±30 g, which corresponded to 51±3%, 26±5%, and 23±5% of the daily energy intake, respectively.

ES and CON interventions Participants received daily emails with reminders and information from a study researcher providing guidance for the tasks to complete each day. During the ES condition, the emails included links to exercise instructional videos, which included both male and female instructors. Participants were asked to complete four 1 min bodyweight exercise snacks per day (totalling eight 1 min exercise snacks over the 48 h ES condition). The exercises assigned to participants were step-ups, box run (running forward, sideways and backwards for approximately 2 m in each direction) or running on the spot; however, in some instances, a different 1 min vigorous-intensity exercise (e.g. lateral shuttle, lateral squat, stair climbing or sit-to-stands, etc.) was substituted if the individual's capacity required adaptation. Participants were advised to space out their exercise snacks by at least 1 h, and were encouraged to perform an exercise snack within 30–60 min after major meals. Participants had autonomy to choose the exact timing of meal consumption and exercise snack completion throughout the day given the real-world nature of the study. Participants were asked to self-report completion of each ES performed within their logbook. Participants were also given a wrist-worn Fitbit Charge 6 (Fitbit, San Francisco, CA, USA) to measure the HR responses to the ES performed. Participants were asked to perform the exercise snacks at an effort that would elicit an RPE of ≥7/10, which corresponds to 'very

hard' [18]. During the 48 h CON condition, participants were asked to consume an identical standardised diet with meals at the same times throughout the day, and to complete no exercise snacks or other structured exercise.

Measurements and calculations

Fasted blood sample analysis During baseline testing, blood samples were taken from an antecubital vein and collected into EDTA tubes. A point-of-care analyser (Afinion 2; Abbott Laboratories, Chicago, IL, USA) was used to measure HbA_{1c}.

CGM analysis CGM data were stored and downloaded from LibreView (Abbott Laboratories) into CSV files. CGM data for each two-day condition were extracted into separate Excel files before subsequent upload to an advanced CGM data analysis website (Diametrics: University of Exeter [20]) to determine data sufficiency and calculate mean glucose, SD, CV, MAGE, TIR (3.9–10.0 mmol/l), TITR (3.9–7.8 mmol/l), TAR (>10.0 mmol/l) and TBR (<3.9 mmol/l) for each 48 h condition. Sensitivity analyses were used to explore these same metrics for daytime (06:00–24:00 hours) and night-time (24:00–06:00 hours) periods. If data sufficiency was <70%, that condition was excluded from the final analysis as recommended in CGM consensus guidelines [21]. Meal timing as recorded in participant logbooks was used to extract the 2 h postprandial glucose data from raw CGM data files, which provide glucose concentrations in intervals of approximately 15 min. Postprandial metrics (2 h average, peak, SD, AUC and iAUC) were calculated in Excel for each meal consumed on each day of a given condition. If data sufficiency was <70% for any 2 h postprandial window, the average, peak and SD were not included in the final analysis. If one data point in the 2 h postprandial window was missing, the AUC and iAUC for that meal were not included in the final analysis.

Activity monitor analysis Fitbit activity logs and HR data were stored and downloaded from Fitabase (San Diego, CA, USA) for all participants who had registered (n=18). The activity log files were cleaned for manually recorded activities and activities lasting 30–180 seconds. The peak HR for each exercise snack was determined using second-by-second HR files downloaded from Fitabase. ActivPAL4 accelerometers were initialised using PALconnect (version 8.11.4.89) to record tri-axial acceleration data at a frequency of 20 Hz, with a dynamic range of ±4 g. Each device was waterproofed using a latex finger cot, and installed using a Tegaderm transparent film dressing (3M Healthcare, St Paul, MN, USA) on the midline anterior aspect of the non-dominant thigh. After device retrieval, .datx files were downloaded using PALconnect (version 9.1.2.168), and processed using PALanalysis (version 9.1.0.102; CREA algorithm version 1.3). Variables of interest were total daily steps, stepping time at a cadence of ≥100 steps per minute (a proxy for minutes of moderate-to-vigorous activity per day [22]), sit-to-stand transitions, total sitting time, and time in bed (primary lying time).

Statistical analysis

Baseline and descriptive characteristics are presented as means ± SD or n (%) for continuous and categorical variables, respectively. To analyse the primary pre-registered outcome of the study (mean glucose), we used a linear mixed model with a fixed effect for condition (ES vs CON), a random effect for participant to account for the correlation arising from repeated measurements within each individual, and adjustments for site and sex as well as the order and time period (given the crossover design). Model assumptions of normality and linearity were assessed visually by inspection of diagnostic plots. Models were run using natural log-transformed outcome variables if departure from model assumptions was observed. Data were analysed on an intention-to-treat basis, with no statistical imputations used to replace missing data. Data are presented as model-derived estimated marginal means and between-condition effect estimates with corresponding 95% CI and p values. Secondary outcomes, including 2 h postprandial glycaemic responses (average, peak, SD, AUC and iAUC), glycaemic variability (CV, SD and MAGE), TIR and TITR, daytime/night-time glucose, together with accelerometer data, were analysed similarly. TAR and TBR were dichotomised for each participant and condition (i.e. did vs did not), and analysed using logistic regression with the same covariates; between-condition differences are reported as odds ratios. Data analyses were conducted in R (version 4.3.2), and statistical significance was established at a two-sided α of 0.05, and no adjustments were applied to secondary and exploratory outcomes.

Results

Participants

Of the 35 participants initially recruited for this study, it was found that four participants did not accurately self-report their eligibility for the study during the screening process. This led to their exclusion, resulting in 31 participants who started and completed both the ES and CON conditions. Of these, 21 were biological females identifying as women and ten were biological males identifying as men. Twenty-nine participants self-reported White ethnicity, with some individuals identifying mixed ethnic backgrounds. The remaining participants reported South Asian, Black, Filipino, Indigenous or Chinese ethnicity (n=1 each, including those reporting mixed ethnic backgrounds). The CONSORT diagram is shown in Fig. 2.

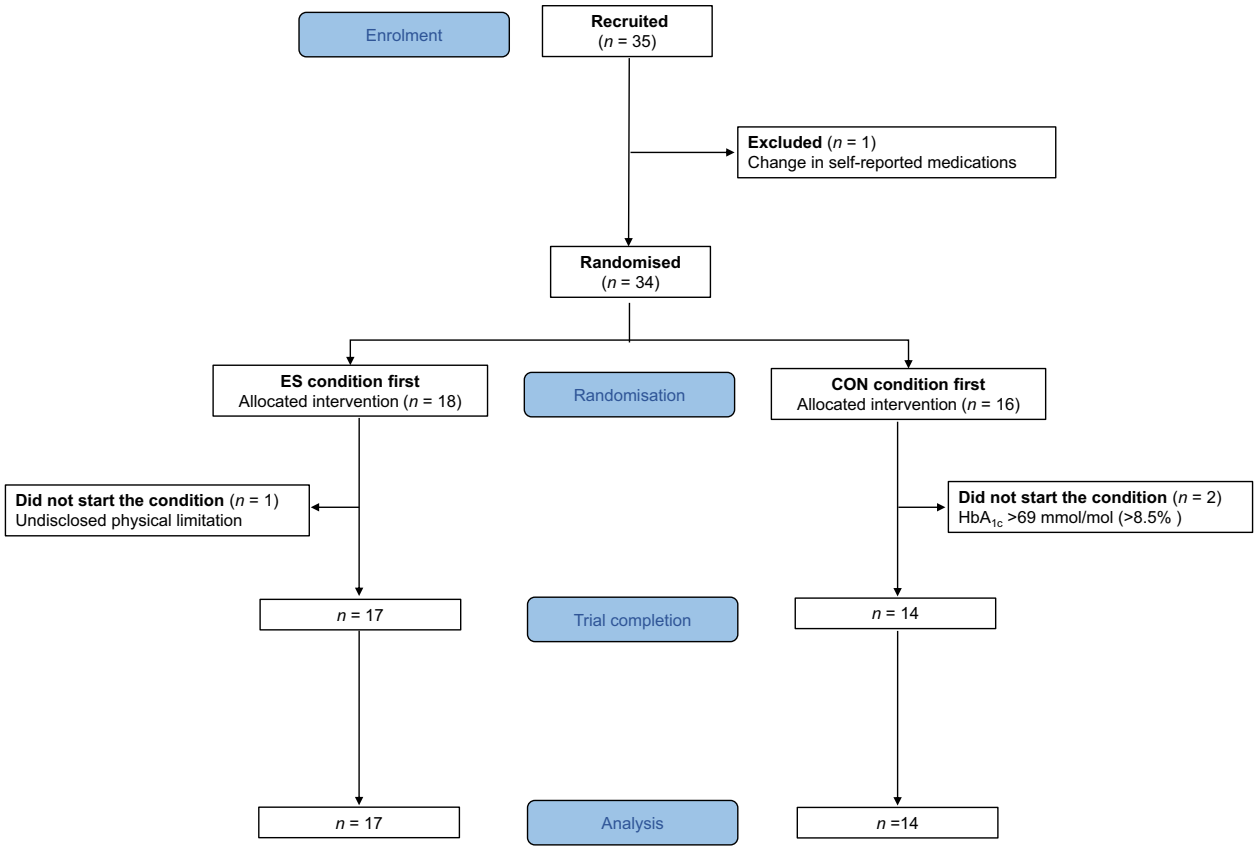


Fig. 2 Participant CONSORT flow diagram

Adherence, exercise intensity and activity monitoring

Participants self-reported completing 4±1 exercise snacks per day or a total of 8±1 exercise snacks across the two-day ES condition. On average, participants competed an exercise snack 47±27 min after breakfast, 49±24 min after lunch, and 54±22 min after dinner. Of those who shared Fitbit data (n=18), participants recorded 3±2 exercise snacks per day on the Fitbit. The peak HR recorded by the Fitbit was 134±18 bpm, representing 80±8% of the age-predicted HR maximum. From ActivPal4 data, participants accumulated more total daily steps (marginal mean 1261; 95% CI 512, 2009; p=0.002), and performed more sit-to-stand transitions (marginal mean 10; 95% CI 5, 15; p<0.001) during the ES condition when compared with CON. However, there was no difference in moderate-to-vigorous physical activity (p=0.146), total sitting time (p=0.432) or sleep/primary lying time (p=0.968) between conditions. Accelerometer data are provided in ESM Table 2.

CGM outcomes

Estimated marginal means as well as between-condition effect estimates with corresponding 95% CI for the CGM-derived metrics for each 48 h condition are presented in Table 2. The between-condition difference for mean glucose did not reach statistical significance (between-condition difference −0.2 mmol/l; 95% CI −0.4, 0.0; p=0.07) (Fig. 3). However, all metrics for glycaemic variability (CV: −1%; 95% CI −2, 0; p=0.007; SD: −0.1 mmol/l; 95% CI −0.2, −0.1; p<0.001; MAGE: −0.3 mmol/l; 95% CI −0.5, 0.0; p=0.04) (Fig. 4) were lower during the ES condition compared with CON. TITR was higher under the ES condition vs the CON condition (3%; 95% CI 0, 6; p=0.04). There were no between-condition effects for TIR, TAR or TBR (all p>0.05). The main CGM findings were supported by sensitivity analyses separating day and night, which revealed significantly lower mean glucose, SD, CV and MAGE (ESM Table 3, all p<0.05) during the daytime period when exercise snacks were performed, with no significant differences at night.

Table 2 Effect estimates for differences in CGM-derived metrics of glucose regulation

	ES	CON	Difference between conditions	*p* value
Full condition metrics				
Mean glucose, mmol/l	6.8 (6.4, 7.3)	7.0 (6.6, 7.5)	−0.2 (−0.4, 0.0)	0.07[a]
Standard deviation, mmol/l	1.4 (1.2, 1.5)	1.5 (1.3, 1.7)	−0.1 (−0.2, −0.1)	<0.001
Coefficient of variation, %	20 (17, 22)	21 (19, 23)	−1 (−2, 0)	0.007
MAGE, mmol/l	3.5 (3.0, 4.1)	3.8 (3.3, 4.4)	−0.3 (−0.5, 0.0)	0.04
TIR (3.9–10.0 mmol/l), %	92 (88, 96)	91 (87, 95)	2 (−1, 5)	0.29
TITR (3.9–7.8 mmol/), %	75 (66, 84)	72 63, 80)	3 (0, 6)	0.04
TAR (>10.0 mmol/l), *n* [b]	22 (71)	22 (71)	0.02 (0.00, 5.79)	0.17
TBR (<3.9 mmol/l), *n* [b]	9 (29)	10 (32)	0.44 (0.04, 5.24)	0.51
2 h postprandial glucose metrics				
Breakfast				
Average, mmol/l	8.5 (7.8, 9.2)	8.9 (8.1, 9.6)	−0.4 (−0.6, −0.1)	0.01[a]
Peak, mmol/l	10.2 (9.3, 11.1)	10.6 (9.7, 11.5)	−0.4 (−0.8, 0.0)	0.049[a]
Standard deviation, mmol/l	1.3 (1.1, 1.5)	1.4 (1.2, 1.6)	−0.1 (−0.2, 0.0)	0.11
AUC, mmol/l × 120 min	1034 (945, 1124)	1083 (994, 1173)	−49 (−83, −15)	0.009[a]
iAUC, mmol/l × 120 min	176 (123, 229)	216 (163, 268)	−40 (−76, 4)	0.04
Lunch				
Average, mmol/l	7.2 (6.6, 7.8)	7.6 (7.0, 8.2)	−0.3 (−0.7, 0.0)	0.08
Peak, mmol/l	8.5 (7.7, 9.3)	8.9 (8.2, 9.7)	−0.4 (−0.9, 0.0)	0.08
Standard deviation, mmol/l	0.9 (0.7, 1.2)	1.1 (0.9, 1.3)	−0.2 (−0.3, 0.0)	0.03
AUC, mmol/l × 120 min	876 (803, 949)	911 (838, 984)	−35 (−78, 7)	0.12
iAUC, mmol/l × 120 min	130 (77, 182)	158 (105, 210)	−28 (−68, 12)	0.18
Dinner				
Average, mmol/l	7.2 (6.6, 7.9)	7.7 (7.0, 8.3)	−0.4 (−0.7, −0.2)	0.005
Peak, mmol/l	8.5 (7.6, 9.3)	9.0 (8.2, 9.9)	−0.6 (−0.9, −0.2)	0.005
Standard deviation, mmol/l	1.0 (0.8, 1.2)	1.1 (0.9, 1.3)	−0.1 (−0.3, 0.0)	0.08
AUC, mmol/l × 120 min	878 (794, 962)	919 (835, 1002)	−40 (−76, −5)	0.03
iAUC, mmol/l × 120 min	124 (72, 175)	162 (111, 213)	−38 (−65, −12)	0.009

Data for glucose metrics and most full condition metrics are presented as estimated marginal means and between-condition effect estimates (95% CI) with corresponding *p* values. Effect estimates are based on intention-to-treat analyses. Data were analysed using a linear mixed model with a fixed effect for condition, adjustments for order, period, site and sex, and a random intercept for participant, except for TBR and TAR. These two outcomes were dichotomised for each participant and condition (i.e. did or did not have TBR or TAR) and analysed using logistic regression with the same covariates. The between-condition differences for TBR and TAR are reported as odds ratios. Analyses are based on *n*=31 unless otherwise noted. Full condition metrics for CON are based on *n*=30. Breakfast outcomes for the ES condition are based on *n*=30. Lunch outcomes under both conditions are based on *n*=30. For dinner in the ES condition, average, peak and standard deviation are based on *n*=30 but AUC and iAUC are based on *n*=29

[a]Main effect of period ($p<0.05$)

[b]Dichotomised as did or did not have, due to skewness and non-normal data distribution

Postprandial glucose outcomes

Estimated marginal means and between-condition effect estimates with corresponding 95% CI for postprandial outcomes are presented in Table 2. The 2 h glucose average, peak, AUC and iAUC after breakfast and dinner were lower in the ES condition compared with CON (all $p<0.05$). There was no between-condition difference for the 2 h SD after breakfast or dinner ($p>0.05$). After lunch, there were no between-condition differences for any 2 h postprandial outcome (all $p>0.05$), except for a reduction in the 2 h SD in the ES condition compared with CON ($p<0.05$). Figure 5 shows the average postprandial glucose curves after breakfast, lunch and dinner for the ES and CON conditions.

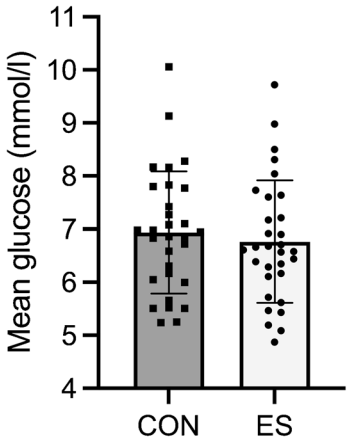


Fig. 3 Mean glucose measured using CGM for each 48 h condition (mean ± SD). Individual symbols represent the mean CGM glucose averaged over the two study days for each condition days for a single participant (ES, *n*=31; CON, *n*=30). A *p* value of 0.07 was obtained for the between-condition difference based on the linear mixed model

Discussion

The major novel finding from the current study was that a total of 4 min of daily vigorous activity performed as bodyweight exercise snacks reduced glycaemic variability and postprandial hyperglycaemia compared with no exercise in adults living with non-insulin-treated type 2 diabetes. Although mean glucose was not different between conditions (p=0.07), all metrics of glycaemic variability, multiple postprandial glucose outcomes and TITR were significantly improved in the ES condition compared with CON. These findings indicate that short bursts of vigorous exercise performed intermittently throughout the day can improve glycaemic regulation in people with type 2 diabetes who are not on insulin therapy. The reductions in glycaemic variability and postprandial hyperglycaemia elicited by daily exercise snacks were statistically significant but small in magnitude. It remains to be determined whether performing daily exercise snacks would lead to clinically significant improvements in glycaemic regulation over weeks or months.

The novelty of the present study lies in the exercise intervention, the real-world setting and the study population. There is increasing scientific interest in exercise snacks [9–11], but, to our knowledge, no study has explored the approach in people with type 2 diabetes in a real-world setting. Prior studies [14, 15] have investigated the impact of breaking up sedentary time with daily short exercise bouts in people with type 2 diabetes, but these were performed in a laboratory setting, and the frequency and duration of the exercise bouts were greater compared with our study (e.g. 3 min of treadmill walking or 3 min of bodyweight exercise every 30 min during a 7 h period). Consistent with our findings, Dempsey et al [14] found lower postprandial hyperglycaemia after breakfast (measured as glucose iAUC) during the walking and bodyweight exercise conditions compared with a non-exercise seated control condition. They also found that mean 22 h glucose was lower for walking and bodyweight exercise conditions compared with a sitting condition [15]. In our study, the overall difference in mean CGM glucose did not reach statistical significance (p=0.07), but was significantly lower (p=0.01) when analysed as mean daytime CGM concentration, i.e. when exercise snacks were performed. The larger and more frequent exercise dose prescribed by Dempsey et al [15] may have a more consistent (and probably more clinically significant) impact on mean glucose compared with the lower amount of intermittent

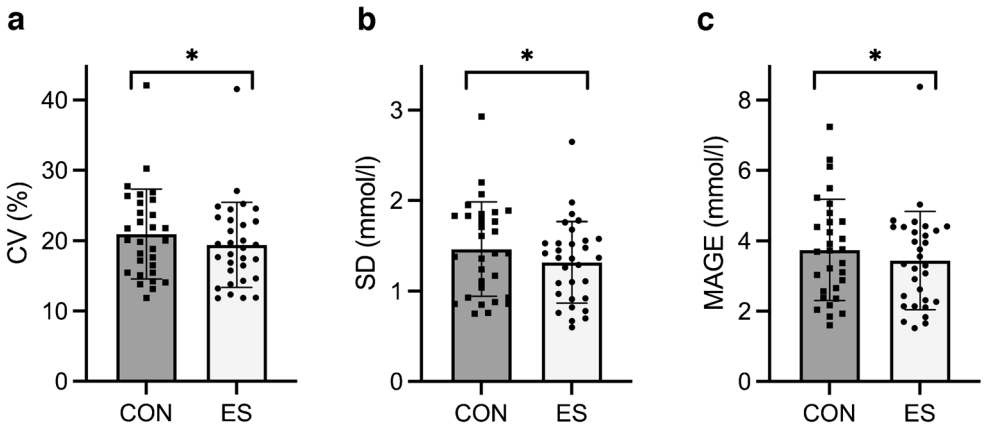


Fig. 4 Glycaemic variability measured using CGM for each 48 h condition. (**a**) Coefficient of variation (CV); (**b**) standard deviation (SD); (**c**) mean amplitude of glycaemic excursion (MAGE). Data are means ± SD. Individual symbols represent the glycaemic variability metric averaged over the two study days for each condition for a single participant (ES, *n*=31; CON, *n*=30). Asterisks indicate a significant difference at $p<0.05$ for the between-condition difference based on the linear mixed model

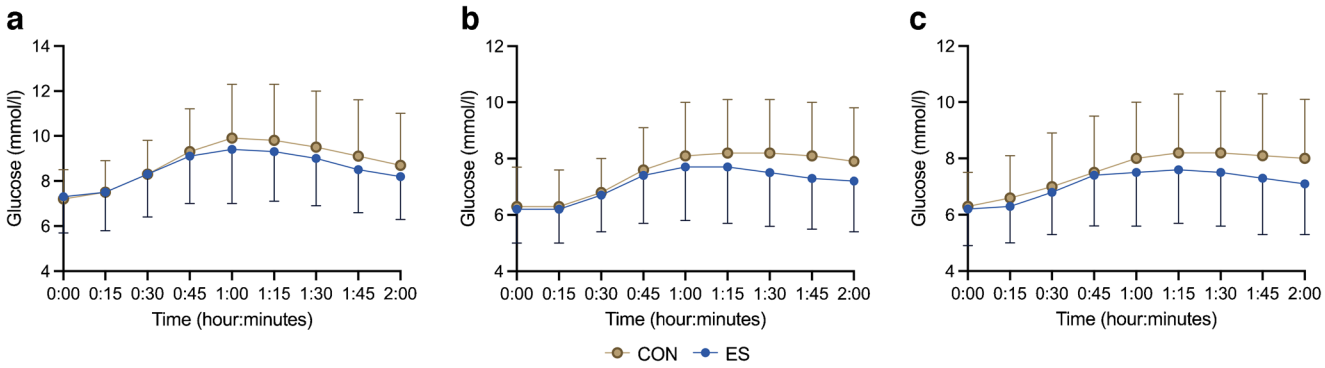


Fig. 5 The 2 h postprandial glucose responses measured by CGM after the standardised meals. (**a**) Breakfast; (**b**) lunch; (**c**) dinner. Each data point and error bar represent the mean and standard deviation, respectively, for the given time point in the 2 h postprandial window. Analyses were based on n=31 unless otherwise noted: n=30 for ES condition breakfast, lunch and dinner, except the 2 h time point for dinner is (n=29); n=30 for CON condition lunch

exercise prescribed in our study. Additionally, Dempsey et al [15] employed a stricter in-laboratory seated control condition, whereas our study has greater ecological validity as it was performed in the real world without mandatory sitting across the day. Another study [8] found that three daily sessions of six 1 min bouts of high-intensity interval walking in individuals with insulin resistance lowered postprandial glycaemia after dinner and reduced 24 h mean glucose when compared with completing a single 30 min moderate-intensity continuous exercise session. Although this study used the term 'exercise snacks', each pre-meal session of six 1 min bouts required approximately 20 min, with a total time commitment of 60 min per day [8], which was much higher than the daily time commitment in our study.

Our findings provide preliminary evidence regarding the utility of 1 min exercise snacks for glucose management in those with type 2 diabetes. The results suggest that performing short isolated bursts of vigorous exercise across the day is a viable exercise strategy compared with traditional approaches for improving glycaemic variability and postmeal glucose responses. Although we cannot identify the mechanisms responsible for the improvements in glycaemic regulation, short bouts of activity (particularly after meals) can activate insulin-independent skeletal muscle glucose uptake, which would be expected to preferentially reduce postprandial glucose excursions and glycaemic variability [23, 24]. Previous studies also indicate improved markers of insulin sensitivity [25], leg blood flow [26] and lipid metabolism [25] when short bouts of vigorous activity are distributed throughout the day, which may contribute to improved glycaemic regulation. It is also possible that the improvements in glycaemic management may be partially attributable to the increase in total steps shown for the ES condition. However, as the prescribed exercise snacks consisted primarily of ambulatory movements (i.e. running on the spot, step-ups, box run), and given the established accuracy and validity of the ActivPAL for measuring ambulatory activity [27], it is likely that the observed increase in total steps reflects adherence to the exercise snacks intervention rather than increased incidental activity.

It is important to emphasise that the magnitudes of the statistically significant reductions in glycaemic variability (a reduction in SD of approximately 0.1 mmol/l and a reduction in CV of approximately 1–2%) and postprandial hyperglycaemia (a reduction of approximately 0.2–0.4 mmol/l in peak glucose and a reduction of approximately 18% in iAUC) and of the increased TITR (approximately 3–4%) in the present study are small compared with more traditional exercise interventions [3, 4]. Although there are no universally accepted minimal clinically important differences defined for glycaemic variability and postprandial glucose markers assessed by CGM, consensus guidelines and prior exercise intervention studies [3, 21] suggest that the magnitudes of improvement seen in the ES condition in this crossover trial are relatively small. The small improvements are probably the result of a combination of factors, including the low volume of exercise, the low number of sedentary breaks and well-controlled HbA_{1c} at baseline, and the variability in glucose-lowering medication use in our sample.

The present study enhances our understanding of how exercise-based diabetes management options can be translated and implemented into practical, real-world environments. Exercise snacks may be particularly suited for individuals who are unable or unwilling to allocate a distinct block of time to perform a longer exercise session. Exercise snacks can be easily incorporated at home or work, and, when performed in this manner, align with the related concept of vigorous intermittent lifestyle physical activity (VILPA). VILPA is the 'non-exercise' equivalent of exercise snacks, and involves physical activity embedded into daily living [28]. Recent work has shown that as little as

approximately 3–4 min of device-measured VILPA per day is associated with a reduced mortality risk in self-identified non-exercisers [29] and a lower risk of major adverse cardiovascular events for women [30]. Although VILPA, by definition, differs from the planned and structured nature of exercise snacks [31], studies on the effects of VILPA on health-related outcomes can provide a valuable framework and lens through which to view the impact of exercise snack interventions in the real world, given the similarities between the two concepts. The total daily duration of VILPA that was found to be effective for improving health and mortality outcomes [29, 30] aligns closely with the daily prescribed duration of exercise snacks in the current study. Incorporating VILPA into daily life may be a feasible strategy to improve glucose regulation among those trying to bridge the gap between planned, structured exercise and optimising incidental activity in everyday life.

The strengths of the current study relate to the balance of experimental rigour and real-life applicability. These include the autonomy given to participants to select the timing and location of the exercise snacks, the real-world nature of the intervention, the dietary controls employed, and use of accelerometers to confirm changes to stepping and sit-to-stand transitions in the ES condition. Providing a standardised but individualised diet to participants during the CGM period helped to mitigate the variability in glucose responses caused by changes in diet, particularly carbohydrate intake [32]. While the real-world nature of this study contributes to the applicability, generalisability and potential future implementation of exercise snacks, it involved limitations (e.g. differences in behaviour, exercise and meal consumption patterns) that can be better controlled in laboratory-based studies. Use of CGM allowed enabled assessment of the impact of exercise snacks on multiple aspects of glycaemic regulation, but it is important to note that some previous studies have indicated that CGM readings may have greater error during prolonged (30–60 min) aerobic exercise in people living with type 1 diabetes [33, 34]. It is currently unknown whether short, 1 min bursts of exercise influence CGM readings in people with type 2 diabetes. Although sex was included in the statistical model and our sample included 68% female participants, the study was not designed or powered to assess sex differences. Real-world vs laboratory-based studies each have distinct strengths and limitations inherent to their designs, and both are valuable to gain a holistic view and better understanding of the impacts of exercise on acute glucose regulation.

In summary, the present study provides novel evidence that as little as four 1 min bouts of vigorous-intensity bodyweight exercise snacks performed in a real-world setting under controlled dietary conditions elicited small but statistically significant improvements in postprandial glucose regulation and glycaemic variability in insufficiently active adults living with type 2 diabetes. Future work is needed to determine the clinical significance of these findings, while continuing to investigate the ideal daily dose of exercise snacks, including trade-offs between frequency and duration, to optimise improvements in mean glucose and other health metrics beyond glycaemic regulation. It is possible that different prescriptions and thresholds of exercise snacks may be required to elicit clinically meaningful changes, highlighting the need for more research in this area. The present findings and the promising epidemiological data on the concept of VILPA call for more research to bridge the gap between the concept of exercise snacks and VILPA as a means to promote the application of brief bouts of vigorous activity to improve health.

Supplementary Information The online version contains peer-reviewed but unedited supplementary material available at https://doi.org/10.1007/s00125-026-06741-2.

Data availability De-identified data may be made available for researchers with an institutional email address for the purpose of preregistered systematic reviews or meta analysis by requesting from the corresponding author via email.

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Authors' relationships and activities MJG is an advisor to and holds equity in Longevity League Ltd, a US-based company whose services in part relate to exercise. The remaining authors declare that there are no relationships or activities that might bias, or be perceived to bias, their work.

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