Diabetologia (2014) 57:1437–1445
DOI 10.1007/s00125-014-3244-6

ARTICLE

‘Exercise snacks’ before meals: a novel strategy to improve glycaemic control in individuals with insulin resistance

Monique E. Francois · James C. Baldi · Patrick J. Manning · Samuel J. E. Lucas · John A. Hawley · Michael J. A. Williams · James D. Cotter

Received: 15 January 2014 / Accepted: 1 April 2014 / Published online: 10 May 2014

Abstract
Aims/hypothesis The aim of this study was to investigate whether small doses of intense exercise before each main meal (‘exercise snacks’) would result in better blood glucose control than a single bout of prolonged, continuous, moderate-intensity exercise in individuals with insulin resistance.
Methods Nine individuals completed three exercise interventions in randomised order. Measures were recorded across 3 days with exercise performed on the middle day, as either: (1) traditional continuous exercise (CONT), comprising 30 min moderate-intensity (60% of maximal heart rate [HR_{max}]) incline walking before dinner; (2) exercise snacking (ES), consisting of 6×1 min intense (90% HR_{max}) incline walking intervals 30 min before each meal; or (3) composite exercise snacking (CES), encompassing 6×1 min intervals alternating between walking and resistance-based exercise, 30 min before meals. Meal timing and composition were controlled within participants for exercise interventions.
Results ES attenuated mean 3 h postprandial glucose concentration following breakfast (by 1.4±1.5 mmol/l, p=0.02) but not lunch (0.4±1.0 mmol/l, p=0.22), and was more effective than CONT following dinner (0.7±1.5 mmol/l below CONT; p=0.04). ES also reduced 24 h mean glucose concentration by 0.7±0.6 mmol/l (p=0.01) and this reduction persisted for the subsequent 24 h (lower by 0.6±0.4 mmol/l vs CONT, relative to their baselines; p=0.01). CES was just as effective as ES (p>0.05 for all glycaemic variables) at improving glycaemic control.
Conclusions/interpretation Dosing exercise as brief, intense ‘exercise snacks’ before main meals is a time-efficient and effective approach to improve glycaemic control in individuals with insulin resistance.

Keywords Continuous glucose monitoring · High-intensity interval exercise · Postprandial glucose · Type 2 diabetes

Abbreviations

CVD	Cardiovascular disease
CES	Composite exercise snacking
CGM	Continuous blood glucose monitoring
CONT	Traditional continuous exercise
ES	Exercise snacking protocol
HIT	High-intensity interval training
HR	Heart rate
HR_{max}	Maximal heart rate
PPG	Postprandial glucose
RER	Respiratory exchange ratio

Electronic supplementary material The online version of this article (doi:10.1007/s00125-014-3244-6) contains peer-reviewed but unedited supplementary material, which is available to authorised users.

M. E. Francois · S. J. E. Lucas · J. D. Cotter (✉)
School of Physical Education, Sport and Exercise Sciences, University of Otago, 46 Union St West, PO Box 56, Dunedin 9076, New Zealand
e-mail: jim.cotter@otago.ac.nz

J. C. Baldi · P. J. Manning · M. J. A. Williams
Dunedin School of Medicine, University of Otago, Dunedin, New Zealand

S. J. E. Lucas
Department of Physiology, University of Otago, Dunedin, New Zealand

S. J. E. Lucas
School of Sport, Exercise and Rehabilitation Sciences, University of Birmingham, Birmingham, UK

J. A. Hawley
Exercise and Nutrition Research Group, Department of Exercise Sciences, Faculty of Health Sciences, Australian Catholic University, Fitzroy, VIC, Australia

J. A. Hawley
Research Institute for Sport and Exercise Sciences, Liverpool John Moores University, Liverpool, UK

RPE Rating of perceived exertion
$\dot{V}O_{2max}$ Maximal oxygen consumption

Introduction

The prevalence of type 2 diabetes and insulin resistance is increasing worldwide [1]. Lifestyle interventions (exercise and diet modification) are proven cost-effective methods to prevent the development of type 2 diabetes [2, 3]. However, fewer than 10% of American and 20% of British adults meet the current exercise recommendations [4, 5], with a 'lack of time' ostensibly a major barrier to regular exercise participation, regardless of sex, age, socioeconomic status and fitness level [6]. Therefore, innovations in exercise prescription that can be incorporated into daily living and induce clinically beneficial health outcomes represent a valuable strategy to reduce the economic burden associated with an inactive lifestyle.

With regard to glycaemic control, peak glucose concentrations typically occur approximately 60–90 min after a meal and, in individuals with insulin resistance, are sustained for several hours [7]. Glycaemic excursions, such as those following meals, correlate with HbA_{1c} levels and play a deleterious role in inducing oxidative stress and inflammation [8–10]. HbA_{1c} levels are also directly associated with increased cardiovascular disease (CVD) risk and all-cause mortality [8]. As such, improved postprandial glucose control in individuals with insulin resistance may prevent the further development of type 2 diabetes and associated complications [11, 12].

Both resistance- and endurance-based exercise increase whole-body glucose uptake [13, 14], an effect that can persist for up to 48 h [15, 16]. The benefits for glycaemic control are most powerful soon after the exercise session, and decay over several hours depending on the intensity of the exercise bout. In this regard, short-term high-intensity interval training (HIT) has been demonstrated to be a time-efficient stimulus to improve blood glucose control in patients with type 2 diabetes [17, 18]. HIT stresses multiple physiological systems by alternating brief, intense exercise with low-intensity recovery periods of similar or greater duration. The high-intensity work bouts vary in duration from 6 s to 4 min and are typically performed at an exercise intensity eliciting at least 90% of maximum heart rate (HR_{max}). HIT has been shown in both healthy and clinical populations to reduce risk factors for chronic disease [19]. It is also worth noting that physiological markers of training adaptation, along with health outcomes, are often superior after HIT compared with the improvements obtained with high-volume traditional endurance exercise [20, 21].

The aim of the present study was to investigate whether three small doses of intense exercise before meals ('exercise snacking') would result in better postprandial blood glucose control than a single bout of (energy-matched) prolonged, continuous, moderate-intensity exercise in individuals with insulin resistance. We further examined whether the type of exercise was an important feature of the exercise snacking approach (time-matched). Given the potent nature of HIT to stimulate glucose uptake, and the time course of this response, we hypothesised that the high-intensity 'exercise snacks' before meals would reduce postprandial glucose excursions and underpin improved 24 h glycaemic control.

Methods

Characteristics and preliminary testing of participants

Following advertisement, 16 volunteers who met the inclusion criteria (age 18–55 years, not medicated for blood glucose or high blood pressure) completed an OGTT after dietary control and an overnight fast (10–12 h). Based on the results of this initial OGTT, seven male and two female participants with insulin resistance (impaired fasting glucose and/or impaired glucose tolerance according to the criteria of the American Diabetes Association) or who were found to have type 2 diabetes (n=2) were recruited into the study. The baseline characteristics of the participants are shown in Table 1. The study protocol was approved by the University of Otago Ethics Committee and participants provided their written, informed consent before entering the study. All participants undertook maximal incremental exercise testing with 12-lead electrocardiography on a treadmill and showed no evidence of inducible ischaemia, as assessed by a cardiologist. Maximal oxygen consumption ($\dot{V}O_{2max}$), respiratory exchange ratio (RER: $\dot{V}CO_2/\dot{V}O_2$) and heart rate (HR) were measured using online gas analysis (Quark b^2 and Quark C12x systems, Cosmed Cardio Pulmonary Exercise Testing; Cosmed, Rome, Italy), from which the workloads required to elicit 60% and 90% HR_{max} were determined for the exercise trials. All participants attained an RER>1.1 and stopped exercise due to volitional exhaustion.

Overview of experimental design

The study was a within-participants, crossover design with allocation to three different exercise interventions in random order (Fig. 1). Female participants completed the trials in the early follicular phase of their menstrual cycle (across three separate cycles), whereas male participants had a minimum of 7 days between trials. Each intervention lasted a total of 5 days, with data being collected across the middle 3 days ('baseline

Table 1 Baseline characteristics of participants

Age (y)	BMI (kg/m^2)	Body fat (%)	$\dot{V}O_{2max}$ (ml kg^{-1} min^{-1})	OGTT (mmol/l)		Mean arterial pressure (mm Hg)	No. of steps per day
				Fasting glucose	2 h glucose		
48±6	36±8	34±10	32±9	6.3±1.0	9.1±2.6	100±9	6,365±3,240

Data are means ± SD of seven male and two female participants

day', 'exercise day' and 'day following exercise') (Fig. 2). The participants visited the study centre for standardised measures and procedures but otherwise undertook their normal activities associated with daily living.

Exercise interventions and dietary control

Traditional continuous exercise (CONT) Participants completed one 30 min bout of treadmill walking at a moderate intensity (60% HR_{max}) 30 min before their evening meal (dinner) in accordance with current physical activity guidelines [22]. Every 5 min, HR (Polar S810i; Polar Electro, Kempele, Finland) was measured, a rating of perceived exertion (RPE, using the BORG 6-20 scale [23]) was made (Fig. 3) and the work rate was adjusted accordingly.

Exercise snacking (ES) Six 1 min work bouts, consisting of walking at 90% HR_{max} with 1 min recovery (slow walk) between each, were completed 30 min before breakfast, lunch and dinner. The total energy cost for CONT and ES were matched (based on metabolic calculations in $\dot{V}O_{2max}$ test). The exercise was undertaken on an incline treadmill, with HR and RPE measured at the end of each interval (Fig. 3).

Composite exercise snacking (CES) Six 1 min work bouts alternating between walking and resistance-based exercise were performed, with 1 min recovery between each bout, 30 min before breakfast, lunch and dinner. The total number of 1 min work bouts balanced the ES regime. The resistance-based exercise bouts were undertaken using resistance bands (as many reps as possible within 60 s), and walking was at 90% HR_{max} on an incline treadmill, with HR and RPE measured at the end of each interval (Fig. 3). The resistance-band exercises worked the musculature of the arms, back and core. All exercise sessions included a 5 min warm-up period and a 3 min cool-down period at a self-selected intensity on a treadmill.

Diet The timing of the three meals was identical between the three exercise trials. For their first trial, participants consumed their habitual diet under free-living conditions while completing a 5-day dietary log. The diet was then replicated for the second and third trials, so that timing, composition and quantity of all food and drink consumed were matched between the three trials. Subsequent dietary analysis (Kai-culator Enhanced 2010 Food Composition Database v0.43; Dunedin, New Zealand) for the main days of interest is shown in Table 2. Physical activity levels for the three trials were monitored using pedometers and activity logs.

Physiological measures

Continuous blood glucose monitoring Blood glucose (extracellular fluid) was recorded using continuous blood glucose monitoring (CGM) (iPro2; Medtronic, Northridge, CA, USA). Capillary glucose samples were obtained from participants three or four times each day to calibrate the CGM. Mean glucose, variation of glucose (SD) and area under the

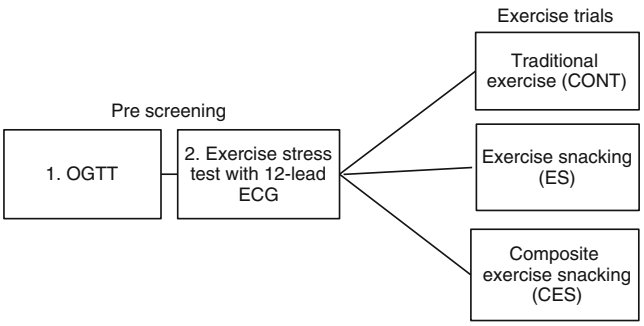


Fig. 1 Flow diagram of the study design. The study consisted of two phases of pre screening before three exercise trials were completed in a randomised order. Exercise trials included monitoring of physiological variables across one baseline day, one exercise day and for 1 day following exercise

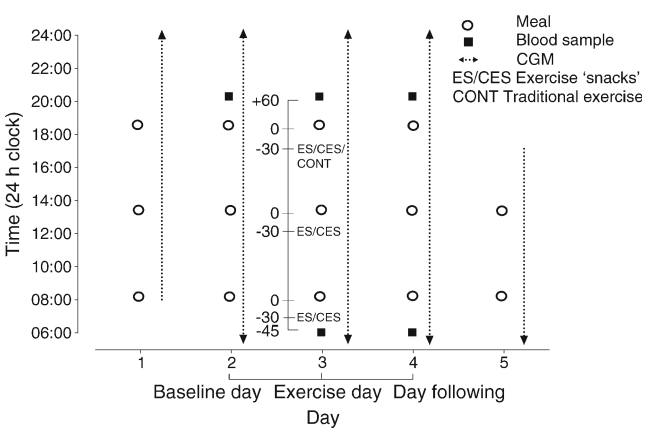


Fig. 2 The experimental design of each 3 day trial

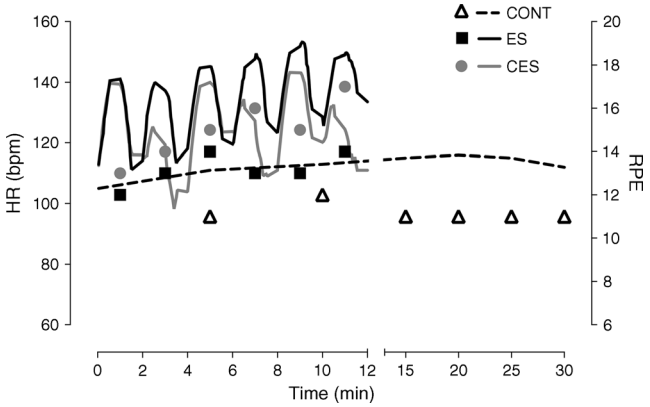


Fig. 3 Typical HR response (bpm) and RPE for one participant during CONT, evening ES and CES. Note that HR is shown using lines, and RPE using symbols

glucose curve were calculated for each 24 h period (baseline day, exercise day and day following exercise) using CGM data. Mean and AUC of postprandial glucose (PPG) were determined from the CGM data for the first 3 h after each meal (3 h PPG). The accuracy of the CGM devices was validated using capillary vs interstitial CGM samples and plasma vs interstitial CGM samples (see electronic supplementary material [ESM] Methods).

Blood analyses Venous blood (6 ml EDTA) was collected from participants when fasting (exercise day and day following exercise) and 1 h after dinner (baseline, exercise day and day following exercise; Fig. 2) for analysis of plasma insulin (Roche Diagnostics, Basel, Switzerland) and glucose concentrations using commercially available kits (Roche, Indianapolis IN, USA).

Statistical analyses

Data were first modelled using the Kolmogorov–Smirnov and Shapiro–Wilk normality tests to confirm normality. Glycaemic effects of the exercise interventions were tested using repeated-measures ANOVA with one factor (condition, e.g. for insulin sensitivity) or two factors (condition × time, e.g. for PPG), for ES vs CONT to test the effect of energy-matched exercise patterns, and for ES vs CES to test the effect of time-matched exercise profiles. Bonferroni-controlled planned simple contrast testing was used to isolate differences following significant ANOVAs ($p<0.05$), for glucose concentrations across the 3 days (baseline day vs exercise day and day following exercise). Differences reported in relation to time (e.g. compared with baseline) are always following a significant interaction effect, and 95% CIs are shown for effects of particular interest.

Table 2 Total daily macronutrient intake for the participants' first experimental trial

Intake	Baseline day	Exercise day	Day following exercise
Energy (kJ)	11,167±3,089	11,974±3,243	12,178±2,978
Carbohydrate (g)	327±86	334±84	361±115
Carbohydrate (% EI)[a]	51±13	47±12	50±16
Fat (g)	102±42	106±36	113±44
Fat (% EI)[a]	34±14	33±11	34±13
Protein (g)	96±30	116±39	107±47
Protein (% EI)[a]	15±5	16±6	15±7

Data are shown as group mean ± SD, $n=9$

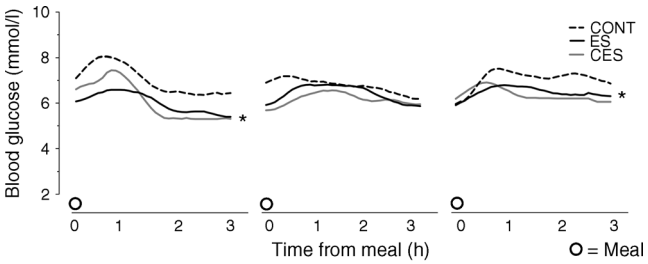
[a] Percentage of daily energy intake (EI)

Results

ES vs CONT

3 h PPG Compared with the baseline day, ES lowered the 3 h mean PPG following breakfast (by 1.0±0.9 mmol/l [mean ± SD]) and dinner (by 0.5±0.8 mmol/l) but not following lunch (−0.0±0.7 mmol/l). The interaction between meal and exercise was quadratic-by-time ($p=0.05$), with the highest PPG concentration, and reduction with exercise, observed in the morning and evening, and the lowest after lunch. In contrast, CONT had no effect on 3 h mean PPG at any time point (bearing in mind that CONT also served as a control condition for breakfast PPG and lunch PPG on the exercise day).

On the exercise day, the 3 h PPG concentration was 1.4±1.5 mmol/l ($p=0.02$) and 0.7±1.5 mmol/l ($p=0.04$) lower with ES than with CONT after breakfast and dinner, respectively, but was not significantly lower after lunch (Fig. 4, 0.4±1.0 mmol/l, $p=0.22$). On this day, ES induced a



	Breakfast	Lunch	Dinner
Energy (kJ)	1,983	3,033	3,832
CHO (g)	78	71	100
PRO (g)	19	29	52
Fat (g)	10	37	34

Fig. 4 The blood glucose responses for participants across the 3 h following breakfast, lunch and dinner for the CONT, ES and CES regimes. The macronutrient content of each meal is shown below the graph. CHO, carbohydrate; PRO, protein. Note that CONT was performed before dinner only. Data are means for $n=9$. *$p<0.05$ for ES vs CONT on exercise day

17% reduction in 3 h post-breakfast AUC, when compared with CONT (Fig. 5a, CONT 1,307±337 mmol/l×3 h vs ES 1,090±178 mmol/l×3 h, p=0.04), and a 13% reduction after dinner (Fig. 5c, CONT 1,285±208 mmol/l×3 h vs ES 1,116±197 mmol/l×3 h, p=0.04). Following lunch there was no difference in the 3 h PPG AUC on exercise day between the ES and CONT regimes (Fig. 5b, p=0.46).

24 h Glycaemic control Compared with baseline, the mean 24 h glucose concentration was 0.6±0.4 mmol/l lower with ES than with CONT (Fig. 6a, p=0.01, 95% CI 0.3, 0.9). The mean glucose concentration was 0.7±0.6 mmol/l lower with ES than with CONT on the exercise day (until 06:00 hours on the following morning; Fig. 6b, p=0.01). Compared with baseline, the mean 24 h glucose concentration throughout the day following exercise remained 0.6±0.4 mmol/l lower with ES (Fig. 7, p=0.01). However, the mean glucose concentration on the day following exercise was not significantly lower for ES compared with CONT (p=0.20).

Compared with baseline, there was no difference in glycaemic variability on the exercise day between ES and CONT (Table 3, p=0.38); this was also the case on the day following exercise (ES −10±44%, CONT +2±13%, p=0.55, 95% CI −45, 25). However, glycaemic variability was 35±46% lower (p=0.05) for ES than CONT on the exercise day, but not on the day following exercise (ES lower by 32±53%, p=0.09).

Compared with baseline, the mean glucose AUC (06:00–06:00 hours the following morning) was lower for ES than CONT, by 609±496 mmol/l×24 h (p=0.01, 95% CI 283, 935). The mean glucose AUC was lower with ES, compared with CONT, by 765±910 mmol/l×24 h (p=0.03, 95% CI 201, 1,329).

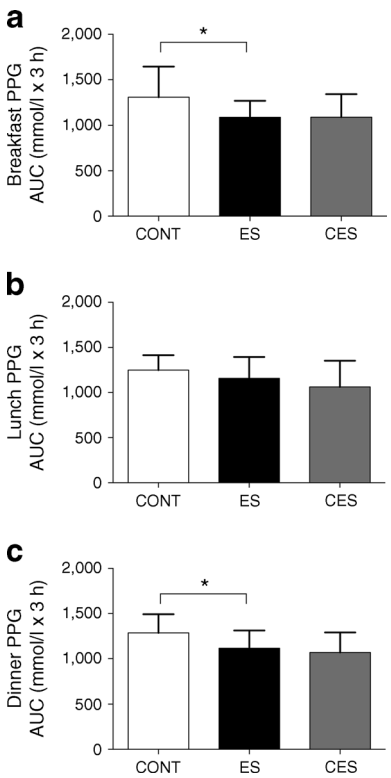


Fig. 5 The 3 h PPG AUC for breakfast (**a**), lunch (**b**) and dinner (**c**) on the exercise day for CONT, ES and CES trials. Data are means ± SD, n=9. *p<0.05 for ES vs CONT for breakfast and dinner PPG AUC

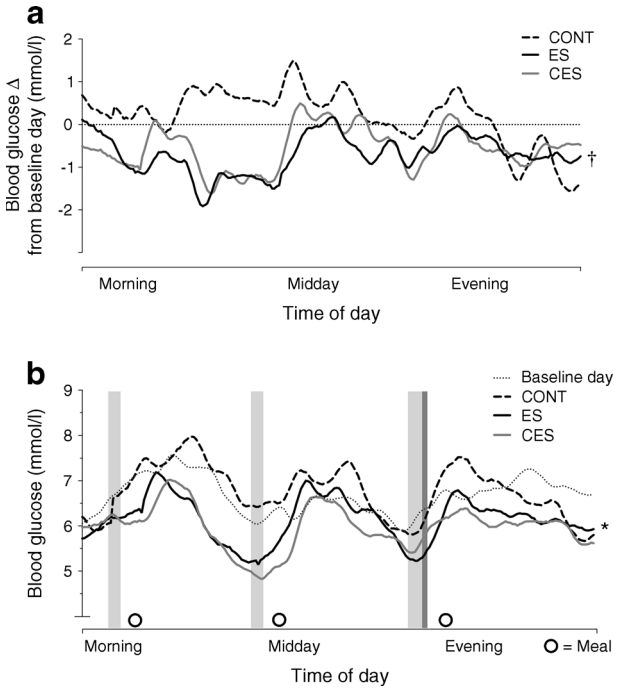


Fig. 6 (**a**) Change in glucose concentration throughout the exercise day relative to baseline, for CONT, ES and CES. Note that CONT is not performed until just before dinner. Data are means for n=9. †p<0.05 for ES vs CONT compared with baseline day (i.e. interaction effect). (**b**) Mean glucose concentrations of participants (n=9) throughout the exercise day (06:00 hours to 24:00 hours) for CONT, ES and CES trials. Dotted grey line, baseline control day; light-grey bars, time-distributed exercise (ES and CES); dark-grey bar, CONT. Exercise was completed 30 min before each main meal. *p<0.05 for ES vs CONT on exercise day (i.e. main effect)

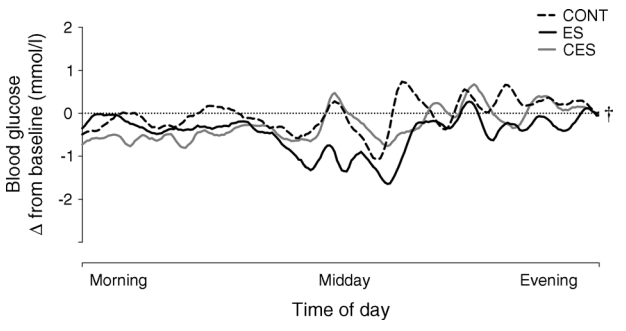


Fig. 7 The changes in glucose concentration throughout the day following exercise, compared with baseline, for CONT, ES and CES. Data are means for n=9. †p<0.05 for ES vs CONT compared with baseline day (i.e. interaction effect)

Table 3 Blood glucose concentration of nine participants across baseline day, the exercise day and the day following exercise

Exercise regime	Blood glucose concentration (mmol/l)		
	Baseline day	Exercise day	Day following exercise
CONT	6.37±0.87	6.74±1.17	6.48±1.03
ES	6.55±1.13	6.04±0.84*†	6.07±0.73†
CES	6.63±1.11	5.95±0.87	6.28±0.91

Data are shown as mean ± variation (SD within-participants)

*$p<0.05$ for ES vs CONT on exercise day (i.e. main effect)

† $p<0.05$ for ES vs CONT compared with baseline day (i.e. interaction effect)

Insulin sensitivity Compared with baseline, the fasting plasma insulin concentration of the participants was similar on the morning following ES and CONT (ES lower by 4.5±6.0 μU/ml, $p=0.26$, 95% CI −11, 20). In response to the same evening meal, plasma glucose and insulin concentrations and the plasma glucose : insulin ratio were similar between ES and CONT ($p>0.11$).

Walking (ES) vs walking and resistance (CES) exercise snacking

The two forms of exercise snacking were equally effective in reducing the mean 3 h PPG and the 3 h PPG AUC following breakfast, lunch and dinner (Figs 4 and 5). ES and CES were also equally effective in reducing mean 24 h glucose concentration on the exercise day and the day following exercise (Figs 5 and 6, no interaction: all $p>0.56$). CES was no different from ES in reducing either glycaemic variability or 24 h glucose concentration on the exercise day (Table 3). Compared with baseline, fasting and postprandial plasma insulin concentrations were similar between CES and ES ($p>0.09$).

Discussion

The novel finding of the present study was that dosing brief bouts of intense exercise immediately before breakfast, lunch and dinner ('exercise snacking') reduced postprandial and subsequent 24 h glucose concentrations in an insulin-resistant population when compared with a single 30 min bout of moderate, continuous exercise undertaken before the evening meal. Moreover, these benefits persisted for the 24 h following the exercise intervention. In contrast, a bout of continuous exercise failed to lower postprandial glucose after dinner or to improve glycaemic control the day following exercise. Previous studies that have employed HIT have reported similar or superior improvements in a multitude of markers of fitness when compared with traditional exercise prescription (e.g. continuous moderate-intensity exercise), despite a substantially lower training time for HIT [24–26]. Superior improvement in insulin sensitivity may result from more intense training regimes [27, 28].

Here we further demonstrate the potency of intense work bouts and show that the timing of exercise is also an important factor for optimal glycaemic control. Specifically, we report that brief, intense exercise before meals is an effective means to reduce postprandial hyperglycaemia. These findings are of clinical relevance because ambulatory postprandial and/or nocturnal glucose excursions, the so-called 'hyperglycaemic spikes', are an early and often undetected feature of the insulin-resistant state [29]. Indeed, these hyperglycaemic spikes may be more predictive for the onset of CVD complications than elevated fasting plasma glucose [30] and are strongly associated with HbA_{1c} levels both in individuals with insulin resistance and patients with diabetes [31]. Whether or not the findings from the present 'acute' intervention might be effective in improving glycaemic control over a longer period remains to be verified. Karstoft et al [32] have reported that 4 months of intense interval walking (five training sessions per week, each lasting 60 min, comprising bouts of 3 min of fast walking [above 70% of each individual's peak rate of energy expenditure] and 3 min of slow walking [below 70% of energy expenditure]) resulted in lower mean and maximum CGM glucose concentrations compared with low-intensity, energy-matched continuous walking (55% of individual peak rate of energy expenditure). Some classic measures of glycaemic control were unaffected in either group (e.g. fasting glucose, OGGT and HbA_{1c}), possibly because post-intervention variables were measured 2–8 days after the last training bout. In that study [32], individuals who undertook the intense walking protocol displayed greater reductions in body mass, fat mass and abdominal visceral adiposity, accompanied by substantial improvements in $\dot{V}O_{2max}$ compared with those who performed continuous walking. These differences were apparent despite the overall energy expenditure being matched between the training groups, and no evidence of differences in dietary intake within or between any of the groups being observed. The findings of better glycaemic control in the interval-walking group may therefore have reflected both training-induced improvements in whole-body fitness (i.e. $\dot{V}O_{2max}$) and improved body composition.

There has been recent interest in 'accumulating physical activity' as brief, repetitive bouts of exercise (as opposed to a single, prolonged, continuous exercise session) to prevent cardiometabolic disease. For example, the deleterious metabolic and cardiovascular consequences of sedentary behaviour have been highlighted [33] and incorporated within some activity guidelines, and it has been questioned whether current guidelines can overcome the consequences of prolonged periods of inactivity that are a typical feature of traditional exercise prescription [33]. Having more breaks in otherwise

sedentary time is beneficial for waist circumference, plasma triacylglycerol and 2 h plasma glucose [34]. Exercise snacking, whether before meals or not, is also conducive to disrupting sedentary time, and may be important in this regard. Public health recommendations typically state that adults should perform at least 150 min of moderate-intensity exercise per week (or 30 min per day, on most days) to obtain health benefits [22]. Such activity should be accumulated in bouts of 10 min or more and may be particularly important for glycaemic control if performed around meal times. For example, in a recent study by DiPietro et al [35], three 15 min post-meal walks were more effective than one 45 min sustained walk in the morning or afternoon for lowering 3 h PPG after dinner, compared with a control day. The results from the current study, along with previous work, clearly demonstrate that low-volume, high-intensity training is a time-effective alternative to CONT for improving glycaemic control [36]. As noted, 30 min of moderate-intensity exercise did not improve glycaemic control in the present study, whereas distributing the same volume of exercise as three brief pre-meal HIT 'exercise snacks' resulted in a 12% reduction in PPG, an effect that was sustained for the subsequent ~18 h following the last exercise snack. Previous research investigating exercise after breakfast has shown reduced postprandial hyperglycaemia. Larsen et al [14] found that cycling for 45 min at moderate intensity (53% $\dot{V}O_{2max}$) led to reductions of ~50% in 4 h PPG and 36% in insulin AUC, compared with a control day. Similar findings were made by Takaishi et al [37] using a 6 min moderate-intensity (60% HR range) stair-walking intervention. In those studies, moderate exercise was performed in a postprandial state after breakfast, and while the PPG was lowered after breakfast, the subsequent midday and evening meal PPG were unaffected. Gillen et al [17] examined 24 h glucose concentration in seven patients with type 2 diabetes in response to an acute HIT session of ten 1 min cycling work bouts at 90% HR_{max}, performed 90 min after breakfast. Substantial improvements in PPG and exposure to hyperglycaemia were seen across 24 h, but mean 24 h glucose was not significantly different from the control day. Taken collectively, the results of the current study, along with previous findings [17, 18, 28], support the benefit of using higher exercise intensities for improving glycaemic control in individuals with impaired glucose tolerance, type 2 diabetes and the metabolic syndrome. However the protocol of 'exercise snacking' employed in the present investigation provides support for the use of brief, intense exercise bouts for improving postprandial glycaemic control in individuals with insulin resistance.

Currently, no research has directly compared the impact of pre- vs postprandial exercise on glycaemic control. Gillen et al [38] reported similar improvements in body composition and oxidative capacity in 16 women who were assigned to either fasted or fed HIT three times per week, for 6 weeks. Despite improvements in body composition, insulin sensitivity was not improved significantly in either group. In the above-mentioned studies [14, 17, 37], if the exercise was intense, postprandial exercise was effective in reducing the PPG from the previous meal [14, 37] or all meals that day but not in reducing 24 h glucose [17]. Pre-meal exercise was chosen for the present study to prime glucose uptake before the peak postprandial period [7, 15] and to avoid gastrointestinal discomfort. Performing the exercise snacks 30 min before meals improved 24 h glycaemic control by reducing the mean PPG following breakfast and dinner but not lunch. Given the time course of the increased glucose uptake with HIT we believe our findings, along with those of others [14, 17], show that the timing of exercise is important for optimally attenuating postprandial hyperglycaemia.

Walking-based (ES) and combined-exercise (CES) snacks improved glycaemic control similarly (Fig. 6). The aim of the CES was to maximise the muscle mass involved and incorporate resistance training, thereby helping meet comprehensive exercise guidelines for health. Previous research has shown that a combination of aerobic-based and resistance-based exercise is superior to either alone [26, 39, 40]. Participants in the current study completed as many reps of the resistance-band exercise as they could during each of the 1 min work bouts in the CES protocol. Although the HR was lower for CES (10±5 bpm below ES), the participants' perceived exertion was significantly higher ('very hard' vs 'hard', Fig. 3), which indicates that this composite form of interval exercise still involved a substantial psychophysical demand. Since glucose concentration was reduced throughout the exercise day, without a change in insulin concentration, we speculate that the ES may have improved glycaemic control by virtue of increased contraction-mediated uptake of glucose. However, it is likely that the following day's lower glucose concentration may be mediated by improved insulin sensitivity.

It should also be acknowledged that exercise causes an acutely elevated (but overall lowered) risk of cardiovascular events. Despite the high-intensity nature of interval exercise regimes, no studies to date have reported a fatal cardiovascular incident with HIT in high-risk populations. After 129,456 h of moderate-intensity exercise and 46,364 h of high-intensity exercise in 4,846 patients with coronary heart failure, Rognmo et al [41] observed one fatal and two non-fatal cardiac arrests, respectively, and concluded that the risk of a cardiovascular event following HIT was low.

In conclusion, we found exercise snacking to be a novel and effective approach to improve glycaemic control in individuals with insulin resistance. Brief, intense interval exercise bouts undertaken immediately before breakfast, lunch and dinner had a greater impact on postprandial and subsequent 24 h glucose concentrations than did a single bout of moderate, continuous exercise undertaken before an evening meal. The practical implications of our findings are that, for individuals who are insulin resistant and who experience marked

postprandial hyperglycaemic excursions, both the timing and the intensity of exercise should be considered for optimising glucose control.

Acknowledgements We would like to acknowledge the dedication and commitment of our participants, and thank L. Hughes (School of Physical Education, Sport and Exercise Sciences, University of Otago) for technical assistance.

Duality of interest The authors declare that there is no duality of interest associated with this manuscript.

Contribution statement MEF and JDC conceived the study, with guidance and knowledge on design from PJM, JCB, MJAW, SJEL and JAH. MEF performed the data collection with help from JCB and MJAW for cardiovascular screening. MEF and JDC contributed to the data analysis. MEF drafted the manuscript and all other authors contributed critically to revisions. All authors declare that they read and approved the final version of the manuscript before submission. JDC is responsible for the integrity of the work as a whole.

Funding This study was supported by the School of Physical Education, Sport and Exercise Sciences and Dunedin School of Medicine, University of Otago.

References

1. Chen L, Magliano DJ, Zimmet PZ (2011) The worldwide epidemiology of type 2 diabetes mellitus—present and future perspectives. Nat Rev Endocrinol 8:228–236
2. Hawley JA, Lessard SJ (2008) Exercise training-induced improvements in insulin action. Acta Physiol (Oxf) 192:127–135
3. Lindström J, Ilanne-Parikka P, Peltonen M et al (2006) Sustained reduction in the incidence of type 2 diabetes by lifestyle intervention: follow-up of the Finnish Diabetes Prevention Study. Lancet 368: 1673–1679
4. Tucker JM, Welk GJ, Beyler NK (2011) Physical activity in US adults: compliance with the physical activity guidelines for Americans. Am J Prev Med 40:454–461
5. Farrell L, Hollingsworth B, Propper C, Shields MA (2013) The socioeconomic gradient in physical inactivity in England. University of Bristol, Bristol
6. Trost SG, Owen N, Bauman AE, Sallis JF, Brown W (2002) Correlates of adults' participation in physical activity: review and update. Med Sci Sports Exerc 34:1996–2001
7. American Diabetes Association (2001) Postprandial blood glucose. Diabetes Care 24:775–778
8. Brownlee M (2005) The pathobiology of diabetic complications: a unifying mechanism. Diabetes 54:1615–1625
9. Ceriello A, Bortolotti N, Motz E et al (1998) Meal-generated oxidative stress in type 2 diabetic patients. Diabetes Care 21:1529–1533
10. Ceriello A, Esposito K, Piconi L et al (2008) Oscillating glucose is more deleterious to endothelial function and oxidative stress than mean glucose in normal and type 2 diabetic patients. Diabetes 57: 1349–1354
11. Da Ros R, Assaloni R, Ceriello A (2005) Postprandial hyperglycemia and diabetic complications. Recenti Prog Med 96:436–444 [article in Italian]
12. de Vegt F, Dekker JM, Jager A et al (2001) Relation of impaired fasting and postload glucose with incident type 2 diabetes in a Dutch population: the Hoorn Study. JAMA 285:2109–2113
13. Koopman R, Manders RJF, Zorenc AHG et al (2005) A single session of resistance exercise enhances insulin sensitivity for at least 24 h in healthy men. Eur J Appl Physiol 94:180–187
14. Larsen J, Dela F, Kjar M, Galbo H (1997) The effect of moderate exercise on postprandial glucose homeostasis in NIDDM patients. Diabetologia 40:447–453
15. Garetto LP, Richter EA, Goodman MN, Ruderman NB (1984) Enhanced muscle glucose metabolism after exercise in the rat: the two phases. Am J Physiol Endocrinol Metab 246:E471–E475
16. Ivy J, Holloszy J (1981) Persistent increase in glucose uptake by rat skeletal muscle following exercise. Am J Physiol Cell Physiol 241: C200–C203
17. Gillen JB, Little JP, Punthakee Z, Tarnopolsky MA, Riddell MC, Gibala MJ (2012) Acute high-intensity interval exercise reduces the postprandial glucose response and prevalence of hyperglycaemia in patients with type 2 diabetes. Diabetes Obes Metab 14:575–577
18. Little JP, Gillen JB, Percival M et al (2011) Low-volume high-intensity interval training reduces hyperglycemia and increases muscle mitochondrial capacity in patients with type 2 diabetes. J Appl Physiol 111:1554–1560
19. Gibala MJ, Little JP, MacDonald MJ, Hawley JA (2012) Physiological adaptations to low-volume, high-intensity interval training in health and disease. J Physiol 590:1077–1084
20. Wisløff U, Støylen A, Loennechen JP et al (2007) Superior cardiovascular effect of aerobic interval training versus moderate continuous training in heart failure patients. Circulation 115:3086–3094
21. Ciolac EG, Bocchi EA, Bortolotto LA, Carvalho VO, Greve JMD, Guimaraes GV (2010) Effects of high-intensity aerobic interval training vs. moderate exercise on hemodynamic, metabolic and neurohumoral abnormalities of young normotensive women at high familial risk for hypertension. Hypertens Res 33:836–843
22. World Health Organization (2010) Global recommendations on physical activity for health. World Health Organization, Geneva
23. Borg GA (1982) Psychophysical bases of perceived exertion. Med Sci Sports Exerc 14:377–381
24. Burgomaster KA, Howarth KR, Phillips SM et al (2008) Similar metabolic adaptations during exercise after low volume sprint interval and traditional endurance training in humans. J Physiol 586:151–160
25. Gibala MJ, Little JP, van Essen M et al (2006) Short-term sprint interval versus traditional endurance training: similar initial adaptations in human skeletal muscle and exercise performance. J Physiol 575:901–911
26. McRae G, Payne A, Zelt JG et al (2012) Extremely low volume, whole-body aerobic–resistance training improves aerobic fitness and muscular endurance in females. Appl Physiol Nutr Metab 37:1124–1131
27. Koshinaka K, Sano A, Howlett KF et al (2008) Effect of high-intensity intermittent swimming on postexercise insulin sensitivity in rat epitrochlearis muscle. Metabolism 57:749–756
28. Tjønna AE, Lee SJ, Rognmo Ø et al (2008) Aerobic interval training versus continuous moderate exercise as a treatment for the metabolic syndrome. Circulation 118:346–354
29. Hay L, Wilmshurst E, Fulcher G (2003) Unrecognized hypo-and hyperglycemia in well-controlled patients with type 2 diabetes mellitus: the results of continuous glucose monitoring. Diabetes Technol Ther 5:19–26
30. Ceriello A (2005) Postprandial hyperglycemia and diabetes complications. Diabetes 54:1–7
31. Praet S, Manders R, Meex R et al (2006) Glycaemic instability is an underestimated problem in type II diabetes. Clin Sci (Lond) 111:119–126
32. Karstoft K, Winding K, Knudsen SH et al (2013) The effects of free-living interval-walking training on glycemic control, body composition, and physical fitness in type 2 diabetic patients: a randomized, controlled trial. Diabetes Care 36:228–236

33. Hamilton MT, Healy GN, Dunstan DW, Zderic TW, Owen N (2008) Too little exercise and too much sitting: inactivity physiology and the need for new recommendations on sedentary behavior. Curr Cardiovasc Risk Rep 2:292–298
34. Healy GN, Dunstan DW, Salmon J et al (2008) Breaks in sedentary time. Diabetes Care 31:661–666
35. DiPietro L, Gribok A, Stevens MS, Hamm LF, Rumpler W (2013) Three 15-min bouts of moderate postmeal walking significantly improves 24-h glycemic control in older people at risk for impaired glucose tolerance. Diabetes Care 36:3262–3268
36. Nybo L, Sundstrup E, Jakobsen MD et al (2010) High-intensity training versus traditional exercise interventions for promoting health. Med Sci Sports Exerc 42:1951–1958
37. Takaishi T, Imaeda K, Tanaka T, Moritani T, Hayashi T (2011) A short bout of stair climbing descending exercise attenuates postprandial hyperglycemia in middle-aged males with impaired glucose tolerance. Appl Physiol Nutr Metab 37:193–196
38. Gillen JB, Percival ME, Ludzki A, Tarnopolsky MA, Gibala M (2013) Interval training in the fed or fasted state improves body composition and muscle oxidative capacity in overweight women. Obesity (Silver Spring) 21:2249–2255
39. Maiorana A, O'Driscoll G, Goodman C, Taylor R, Green D (2002) Combined aerobic and resistance exercise improves glycemic control and fitness in type 2 diabetes. Diabetes Res Clin Pract 56:115–123
40. Sigal RJ, Kenny GP, Boula NG et al (2007) Effects of aerobic training, resistance training, or both on glycemic control in type 2 diabetes. Ann Intern Med 147:357–369
41. Rognmo Ø, Moholdt T, Bakken H et al (2012) Cardiovascular risk of high-versus moderate-intensity aerobic exercise in coronary heart disease patients. Circulation 126:1436–1440