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Low-volume combined aerobic and resistance high-intensity interval training in type 2 diabetes: a randomised controlled trial

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ABSTRACT

Objective The objective of this study was to compare the effects of novel, time-efficient, low-volume combined aerobic and resistance high-intensity interval training (C-HIIT), and current exercise guidelines (210 min/week of combined moderate-intensity continuous training (C-MICT)), with waitlist control (CON) on glycaemic control in people with type 2 diabetes mellitus (T2D).

Methods Sixty-nine low-active people with T2D were randomised to 8 weeks of supervised C-HIIT (78 min/week), supervised C-MICT (210 min/week), or waitlist CON. Those in waitlist CON were re-randomised to supervised C-HIIT/C-MICT at week 8. Following 8 weeks of supervised training, participants completed 10 months of self-directed exercise. Outcomes were assessed at baseline, week 8 and month 12. Participants in waitlist CON were only included in the exercise groups for the month 12 analysis. Analyses were completed using intention-to-treat analysis of covariance (n=69; week 8) and linear mixed modelling (n=63; month 12).

Results Compared with CON, at week 8, HbA$_{1c}$ decreased in C-HIIT (adjusted mean difference: −0.7% (95% CI −1.3, −0.2%)) and C-MICT (−1.2% (−1.9, −0.6%)). There were also improvements in C-HIIT and C-MICT versus CON at week 8 for fat mass (−1.9 (−3.1, −0.6) and −1.5 (−2.6, −0.4) kg, respectively), lean mass (1.5 (0.8, 2.3) and 0.9 (0.1, 1.7) kg), and exercise capacity (124 (77, 171) and 49 (5, 93) s). At month 12, adherence was low, and most measures returned to baseline.

Conclusions Low-volume C-HIIT (78 min/week) and C-MICT (210 min/week) improved glycaemic control, body composition and exercise capacity similarly over 8 weeks in people with T2D. However, at month 12, improvements were not maintained following self-directed exercise. Regardless, these data suggest that supervised low-volume C-HIIT is a time-efficient and effective strategy for improving outcomes in T2D.

WHAT IS ALREADY KNOWN ON THIS TOPIC

⇒ Aerobic exercise improves insulin sensitivity and glucose transporter type-4 expression while resistance/strength training increases muscle mass and glucose transporter type-4 expression, improving glucose uptake. Meta-analyses suggest that combined aerobic and resistance moderate-intensity continuous training (C-MICT) induces greater improvements in glycaemic control than either modality alone in people with type 2 diabetes (T2D). However, lack of time is a commonly cited barrier to exercise in people with T2D; therefore, there is a need for time-efficient but effective alternatives to 150–210 min/week of moderate-intensity exercise that still have a positive impact on relevant health indicators.

WHAT THIS STUDY ADDS

⇒ Our results suggest that supervised low-volume combined aerobic and resistance high-intensity interval training (C-HIIT; 78 min/week) was as effective as C-MICT (210 min/week) for improving glycaemic control, body composition and cardiovascular health in the short term in people with T2D; however, improvements were not maintained long term following self-directed exercise.

HOW THIS STUDY MIGHT AFFECT RESEARCH, PRACTICE, OR POLICY

⇒ Results suggest that supervised low-volume C-HIIT may be used as a time-efficient and effective alternative to C-MICT for improving glycaemic control in people with T2D; however, strategies to improve long-term adherence to self-directed exercise are needed.

INTRODUCTION

Combined aerobic and resistance training is synergistic for glycaemic control[1][2] and recommended in exercise training guidelines for people with type 2 diabetes mellitus (T2D).[3][4] These position statements suggest ≥150–210 min/week of moderate-intensity exercise. High-intensity interval training (HIIT), consisting of quick, intense bursts of exercise followed by short recovery periods,

is an alternative option to moderate-intensity continuous training (MICT). Studies suggest that HIIT induces comparable, or greater, improvements to MICT for cardiorespiratory fitness, various health outcomes, and quality of life, in healthy and clinical populations.[5–8] However, many of these studies included high-volume HIIT sessions of similar duration to MICT ($\approx$40 min/session). Low-volume HIIT is defined as <15 min of high-intensity effort,[9] with recent studies demonstrating safety and efficacy of this approach in healthy and clinical populations,[10 11] including reduced glycated haemoglobin (HbA$_{1c}$) after 8 weeks in people with T2D.[12] Furthermore, we have previously reported improved vascular health after 8 weeks of low-volume HIIT in people with T2D.[13]

Despite the benefits on cardiometabolic health, body composition, cardiovascular disease risk, and quality of life,[14–16] initiation and maintenance of regular exercise are challenging. Most people with T2D are physically inactive[17] with only 23% of older adults with T2D completing >60 min/week of physical activity and 55% reporting no weekly physical activity.[18] Furthermore, while supervised training studies report high attendance,[6] exercise training may not be maintained long term once supervision is removed.[19] Because lack of time is a commonly cited barrier to exercise in people with T2D,[20] there is a need for time-efficient but equally effective alternatives to 150–210 min/week of exercise, which will still have a positive impact on relevant health indicators in the short- and long- term.

The primary aim of this study was to compare the effects of low-volume combined aerobic and resistance high-intensity interval training (C-HIIT), and 210 min/week (current exercise guidelines) of combined moderate-intensity continuous training (C-MICT), with waitlist control (CON), on glycaemic control in people with T2D. The hypothesis was that both C-HIIT and C-MICT would be superior to CON for improving HbA$_{1c}$ at week 8. We also assessed the effectiveness of C-HIIT and C-MICT on T2D- and health-related outcomes at month 12 (after 10 months of self-directed exercise, which followed 8 weeks of supervised training). The hypothesis for this secondary aim was that improvements in glycaemic control would be maintained in both training groups at month 12 compared with baseline.

METHODS
The "Exercise For Diabetes (E4D)" Trial was a single-centre, prospective, randomised, waitlist-controlled trial, completed at The University of Queensland. The study was prospectively registered with the Australian New Zealand Clinical Trials Registry (ACTRN12615000475549).

Eligibility criteria
Low-active male and female participants aged 18–80 years with written confirmation of their T2D diagnosis from their physician and baseline HbA$_{1c}$ ≥6.0% (no upper limit) were included. Participants were excluded if they self-reported ≥150 min/week of moderate or ≥75 min/week of vigorous physical activity (or equivalent combination), or had absolute contraindications to exercise per American College of Sport Medicine (ACSM) guidelines[21] (full eligibility criteria described in online supplemental table 1). All participants provided written informed consent.

Randomisation
Participants were randomised, by an individual not associated with this study, using permuted blocks (blocks of six), 1:1:1 to C-HIIT, C-MICT or CON (figure 1), stratified based on age and sex. Participants in waitlist CON were re-randomised 1:1 to C-HIIT or C-MICT at week 8 using the same procedure. Further details are provided in online supplemental methods 1.

Trial design and intervention
There were two phases for the C-HIIT and C-MICT groups (figure 1): phase 1 involved 8 weeks of supervised exercise training while phase 2 was 10 months of self-directed exercise. Those in waitlist CON continued with usual care for 8 weeks during phase 1, before being re-randomised to C-HIIT or C-MICT and completing 8 weeks of supervised training and 10 months of self-directed training. Outcomes were assessed at baseline and week 8 in people in C-HIIT, C-MICT and CON, and at month 12 in C-HIIT or C-MICT (including those in waitlist CON re-randomised to C-HIIT and C-MICT). Participants in waitlist CON were not included in the exercise groups for analysis at week 8, but were included in the exercise groups for the month-12 analysis.

Aerobic exercise was either on a treadmill, upright bike or recumbent bike. Resistance-based exercises involved a combination of machine-based, bodyweight and free-weight exercises. Exercises were completed in the following order: (1) leg press, (2) chest press, (3) leg press repeated, (4) seated row, (5) calf raises, (6) shoulder press, (7) abdominal crunch and (8) bicep curls. Resistance exercise intensity was progressive, individualised and adjusted (based on the Borg Rating of Perceived Exertion (RPE; 6–20 scale)) throughout phase 1.[22]

During supervised sessions, workload, number of repetitions during resistance training, heart rate (HR) and RPE were recorded for each participant, to monitor exercise intensity adherence. Accredited exercise physiologists supervised all exercise sessions, standing alongside participants, providing verbal feedback/encouragement and adjusting workload (eg, resistance exercise weight would be increased so participants adhered to the prescribed intensity when RPE decreased below prescription for an exercise or if the number of repetitions completed exceeded prescription (specific to C-HIIT)) as required. Staff to participant ratio was a maximum of 1:2.

The *C-HIIT group* trained for 26 min, 3×/week (78 min/week), on non-consecutive days. Each session consisted of a 3-min aerobic warm-up before 1×4 min of high-intensity aerobic exercise (85%–95% of HRpeak; goal was to reach
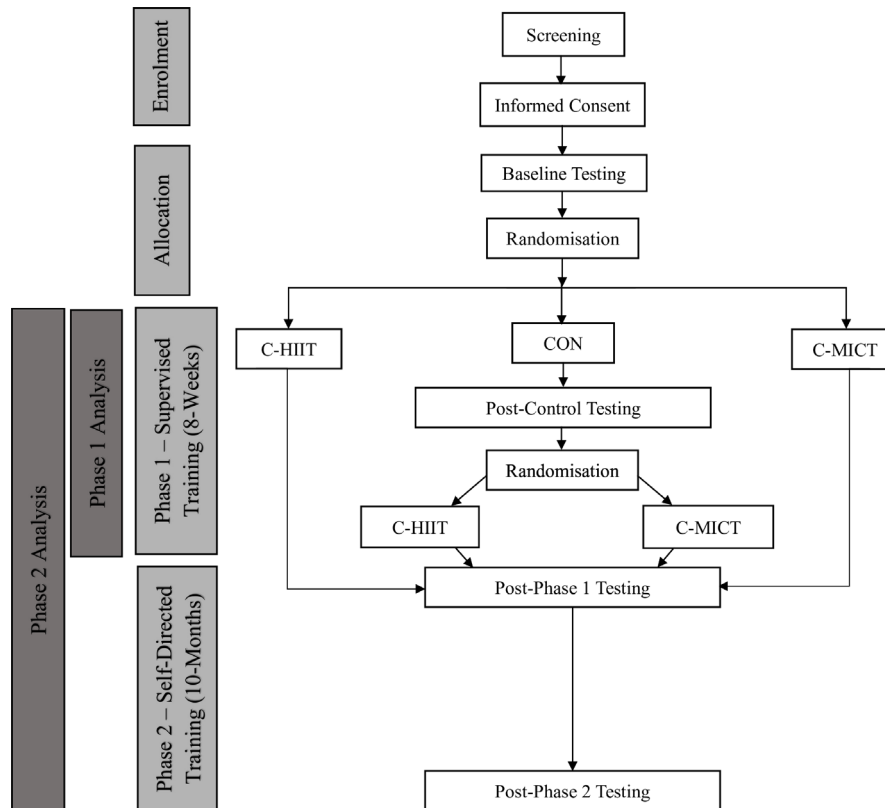
Figure 1 Study design. C-HIIT, combined high-intensity interval training; C-MICT, combined aerobic and resistance moderate-intensity continuous training; CON, waitlist control.

target HR zone within 2 min). This 1×4 min approach was selected based on previous studies demonstrating efficacy.[23][24] After a 1-min rest, participants completed 8×1 min intervals of high-intensity resistance exercise with each interval separated by 1 min of rest, before a 3-min cool-down. Each resistance exercise was completed at an RPE of ≥17 (very hard) with participants completing as many repetitions as possible (≥5, aiming for 10–25) with correct technique within each 1-min interval. RPE has been used previously to prescribe high-intensity interval resistance exercise in people with T2D.[25]

The C-MICT programme was based on current exercise recommendations for people with T2D[3] with both aerobic and resistance components completed at a moderate intensity. Those in C-MICT trained for 52.5 min 4×/week (210 min/week)—two sessions combining both aerobic and resistance exercise, and two sessions involving aerobic exercise only. For the combined sessions, participants completed 22.5 min of aerobic exercise (55%–69% of HRpeak) followed by 30 min of resistance-type exercises (RPE of 11–13 (fairly light to somewhat hard)). The resistance-based exercises were identical to C-HIIT, except prescription was 2 sets of 10 repetitions of each exercise (each set separated by 1-min rest). For the two aerobic-only sessions, participants completed 52.5 min of aerobic exercise only (55%–69% of HRpeak).

Following the supervised exercise phase and assessment of outcomes, all participants commenced phase 2 (10 months of self-directed exercise training) and

were asked to continue to follow their C-HIIT/C-MICT programme from phase 1. Participants were provided a logbook containing information about exercises they could complete at home with their bodyweight or equipment that was readily available to them. The programme attempted to replicate their supervised C-HIIT/C-MICT programme and was demonstrated to participants at the end of phase 1. Participants were asked to complete training logs to aid tracking of adherence, including information about intensity via HR (where possible) or RPE. Participants were also offered optional, once-monthly supervised training sessions at the university that was identical to their allocated group, to support progress.

Outcomes
Biochemical analyses
Following standard protocol, a fasting venous blood sample was taken to measure HbA_{1c} (primary outcome), fasting plasma glucose and insulin, serum lipid profile (total cholesterol (TC), low-density lipoprotein cholesterol (LDL-C), high-density lipoprotein cholesterol (HDL-C), triglycerides), C-peptide and plasma high-sensitivity C reactive protein. Participants then consumed a 300 mL drink containing 75 g of glucose and completed a 2-hour oral glucose tolerance test (OGTT). Insulin and C-peptide Homeostatic Model Assessment (HOMA) indices were calculated using the HOMA2 calculator (V.2.2.3; http://www.dtu.ox.ac.uk). Matsuda, insulinogenic and

disposition indices were calculated using the glucose and insulin response during the OGTT.[26] Further details are provided in online supplemental methods.

Exercise tests

Participants completed a graded cardiopulmonary exercise test to determine peak oxygen uptake ($\dot{V}O_{2peak}$) and exercise capacity (time on test). HRpeak achieved during the test was used to prescribe intensity for the aerobic component of the exercise training programme. Ventilatory threshold (VT) was assessed using the V-slope method. Further details are provided in online supplemental methods 1.

Neuromuscular fitness tests, completed during a separate visit, included the 30-s sit-to-stand, arm curl, 6-m gait speed at usual walking speed, floor-rise-to-standing, peak handgrip strength (both arms), 90° seated leg press one repetition maximum (1RM), and chest press 1RM tests. Further details are provided in online supplemental methods 1.

Anthropometric measures

Body composition was determined using dual-energy X-ray absorptiometry (Discovery, Hologic, Bedford, Massachusetts, USA). Body mass, height, waist and hip circumferences were assessed according to standard methods.[27] Further details are provided in online supplemental methods 1.

Physical activity and diet

Participants were asked to maintain their usual physical activity (outside intervention training sessions) and dietary habits. Physical activity and dietary intake were assessed at baseline, week 8 and month 12. Physical activity was assessed using a waist-worn accelerometer during waking hours (Actigraph GT3X+, Pensacola, Florida, USA). Daily estimates of steps (steps/day), and time spent in light-activity, moderate-to-vigorous physical activity and sedentary behaviour were derived from the vertical axis data using ActiLife software (ActiGraph, V.6, Pensacola, Florida, USA) and previously established cut-points.[28 29] Dietary intake was assessed using a 24-hour recall and analysed using FoodWorks (Xyris, V.9, Brisbane, Queensland, Australia). Further details are provided in online supplemental methods 1.

Exercise attendance and adherence

Attendance (sessions completed as a proportion of total prescribed) and intensity adherence (based on achievement of prescribed HR/RPE during each session) were determined using supervised exercise records (phase 1) and self-report logs (phase 2).

Sample size calculation and statistical analyses

A sample size of 66 was determined using an alpha level of 0.05 and β of (1–0.80), assuming a clinically significant difference in HbA$_{1c}$ of –0.6% would be seen when comparing C-HIIT with CON, and C-MICT with CON.

An SD of 2.4% was assumed resulting in an effect size (f) of 0.25 for these comparisons.

Comparisons of measures between groups at week 8 (phase 1 end) were completed using intention-to-treat analysis of covariance, adjusting for baseline, with the change score used as the dependent variable.[30] To reduce risk of bias, group mean change scores were imputed for dropouts and missing data at week 8 for participants with baseline data.[31]

Comparisons of measures at month 12 (phase 2 end) were completed using intention-to-treat analysis with linear mixed modelling; participants as random factors, and exercise groups (C-HIIT, C-MICT) and time points (baseline, month 12) as fixed factors. This month-12 analysis included waitlist CON participants who were re-randomised to C-HIIT or C-MICT following the end of phase 1; this follows recommendations by Kahan *et al*[32] to ensure unbiased estimates of a treatment effect. Missing data were accounted for using maximum likelihood estimation on all available data.

Analyses were completed using SPSS (V.26, SPSS). Significance was set at $p<0.05$. Normality was assessed using the Shapiro-Wilk test and Q–Q plots. Adjustment for multiple comparisons was made using the Bonferroni approach. Data are presented as mean±SD and mean (95% CIs).

Patient and public involvement

Patients and/or the public were not involved in the design, or conduct, or reporting, or dissemination plans of this research.

RESULTS

Sixty-nine eligible participants completed baseline testing and were randomised (online supplemental figure 1). Baseline characteristics are shown in table 1. Sixty-three participants entered phase 2 of the study (online supplemental figure 2). Recruitment started 24 October 2015 and ended 24 November 2018, while follow-up ended 2 February 2020.

Phase 1

Sixty-nine participants were included in the phase 1 analysis. At week 8, compared with CON, C-HIIT decreased HbA$_{1c}$ by 0.7% (95% CI –1.3% to –0.2%) and C-MICT by 1.2% (–1.9% to –0.6%; table 2; figure 2A). The Matsuda Index decreased more in C-MICT than C-HIIT, but there were no differences between exercise groups and CON. Insulin HOMA-β cell function increased more in C-HIIT than CON, while insulin HOMA-insulin resistance (HOMA-IR) increased in C-HIIT versus C-MICT. C-peptide increased in C-HIIT and C-MICT versus CON, and in C-MICT versus C-HIIT. C-peptide HOMA-IR increased in C-HIIT versus C-MICT. HDL-C increased in C-HIIT versus CON. There were no between-group differences in the other metabolic measures at week 8.

Compared with CON, C-HIIT and C-MICT reduced fat mass, body fat percentage, trunk fat mass and trunk fat

Table 1 Baseline characteristics

Variable	All	C-HIIT	C-MICT	CON
	n=69	n=23	n=23	n=23
Sex, male/female	42/27	14/9	14/9	14/9
Age, years)	59.5±8.8	59.0±8.8	60.1±7.3	59.4±10.2
Self-identified ethnicity, n (%)				
Caucasian	61 (88.4)	20 (87.0)	20 (87.0)	21 (91.3)
Asian	3 (4.3)	0 (0)	2 (8.7)	1 (4.3)
Māori	1 (1.4)	0 (0)	1 (4.3)	0 (0)
Other	4 (5.8)	3 (13.0)	0 (0)	1 (4.3)
Education Level, n (%)				
High School	10 (14.5)	5 (21.7)	2 (8.7)	3 (13.0)
Trade/technical school	18 (26.1)	8 (34.8)	4 (14.7)	6 (26.1)
University	41 (59.4)	10 (43.5)	17 (73.9)	14 (60.9)
Employment status, n (%)				
Unemployed	2 (2.9)	2 (8.7)	0 (0)	0 (0)
Employed	42 (60.9)	13 (56.5)	18 (78.3)	11 (47.8)
Studying	3 (4.3)	1 (4.3)	1 (4.3)	1 (4.3)
Retired	22 (31.9)	7 (30.4)	4 (17.4)	11 (47.8)
Smoking status, n (%)				
Ex-smoker	15 (21.7)	5 (21.7)	5 (21.7)	5 (21.7)
Never	54 (78.3)	18 (78.3)	18 (78.3)	18 (78.3)
Duration of diabetes, years	10.4±7.8	9.2±7.4	10.6±8.4	11.3±7.3
Oral antihyperglycaemics, n (%)	61 (88.4)	20 (87.0)	20 (87.0)	21 (91.3)
Insulin, n (%)	15 (21.7)	4 (17.4)	3 (13.0)	8 (34.8)

Data are presented as mean±SD for continuous variables and n (%) for categorical variables.
C-HIIT, combined aerobic and resistance high-intensity interval training; C-MICT, combined aerobic and resistance moderate-intensity continuous training; CON, waitlist control.

percentage, and increased lean mass (table 3). Changes in other anthropometric measures were not different between groups at week 8.

Exercise capacity (time-on-test) increased in C-HIIT and C-MICT versus CON at week 8 (table 3). Exercise capacity was higher in C-HIIT versus C-MICT at week 8. Relative $\dot{V}O_{2peak}$ increased in C-HIIT and C-MICT, while absolute $\dot{V}O_{2peak}$ increased only in C-MICT versus CON. Absolute and relative VT was higher in C-MICT versus C-HIIT while relative VT was higher in C-MICT than CON. The 30-s sit-to-stand and 30-s arm curl scores increased in C-HIIT and C-MICT versus CON. Dominant-hand grip strength was higher in C-HIIT and C-MICT than CON. Leg press 1RM was similar between groups at week-8, but 1RM chest press was higher in C-MICT than CON.

Phase 2

At month 12, HbA$_{1c}$ was not significantly different from baseline (mean change: 0.1±1.8% and –0.5±1.9% in C-HIIT and C-MICT, respectively; table 4; figure 2B). Blood glucose at 2 hours of the OGTT decreased in C-MICT versus C-HIIT at month 12 compared with

baseline. At month 12, TC and LDL-C increased, while body mass, waist and hip circumferences, and lean mass decreased, versus baseline. At month 12, exercise capacity, and 30-s sit-to-stand and 30-s arm curl scores increased, while VT and 6-m gait speed decreased, versus baseline (table 5).

Diet and physical activity

Energy intake and physical activity changes from baseline at week 8 (online supplemental table 2) and month 12 (online supplemental table 3) were comparable across groups and timepoints except sedentary time, which was lower at month-12 versus baseline.

Adherence to exercise

Attendance and intensity adherence to the prescribed intensity during supervised training was high in C-HIIT (96.7±6.0% and 82.0±17.4%, respectively) and C-MICT (94.1±6.2% and 87.0±9.1%, respectively). During the self-directed phase, the proportion of total prescribed sessions completed and adherence to intensity decreased (compared with the supervised phase) in both C-HIIT

Table 2 Changes in glycaemic control and lipids from baseline to 8 weeks

Variable		Mean±SD			Adjusted mean difference (95% CI); sample size; p value		
		C-HIIT	C-MICT	CON	C-HIIT–CON	C-MICT–CON	C-HIIT–C-MICT
HbA$_{1c}$ (%)	Baseline	8.6±2.2	9.0±1.8	8.1±1.3	−0.7 (−1.3, −0.2); n=45; p=0.014	−1.2 (−1.9, −0.6); n=45; p=0.001	0.4 (−0.3, 1.2); n=44; p=0.229
	8 weeks	8.4±2.0	8.3±1.9	8.8±1.5			
	Δ	−0.2±1.2	−0.7±1.3	0.7±0.8			
HbA$_{1c}$ (mmol·mol)	Baseline	70±24	75±20	65±14	−8 (−15, −2); n=45; p=0.014	−14 (−21, −6); n=45; p=0.001	5 (−3, 13); n=44; p=0.229
	8 weeks	69±21	67±21	72±16			
	Δ	−2±13	−8±14	8±9			
Fasting plasma glucose (mmol·L)	Baseline	9.0±2.9	9.1±2.8	8.6±2.6	−0.1 (−1.5, 1.3); n=44; p=0.709	−0.6 (−2.1, 0.8); n=45; p=0.400	0.6 (−0.8, 1.9); n=45; p=0.386
	8 weeks	8.9±2.8	8.5±2.3	8.8±2.9			
	Δ	0.0±2.3	−0.7±2.9	0.3±2.8			
2-hour OGTT glucose (mmol·L)*	Baseline	16.6±5.3	17.5±4.2	14.2±2.4	−0.8 (−4.0, 2.5); n=28; p=0.625	−1.5 (−3.9, 0.9); n=31; p=0.212	0.5 (−1.6, 2.6); n=35; p=0.628
	8 weeks	17.0±5.9	17.3±4.2	15.7±4.8			
	Δ	0.5±3.9	−0.2±1.9	1.5±3.9			
Glucose OGTT AUC (mmol·L)*	Baseline	679.6±256.6	833.2±259.3	729.0±211.4	93.9 (−64.3, 252.1); n=22; p=0.229	81.3 (−35.9, 198.4); n=22; p=0.163	−9.6 (−113.8, 133.0); n=28; p=0.874
	8 weeks	702.9±241.2	808.2±226.8	641.4±205.3			
	Δ	23.3±200.8	−25.1±122.6	−87.5±151.3			
Fasting blood insulin (pmol·mL)	Baseline	134.3±77.4	145.9±109.6	166.5±174.6	21.6 (−2.6, 45.7); n=43; p=0.078	−16.7 (−50.2, 16.9); n=44; p=0.322	30.6 (−0.2, 61.5); n=45; p=0.052
	8 weeks	152.2±102.7	130.9±79.2	167.4±199.9			
	Δ	17.9±42.7	−15.0±63.0	0.9±43.1			
2-hour OGTT insulin (pmol·mL)*	Baseline	597.8±489.6	388.1±256.0	678.4±455.2	52.5 (−116.8, 221.8); n=27; p=0.528	12.9 (−149.4, 175.2); n=30; p=0.872	58.0 (−50.7, 166.7); n=35; p=0.286
	8 weeks	581.4±372.9	376.4±235.3	587.3±439.6			
	Δ	−16.4±221.2	−11.7±153.7	−91.1±272.4			
Insulin OGTT AUC (pmol·mL; ×10^{-3})*	Baseline	45.9±45.1	23.1±19.2	48.8±24.9	4.7 (−9.1, 18.5); n=20; p=0.483	−4.3 (−14.3, 5.7); n=19; p=0.377	0.4 (−10.7, 11.5); n=25; p=0.936
	8 weeks	49.4±58.1	21.0±19.3	48.3±25.1			
	Δ	3.6±18.3	−2.1±6.9	−0.5±9.0			
Matsuda Index*	Baseline	1.85±0.92	2.88±2.09	1.34±0.55	−0.31 (−0.67, 0.06); n=24; p=0.096	0.53 (−0.34, 1.40); n=21; p=0.215	−0.83 (−1.43, −0.24); n=27; p=0.008
	8 weeks	1.54±0.65	2.99±1.66	1.47±0.81			
	Δ	−0.30±0.45	0.11±1.18	0.13±0.41			
Insulinogenic Index*	Baseline	0.43±0.42	0.31±0.25	0.53±0.34	0.18 (−0.13, 0.50); n=25; p=0.236	0.06 (−0.14, 0.25); n=27; p=0.559	0.11 (−0.08, 0.30); n=36; p=0.264
	8 weeks	0.52±0.63	0.28±0.26	0.47±0.55			
	Δ	0.10±0.37	−0.03±0.14	−0.06±0.32			

Continued

Table 2 Continued

Variable		Mean±SD			Adjusted mean difference (95% CI); sample size; p value		
		C-HIIT	C-MICT	CON	C-HIIT−CON	C-MICT−CON	C-HIIT−C-MICT
Disposition Index*	Baseline	0.57±0.50	0.44±0.27	0.59±0.31	0.28 (−0.12, 0.69); n=23; p=0.162	0.17 (−0.14, 0.49); n=21; p=0.264	−0.05 (−0.24, 0.33); n=28; p=0.731
	8 weeks	0.73±1.00	0.47±0.35	0.48±0.64			
	Δ	0.16±0.58	0.03±0.18	−0.11±0.47			
HOMA-β*	Baseline	74.1±46.6	60.5±44.8	86.1±38.2	19.2 (2.0, 36.4); n=31; p=0.030	9.7 (−5.1, 24.4); n=33; p=0.190	3.7 (−13.1, 20.5); n=38; p=0.660
	8 weeks	80.2±56.7	64.7±35.8	73.0±34.4			
	Δ	6.0±25.4	4.1±25.6	−13.2±17.6			
HOMA-%S*	Baseline	41.3±21.3	56.6±41.1	34.1±12.2	−6.0 (−14.6, 2.6); n=31; p=0.164	5.3 (−9.8, 20.5); n=33; p=0.478	−11.9 (−24.7, 1.0); n=38; p=0.070
	8 weeks	35.7±15.4	55.8±32.7	37.1±17.0			
	Δ	−5.6±15.9	−0.8±29.7	3.0±6.6			
HOMA-IR	Baseline	2.74±1.41	3.05±2.35	3.25±2.97	0.39 (−0.09, 0.88); n=43; p=0.108	−0.43 (−1.13, 0.26); n=44; p=0.214	0.65 (0.00, 1.30); n=45; p=0.049
	8 weeks	3.09±1.86	2.64±1.50	3.24±3.15			
	Δ	0.35±0.82	−0.40±1.54	−0.01±0.75			
C-peptide (nmol/L)	Baseline	1.14±0.49	1.16±0.48	1.05±0.51	0.25 (0.07, 0.43); n=32; p=0.008	2.36 (1.98, 2.74); n=33; p<0.001	−2.17 (−2.55, −1.80); n=33; p<0.001
	8 weeks	1.30±0.62	3.47±1.08	0.97±0.56			
	Δ	0.16±0.26	2.32±0.75	−0.09±0.22			
C-peptide HOMA-β	Baseline	84.7±41.9	65.4±27.8	73.0±37.4	9.8 (−8.2, 27.8); n=32; p=0.276	9.9 (−3.5, 23.3); n=33; p=0.141	−1.2 (−17.7, 15.4); n=33; p=0.885
	8 weeks	89.0±50.1	72.0±26.4	68.3±37.7			
	Δ	4.4±26.7	6.6±16.6	−4.6±21.7			
C-peptide HOMA-%S	Baseline	38.6±28.4	38.1±20.3	70.9±99.1	−7.8 (−17.3, 1.8); n=32; p=0.106	−10.1 (−22.1, 1.8); n=33; p=0.093	0.6 (−11.0, 12.2); n=33; p=0.916
	8 weeks	38.1±41.9	36.9±11.4	84.0±115.4			
	Δ	−0.5±15.9	−1.1±16.3	13.0±20.0			
C-peptide HOMA-IR	Baseline	3.17±0.96	3.23±1.62	2.75±1.30	0.54 (0.00, 1.07); n=32; p=0.050	0.02 (−0.59, 0.63); n=33; p=0.947	0.68 (0.07, 1.29); n=33; p=0.029
	8 weeks	3.65±1.30	3.01±1.01	2.65±1.59			
	Δ	0.48±0.80	−0.22±1.15	−0.10±0.64			
hs-CRP (mg/L)	Baseline	2.83±3.27	3.39±3.69	3.10±2.89	−1.05 (−3.71, 1.62); n=33; p=0.428	−0.64 (−3.68, 2.40); n=33; p=0.669	−0.58 (−2.42, 1.26); n=34; p=0.524
	8 weeks	2.88±2.71	3.89±4.49	4.22±6.51			
	Δ	0.06±1.82	0.51±3.37	1.12±4.95			
TC (mmol/L)	Baseline	4.00±0.78	4.38±1.06	3.99±0.79	0.21 (−0.07, 0.49); n=43; p=0.135	0.00 (−0.38, 0.38); n=44; p=0.984	0.25 (−0.10, 0.59); n=45; p=0.155
	8 weeks	4.24±1.00	4.37±1.16	4.02±0.93			
	Δ	0.24±0.39	0.00±0.68	0.03±0.52			

Continued

Table 2 Continued

Variable		Mean±SD			Adjusted mean difference (95% CI); sample size; p value		
		C-HIIT	C-MICT	CON	C-HIIT–CON	C-MICT–CON	C-HIIT–C-MICT
HDL-C (mmol/L)	Baseline	1.16±0.35	1.19±0.27	1.24±0.31	0.06 (0.00, 0.12); n=43; p=0.043	0.03 (−0.03, 0.10); n=44; p=0.324	0.04 (−0.01, 0.09); n=45; p=0.147
	8 weeks	1.19±0.30	1.19±0.30	1.19±0.29			
	Δ	0.03±0.09	−0.01±0.08	−0.04±0.13			
LDL-C (mmol/L)	Baseline	2.46±0.89	2.82±1.05	2.23±0.79	0.06 (−0.20, 0.32); n=43; p=0.639	−0.09 (−0.42, 0.25); n=44; p=0.610	0.19 (−0.12, 0.50); n=45; p=0.214
	8 weeks	2.65±1.07	2.82±1.15	2.35±0.87			
	Δ	0.19±0.40	0.00±0.58	0.12±0.44			
Triglycerides (mmol/L)	Baseline	1.59±0.82	1.57±0.86	1.60±0.75	0.16 (−0.08, 0.40); n=43; p=0.175	0.07 (−0.25, 0.39); n=44; p=0.665	0.09 (−0.22, 0.40); n=45; p=0.570
	8 weeks	1.65±0.89	1.54±0.77	1.49±0.62			
	Δ	0.06±0.29	−0.03±0.70	−0.11±0.49			

Data are presented as mean ± SD.

*Includes only those participants not on insulin (C-HIIT, n = 19; C-MICT, n = 20; CON, n = 15).

AUC, area under the curve; C-HIIT, combined aerobic and resistance high-intensity interval training; C-MICT, combined aerobic and resistance moderate-intensity continuous training; CON, waitlist control; HbA_{1c}, glycated haemoglobin; HDL–C, high-density lipoprotein cholesterol; 2h OGTT, 2-hour oral glucose tolerance test; HOMA, homeostatic model assessment; C-peptide HOMA-IR, C-peptide HOMA of insulin resistance; HOMA-IR, HOMA of insulin resistance; C-peptide HOMA-%S, C-peptide HOMA of insulin sensitivity; HOMA-%S, HOMA of insulin sensitivity; C-peptide HOMA-β, C-peptide HOMA of beta cell function; HOMA-β, HOMA of beta cell function; hs-CRP, high-sensitivity C reactive protein; LDL-C, low-density lipoprotein cholesterol; TC, total cholesterol.
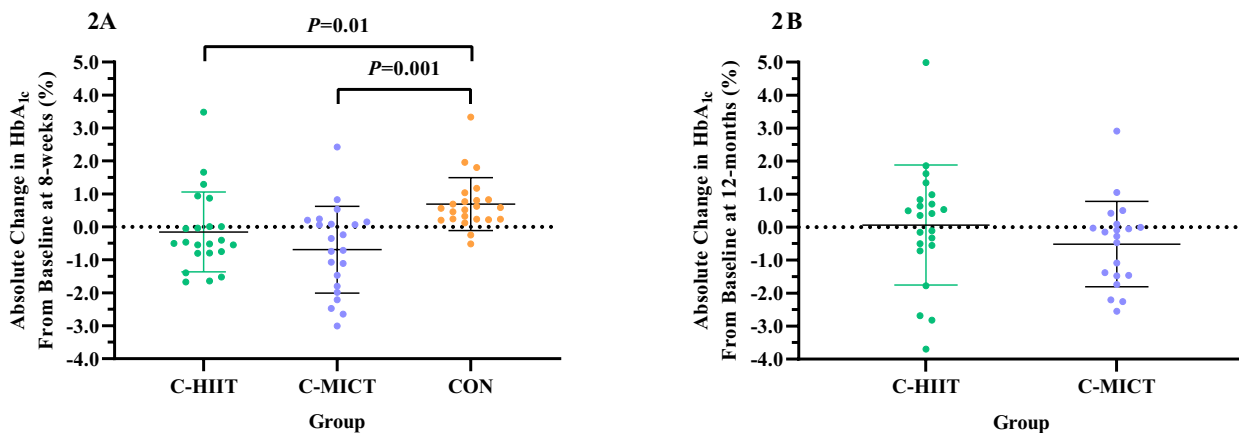
Figure 2 The absolute change in HbA$_{1c}$ from baseline to 8 weeks (2A) and 12 months (2B). C-HIIT, combined aerobic and resistance high-intensity interval training; C-MICT, combined aerobic and resistance moderate-intensity continuous training; CON, waitlist control; HbA$_{1c}$, glycated haemoglobin.

(40.6±25.6% and 67.1±34.6%, respectively) and C-MICT (60.6±27.5% and 79.8±20.9%). The optional monthly supervised sessions were not included in this calculation.

There were no group differences during the self-directed phase in attendance at the optional monthly supervised training sessions; 46/57 (81%; C-HIIT=24/30 (80%); C-MICT=22/27 (81%)) participants attended at least one session, 33/57 (58%; C-HIIT=17/30 (57%); C-MICT=16/27 (59%)) attended at least five sessions, 17/57 (30%; C-HIIT=8/30 (27%); C-MICT=9/27 (33%)) attended all nine sessions, and 11/57 (19%; C-HIIT=6/30 (20%); C-MICT=5/27 (19%)) attended zero sessions.

DISCUSSION

This is the first randomised controlled trial comparing the effect of novel low-volume C-HIIT (78 min/week), and C-MICT (210 min/week), with CON on glycaemic control in low-active adults with T2D. The main finding was a clinically relevant improvement in HbA$_{1c}$ at week 8 favouring both C-HIIT and C-MICT versus CON. Additionally, there were improvements in C-peptide, body composition and physical fitness and function at week 8 in C-HIIT and C-MICT versus CON. However, not all these improvements were maintained through to month 12, following 10 months of self-directed exercise. These data suggest that time-efficient supervised low-volume C-HIIT, and C-MICT, are both effective at improving glycaemic control, body composition and cardiovascular health in the short term in people with T2D.

Both C-HIIT (−0.7%) and C-MICT (−1.2%) decreased HbA$_{1c}$ at week 8 versus CON. This is consistent with other studies demonstrating reduced HbA$_{1c}$ with aerobic HIIT and C-MICT in people with T2D. Since for every 1% increase in HbA$_{1c}$ there is an increase of 25% in cardiovascular mortality and 15% all-cause mortality,[33] [34] this clinically relevant difference between C-HIIT, C-MICT

and CON is likely to have a substantial impact on health if exercise is maintained.

The positive effect on HbA$_{1c}$ at week 8 was comparable for C-HIIT and C-MICT, suggesting that supervised C-HIIT and supervised C-MICT are both effective at improving HbA$_{1c}$, despite a lower time commitment with C-HIIT (78 vs 210 min/week and 3× vs 4×/week). This is important considering the low rates of exercise adherence among people with T2D,[35] with lack of time a commonly reported barrier to exercise.[20] Therefore, the findings in this study suggest that low-volume C-HIIT may be a time-efficient, effective, alternative to the current guidelines of 210 min/week of C-MICT. However, it is important to note that C-HIIT may not be effective for long-term improvement of HbA$_{1c}$. Specifically, at month 12 (phase 2 end), following 10 months of self-directed exercise, HbA$_{1c}$ was not different from baseline. This finding is similar to other studies involving self-directed training in people with T2D, where changes to glycaemic control were unable to be maintained or match improvements observed with supervised exercise training.[19] [36] Sessions completed and intensity adherence during self-directed exercise in this study were low, which may explain the regression to baseline in HbA$_{1c}$. Interestingly, the proportion of total prescribed sessions completed and intensity adherence during self-directed exercise were higher with C-MICT than C-HIIT. Collectively, these findings indicate a need to improve long-term exercise participation so that the benefits achieved during supervised training can be maintained, although the ability of participants to continue to exercise at a high intensity is less likely. This agrees with a recent analysis of long-term adherence to HIIT.[37]

A novel feature of C-HIIT in the current study was the addition of high-intensity interval resistance training to aerobic HIIT. Our finding of reduced HbA$_{1c}$ with

Table 3 Changes in body composition, cardiorespiratory fitness, and neuromuscular fitness from baseline to 8 weeks

Variable		Mean±SD			Adjusted mean difference (95% CI); sample size; P value		
		C-HIIT	C-MICT	CON	C-HIIT−CON	C-MICT−CON	C-HIIT−C-MICT
Body mass (kg)	Baseline	93.2±15.9	97.5±19.6	103.0±21.6	-0.0 (-1.6, 1.6); n=46; p=0.995	-0.4 (-1.7, 0.8); n=46; p=0.479	0.4 (-0.7, 1.6); n=46; p=0.431
	8 weeks	93.8±14.8	97.4±19.4	103.4±22.2			
	Δ	0.5±2.5	-0.1±1.4	0.4±2.6			
Fat mass (kg)	Baseline	36.5±9.5	38.7±13.7	41.2±11.6	-1.9 (-3.1, -0.6); n=46; p=0.005	-1.5 (-2.6, -0.4); n=46; p=0.007	-0.4 (-1.2, 0.4); n=46; p=0.309
	8 weeks	35.8±8.9	38.2±13.2	42.2±12.2			
	Δ	-0.8±1.8	-0.5±1.0	1.0±2.3			
Body fat (%)	Baseline	39.3±6.3	39.2±8.4	40.3±6.9	-1.6 (-2.4, -0.8); n=46; p<0.001	-1.1 (-1.8, -0.4); n=46; p=0.003	-0.5 (-1.2, 0.2); n=46; p=0.129
	8 weeks	38.5±6.4	38.8±8.4	41.0±6.9			
	Δ	-0.9±1.2	-0.4±1.0	0.7±1.4			
Trunk fat mass (kg)	Baseline	20.6±4.9	21.9±7.3	23.3±6.8	-1.3 (-2.1, -0.4); n=46; p=0.004	-1.0 (-1.8, -0.3); n=46; p=0.009	-0.3 (-1.0, 0.3); n=46; p=0.341
	8 weeks	20.1±4.7	21.7±7.1	24.1±7.2			
	Δ	-0.5±1.2	-0.2±1.0	0.8±1.5			
Trunk fat (%)	Baseline	42.1±5.1	42.3±8.1	43.0±6.6	-1.9 (-2.9, -0.8); n=46; p=0.001	-1.3 (-2.3, -0.4); n=46; p=0.005	-0.5 (-1.5, 0.4); n=46; p=0.280
	8 weeks	41.3±5.5	42.0±8.1	44.1±6.7			
	Δ	-0.8±1.8	-0.3±1.3	1.1±1.7			
Lean mass (kg)	Baseline	53.3±9.4	55.5±10.6	57.9±13.3	1.5 (0.8, 2.3); n=46; p<0.001	0.9 (0.1, 1.7); n=46; p=0.034	0.7 (-0.0, 1.3); n=46; p=0.060
	8 weeks	54.4±9.4	55.9±11.0	57.6±13.8			
	Δ	1.1±0.9	0.4±1.3	-0.4±1.5			
Waist circumference (cm)	Baseline	107.3±12.0	109.3±15.1	111.5±13.7	-1.3 (-3.8, 1.2); n=45; p=0.288	-0.2 (-2.3, 1.8); n=45; p=0.808	-0.9 (-3.2, 1.3); n=46; p=0.418
	8 weeks	106.4±11.6	109.2±15.0	111.6±13.5			
	Δ	-0.8±4.7	-0.1±2.9	0.1±3.7			
Hip circumference (cm)	Baseline	111.0±11.2	113.9±14.6	116.9±13.3	-0.1 (-1.5, 1.2); n=45; p=0.864	-0.8 (-2.0, 0.4); n=45; p=0.183	0.6 (-0.7, 1.9); n=46; p=0.374
	8 weeks	110.9±11.5	113.2±14.4	116.9±13.5			
	Δ	-0.1±2.4	-0.8±2.0	0.0±1.9			
Waist-to-hip ratio	Baseline	0.97±0.10	0.96±0.08	0.96±0.08	-0.01 (-0.03, 0.02); n=45; p=0.535	-0.00 (-0.01, 0.02); n=45; p=0.656	-0.01 (-0.03, 0.01); n=46; p=0.283
	8 weeks	0.96±0.10	0.97±0.08	0.96±0.09			
	Δ	-0.01±0.04	0.00±0.02	0.00±0.03			
Exercise capacity (s)	Baseline	812±156	737±110	841±235	124 (77, 171); n=46; p<0.001	49 (5, 93); n=46; p=0.028	54 (10, 99); n=46; p=0.018
	8 weeks	915±215	772±123	822±236			
	Δ	104±83	36±66	-19±74			

Continued

Table 3 Continued

Variable		Mean±SD			Adjusted mean difference (95% CI); sample size; P value		
		C-HIIT	C-MICT	CON	C-HIIT−CON	C-MICT−CON	C-HIIT−C-MICT
VO$_{2peak}$ (L/min)	Baseline	2.25±0.55	2.37±0.65	2.35±0.51	0.11 (−0.04, 0.26); n=46; p=0.142	0.15 (0.04, 0.26); n=46; p=0.008	−0.04 (−0.20, 0.12); n=46; p=0.609
	8 weeks	2.29±0.51	2.44±0.66	2.26±0.53			
	Δ	0.04±0.33	−0.06±0.20	−0.09±0.16			
VO$_{2peak}$ (mL/kg/min)	Baseline	24.3±5.1	24.7±7.0	23.3±5.3	1.5 (0.0, 3.0); n=46; p=0.049	1.9 (0.9, 2.9); n=46; p=0.001	−0.6 (−2.4, 1.1); n=46; p=0.450
	8 weeks	24.5±4.3	25.5±7.3	22.2±4.9			
	Δ	0.2±3.8	0.8±1.9	−1.0±1.4			
VT (L/min)	Baseline	1.62±0.40	1.87±0.47	1.68±0.32	−0.07 (−0.18, 0.05); n=43; p=0.234	0.07 (−0.04, 0.18); n=44; p=0.197	−0.15 (−0.29, −0.02); n=43; p=0.028
	8 weeks	1.54±0.28	1.90±0.51	1.64±0.30			
	Δ	−0.08±0.27	0.03±0.17	−0.03±0.18			
VT (mL/kg/min)	Baseline	17.9±3.5	19.3±6.3	16.9±4.1	−0.2 (−1.3, 1.0); n=43; p= 0.760	1.3 (0.3, 2.3); n=44; p=0.015	−1.7 (−3.1, −0.4); n=43; p=0.015
	8 weeks	16.8±2.7	19.7±5.9	16.3±3.4			
	Δ	−1.1±2.8	0.3±2.0	−0.6±1.6			
30-s sit to stand (#)	Baseline	12±2	11±2	12±3	2 (0, 3); n=46; p=0.008	1 (1, 2); n=46; p=0.002	0 (−1, 1); n=46; p=0.961
	8 weeks	12±3	12±2	11±3			
	Δ	1±2	1±2	−1±1			
30-s arm curl (#)	Baseline	17±4	17±5	17±5	2 (1, 4); n=46; p=0.004	4 (2, 6); n=46; p<0.001	−2 (−4, 1); n=46; p=0.146
	8 weeks	18±4	20±6	16±4			
	Δ	1±3	3±4	−1±3			
6-m gait speed time (s)	Baseline	5.39±0.89	5.37±0.97	5.26±0.97	−0.45 (−0.74, −0.15); n=46; p=0.004	−0.64 (−0.97, −0.31); n=46; p<0.001	0.19 (−0.11, 0.49); n=46; p=0.214
	8 weeks	5.47±0.84	5.26±1.03	5.81±0.96			
	Δ	0.08±0.47	−0.10±0.56	0.55±0.56			
Floor rise to standing (s)	Baseline	5.15±2.21	5.11±1.72	5.96±3.22	−0.67 (−0.99, −0.35); n=43; p<0.001	−0.98 (−1.42, −0.54); n=41; p<0.001	0.27 (−0.09, 0.64); n=42; p=0.141
	8 weeks	4.81±2.30	4.51±1.28	6.38±3.71			
	Δ	−0.33±0.49	−0.60±0.71	0.42±0.67			
Grip strength—dominant (kg)	Baseline	36.4±9.6	38.6±9.4	38.9±12.4	1.9 (0.2, 3.7); n=46; p=0.033	2.1 (0.3, 3.9); n=46; p=0.026	−0.2 (−1.8, 1.3); n=46; p=0.772
	8 weeks	37.3±9.6	39.6±9.7	37.9±12.9			
	Δ	0.9±2.4	1.1±2.8	−1.0±3.3			
Grip strength—non-dominant (kg)	Baseline	35.1±9.0	35.7±10.1	36.2±11.1	0.3 (−1.2, 1.9); n=46; p=0.662	1.5 (−0.4, 3.3); n=46; p=0.114	−1.2 (−2.7, 0.3); n=46; p=0.126
	8 weeks	35.0±9.1	36.8±10.3	35.8±12.0			
	Δ	−0.1±1.9	1.1±3.0	−0.4±3.1			

Continued

Table 3 Continued

Variable		Mean±SD			Adjusted mean difference (95% CI); sample size; P value		
		C-HIIT	C-MICT	CON	C-HIIT−CON	C-MICT−CON	C-HIIT−C-MICT
Leg press 1RM (kg)	Baseline	112.0±17.6	98.8±34.2	118.9±25.5	0.0 (−35.4, 35.4); n=23; p=0.999	4.1 (−16.8, 24.9); n=23; p=0.689	8.6 (−34.6, 51.7); n=20; p=0.679
	8 weeks	145.9±19.8	120.3±33.6	132.0±30.4			
	Δ	33.9±20.1	21.5±29.2	13.1±16.4			
Chest press 1RM (kg)	Baseline	53.4±19.1	54.5±20.2	51.8±21.9	2.7 (−1.2, 6.6); n=41; p=0.170	2.8 (0.5, 5.1); n=44; p=0.018	−0.1 (−4.1, 3.8); n=41; p=0.948
	8 weeks	57.3±21.0	58.6±21.7	53.0±22.4			
	Δ	3.9±8.1	4.1±3.9	1.2±3.6			

Data are presented as mean ± SD.
C-HIIT, combined aerobic and resistance high-intensity interval training; C-MICT, combined aerobic and resistance moderate-intensity continuous training; CON, waitlist control; 1RM, one repetition maximum; $\dot{V}O_{2peak}$, peak oxygen uptake; VT, ventilatory threshold.

supervised C-HIIT at week 8 contrasts a study that compared supervised aerobic HIIT and supervised MICT, combined with an identical resistance exercise-training programme (intensity was not objectively defined), in people with T2D. They found that neither intervention had a significant impact on HbA_{1c} after 1 year.[38] Similarly, in another study, 12 weeks of aerobic HIIT combined with resistance training of increasing intensity had no effect on HbA_{1c} in people with T2D.[39] The main difference between these studies and the current study was that C-HIIT in the current study included high-intensity resistance exercise, which may have provided greater benefits for HbA_{1c}, possibly due to increased muscle mass and glucose transporter type-4 content. This aligns with a previous meta-analysis that found HbA_{1c} improvement was greater with high- versus low-to-moderate intensity resistance training.[40]

Fat, trunk fat and lean masses were improved with supervised C-HIIT and C-MICT, observations similar to previous findings in exercise training studies,[41] including with HIIT in people with T2D.[42] Interestingly, despite lower weekly average energy expenditure with C-HIIT versus C-MICT (approximately 1226 kJ vs 4564 kJ), body composition changes were comparable across groups. These findings suggest that positive body composition changes can be achieved with supervised low-volume C-HIIT in people with T2D. At month 12, fat and trunk fat masses were no longer significantly improved compared with baseline. Furthermore, lean mass was significantly lower at month 12 compared with baseline, which may explain, in part, the decrease in body mass and hip circumference. These findings suggest that the positive body composition findings at week 8 were not maintained through to month 12.

Cardiorespiratory fitness ($\dot{V}O_{2peak}$), exercise capacity (time-on-test), 30-s sit-to-stand, 30 s arm curl, 6-m gait speed, floor rise to standing and dominant hand grip strength were improved with C-HIIT and C-MICT versus CON at week 8. There was also a greater increase in exercise capacity with C-HIIT than C-MICT, which was not reflected in cardiorespiratory fitness differences between the two groups.

According to accelerometry estimates, sedentary time decreased from baseline at 12 months. This decrease in sedentary time was not reflected in increased time spent being physically active. This suggests that it may have been reallocated into time spent in unmeasured behaviours, such as sleep or in periods of non-wear time. As sedentary time may increase time spent in a hyperglycaemic state in people with T2D,[43] exploring the effect of exercise training on time spent sedentary in more detail warrants further research, particularly using 24 hours monitoring and device-based measures that specifically capture posture, such as ActivPAL.

The analysis at month 12 was impacted by reduced adherence to the exercise programme. This may have impacted findings and suggests a need to better facilitate self-directed training for people with T2D. This study was

Table 4 Changes in glycaemic control and lipids from baseline to 12 months

Variable		Mean±SD		Mean difference (95% CI); sample size 12 months − baseline	Time, p value	Group × time, p value
		C-HIIT	C-MICT			
HbA$_{1c}$ (%)	Baseline	8.8±2.1	8.8±1.6	-0.2 (-0.7, 0.3);n=60	0.412	0.189
	12 months	9.0±2.2	8.4±1.9			
	Δ	0.1±1.8	-0.5±1.9			
HbA$_{1c}$ (mmol·mol)	Baseline	73±23	73±18	-2 (-7, 3);n=60	0.412	0.189
	12 months	75±24	68±21			
	Δ	1±19	-6±21			
Fasting plasma glucose (mmol·L)	Baseline	9.1±3.0	9.1±2.8	-0.2 (-1.1, 0.6);n=63	0.606	0.459
	12 months	9.3±2.7	8.7±1.6			
	Δ	0.1±3.3	-0.5±3.5			
2h OGTT Gluc. (mmol·L)*	Baseline	16.3±5.3	17.1±4.4	-1.1 (-2.5, 0.3);n=45	0.119	0.044
	12 months	16.5±5.8	15.1±3.9			
	Δ	0.3±4.6	-2.6±4.8			
Glucose OGTT AUC (mmol·L)*	Baseline	638.8±230.6	807.5±250.6	39.4 (-32.6, 111.4);n=38	0.266	0.276
	12 months	711.6±270.4	874.4±242.9			
	Δ	78.0±187.6	0.8±230.8			
Fasting blood insulin (pmol·mL)	Baseline	161.3±163.6	149.8±106.7	-0.4 (-30.4, 29.6);n=62	0.978	0.416
	12 months	184.6±216.7	140.7±111.6			
	Δ	11.8±113.5	-12.6±120.4			
2h OGTT insulin (pmol·mL)*	Baseline	637.6±503.3	407.0±255.1	-39.2(-146.1,67.8);n=44	0.461	0.840
	12 months	680.4±738.3	365.0±195.4			
	Δ	-28.5±340.0	-49.8±354.7			
Insulin OGTT AUC (pmol·mL; ×10^{-3})*	Baseline	46.3±41.1	26.4±20.2	-9.6 (-20.6, 1.4);n=34	0.085	0.587
	12 months	37.9±36.0	21.0±11.5			
	Δ	-12.5±26.8	-6.7±33.7			
Matsuda Index*	Baseline	1.81±0.96	2.57±1.94	0.28 (-0.19, 0.76);n=37	0.224	0.281
	12 months	1.64±0.89	2.61±1.78			
	Δ	0.03±1.25	0.53±1.43			
Insulinogenic Index*	Baseline	0.46±0.48	-1.16±7.21	-0.08 (-0.19, 0.03);n=46	0.146	0.356
	12 months	0.39±0.39	0.30±0.27			
	Δ	-0.13±0.36	-0.03±0.37			
Disposition Index*	Baseline	0.57±0.57	0.46±0.26	-0.08 (-0.27, 0.11);n=37	0.392	0.350
	12 months	0.44±0.34	0.42±0.31			
	Δ	-0.16±0.51	0.01±0.57			

Continued

Table 4 Continued

Variable		Mean±SD		Mean difference (95% CI); sample size 12 months−baseline	Time, p value	Group × time, p value
		C-HIIT	C-MICT			
HOMA-β*	Baseline	73.4±45.5	62.2±41.8	−1.7 (−11.4, 8.0); n=50	0.718	0.236
	12 months	70.2±57.7	67.8±45.8			
	Δ	−7.5±27.4	4.0±27.9			
HOMA-%S*	Baseline	40.1±20.0	51.8±38.7	4.6 (−4.3, 13.5); n=50	0.298	0.831
	12 months	41.4±24.1	58.6±42.5			
	Δ	3.7±29.4	5.6±32.6			
HOMA-IR	Baseline	3.17±2.54	3.12±2.26	−0.13 (−0.74, 0.49); n=62	0.679	0.569
	12 months	3.03±3.22	2.85±2.19			
	Δ	0.05±2.32	−0.30±2.42			
TC (mmol/L)	Baseline	4.05±0.85	4.13±1.03	0.20 (0.04, 0.36); n=62	0.016	0.056
	12 months	4.45±1.09	3.97±1.02			
	Δ	0.35±0.60	0.43±0.64			
HDL-C (mmol/L)	Baseline	1.16±0.31	1.19±0.29	0.03 (−0.01, 0.07); n=62	0.089	0.844
	12 months	1.20±0.29	1.25±0.34			
	Δ	0.04±0.15	0.03±0.15			
LDL-C (mmol/L)	Baseline	2.49±0.93	2.61±1.01	0.16 (0.01, 0.31); n=62	0.038	0.066
	12 months	2.95±1.16	2.68±1.12			
	Δ	0.30±0.60	0.02±0.57			
Triglycerides (mmol/L)	Baseline	1.62±0.74	1.46±0.80	0.13 (−0.02, 0.28); n=62	0.078	0.138
	12 months	1.91±0.88	1.23±0.51			
	Δ	0.24±0.55	0.02±0.59			

Data are presented as mean ± SD.
*Includes only those participants not on insulin (C-HIIT, n = 26; C-MICT, n = 25).
AUC, area under the curve; C-HIIT, combined aerobic and resistance high-intensity interval training; C-MICT, combined aerobic and resistance moderate-intensity continuous training; CON, waitlist control; HbA$_{1c}$, glycated haemoglobin; HDL-C, high-density lipoprotein cholesterol; 2h OGTT, 2-hour oral glucose tolerance test; HOMA, homeostatic model assessment; HOMA-IR, HOMA of insulin resistance; HOMA-%S, HOMA of insulin sensitivity; HOMA-β, HOMA of beta cell function; LDL-C, low-density lipoprotein cholesterol; TC, total cholesterol.

Table 5 Changes in body composition, cardiorespiratory fitness, and neuromuscular fitness from baseline to 12 months

Variable		Mean±SD		Mean difference (95% CI); sample size 12 months−baseline	Time, p value	Group × time, p value
		C-HIIT	C-MICT			
Body mass (kg)	Baseline	97.0±17.9	99.6±22.1	−1.5 (−2.6, −0.3);n=63	0.013	0.390
	12 months	95.8±15.6	94.3±19.9			
	Δ	−1.0±4.3	−2.0±4.6			
Fat mass (kg)	Baseline	39.0±11.2	39.2±13.3	−0.5 (−1.2, 0.3);n=63	0.214	0.631
	12 months	38.9±11.0	35.9±11.2			
	Δ	−0.3±2.9	−0.7±3.1			
Body fat (%)	Baseline	40.2±6.7	39.1±8.0	0.0 (−0.5, 0.5);n=63	0.988	0.914
	12 months	40.3±7.0	38.0±7.6			
	Δ	0.0±2.0	0.0±2.1			
Trunk fat mass (kg)	Baseline	22.0±6.2	22.3±7.0	−0.0 (−0.5, 0.5);n=63	0.893	0.965
	12 months	21.7±5.9	21.1±6.6			
	Δ	−43.3±1.8	−21.9±2.0			
Trunk fat (%)	Baseline	43.1±6.0	42.3±7.5	0.3 (−0.4, 0.9);n=63	0.390	0.652
	12 months	43.0±6.6	41.6±7.7			
	Δ	0.1±2.4	0.4±2.5			
Lean mass (kg)	Baseline	54.5±9.7	57.0±13.3	−0.7 (−1.4, −0.0);n=63	0.038	0.402
	12 months	53.8±8.5	55.3±12.5			
	Δ	−0.4±2.6	−1.0±2.7			
Waist circumference (cm)	Baseline	108.7±12.1	110.2±15.6	−2.3(−4.0, −0.5);n=62	0.012	0.639
	12 months	106.9±8.9	106.2±15.7			
	Δ	−1.9±6.4	−2.7±7.0			
Hip circumference (cm)	Baseline	113.3±13.2	114.5±14.3	−2.6(−3.7, −1.5);n=62	< 0.001	0.494
	12 months	111.0±13.1	109.8±12.3			
	Δ	−2.9±4.0	−2.2±4.4			
Waist-to-hip ratio	Baseline	0.97±0.10	0.96±0.08	0.00 (−0.01,0.02);n=62	0.774	0.434
	12 months	0.97±0.08	0.97±0.10			
	Δ	0.01±0.05	0.00±0.05			
Exercise capacity (sec)	Baseline	813±196	756±138	62 (27, 97);n=62	0.001	0.751
	12 months	895±253	801±171			
	Δ	67±133	56±138			

Continued

Table 5 Continued

Variable		Mean±SD		Mean difference (95% CI); sample size 12 months−baseline	Time, p value	Group × time, p value
		C-HIIT	**C-MICT**			
VO$_{2peak}$ (L/min)	Baseline	2.17±0.51	2.41±0.63	−0.02(−0.09,0.06);n=62	0.646	0.896
	12 months	2.16±0.51	2.40±0.67			
	Δ	−0.02±0.28	−0.01±0.30			
VO$_{2peak}$ (mL/kg/min)	Baseline	22.6±4.7	24.6±6.5	0.1 (−0.8, 1.0);n=62	0.824	0.687
	12 months	22.5±4.6	25.4±6.4			
	Δ	−0.1±3.4	0.3±3.6			
VT (L/min)	Baseline	1.58±0.35	1.84±0.44	−0.11 (−0.19, −0.03);n=59	0.009	0.840
	12 months	1.50±0.28	1.71±0.49			
	Δ	−0.12±0.31	−0.10±0.30			
VT (mL/kg/min)	Baseline	16.8±3.7	18.9±5.7	−1.0 (−1.9, −0.1);n=59	0.031	0.524
	12 months	15.9±3.0	18.7±5.0			
	Δ	−1.3±3.5	−0.7±3.4			
30-s sit to stand (#)	Baseline	11±3	11±2	1 (0, 2);n=63	0.001	0.056
	12 months	12±2	13±2			
	Δ	0±2	2±2			
30-s arm curl (#)	Baseline	17±4	18±5	3 (1, 4);n=63	< 0.001	0.141
	12 months	19±4	21±5			
	Δ	2±5	3±5			
6-m gait speed time (s)	Baseline	5.50±0.81	5.44±1.08	−0.35 (−0.61, −0.09);n=63	0.009	0.478
	12 months	5.25±0.62	5.01±0.83			
	Δ	−0.26±1.00	−0.44±1.06			
Floor rise to standing (s)	Baseline	6.00±3.45	5.05±1.69	−0.16 (−0.95, 0.63);n=58	0.680	0.435
	12 months	6.13±4.17	4.34±1.03			
	Δ	0.15±2.77	−0.47±3.05			
Grip strength−dominant (kg)	Baseline	35.8±10.3	40.2±11.1	−0.5 (−1.7, 0.6);n=63	0.364	0.636
	12 months	35.0±10.0	39.0±10.9			
	Δ	−0.8±4.5	−0.3±4.8			
Grip strength−non-dominant (kg)	Baseline	35.0±9.9	36.8±11.0	−0.8 (−1.8, 0.3);n=63	0.149	0.385
	12 months	34.3±9.3	35.3±8.7			
	Δ	−1.2±3.9	−0.3±4.2			

Continued

Table 5 Continued

Variable		Mean±SD		Mean difference (95% CI); sample size 12 months−baseline	Time, p value	Group × time, p value
		C-HIIT	C-MICT			
Leg press 1RM (kg)	Baseline	126.4±24.3	121.8±45.2		0.075	0.272
	12 months	126.1±26.1	129.8±37.2			
	Δ	4.9±40.3	19.4±36.0	12.2 (−1.4, 25.7); n=36		
Chest press 1RM (kg)	Baseline	53.9±19.0	55.8±21.7		0.399	0.819
	12 months	56.5±21.0	53.2±21.6			
	Δ	1.6±10.6	0.9±10.9	1.2 (−1.7, 4.1); n=56		

Data are presented as mean ± SD.
C-HIIT, combined aerobic and resistance high-intensity interval training; C-MICT, combined aerobic and resistance moderate-intensity continuous training; CON, waitlist control; 1RM, one repetition maximum; VO_{2peak}, peak oxygen uptake; VT, ventilatory threshold.

designed to compare C-HIIT with CON and C-MICT with CON. The study was not sufficiently powered to complete a non-inferiority study to directly compare C-HIIT with C-MICT. This would have required >400 participants per group.

Supervised C-HIIT and C-MICT both improved glycaemic control after 8 weeks in low-active people with T2D. C-HIIT had around one-third the weekly time commitment and one fewer session per week compared with C-MICT. Furthermore, C-HIIT and C-MICT improved body composition and measures of aerobic and neuromuscular fitness after 8 weeks. However, improvements were generally not maintained following the 10 months of self-directed exercise, when there was reduced adherence to exercise.

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REFERENCES

1. Oliveira C, Simões M, Carvalho J, *et al*. Combined exercise for people with type 2 diabetes mellitus: a systematic review. *Diabetes Res Clin Pract* 2012;98:187–98.
2. Church TS, Blair SN, Cocreham S, *et al*. Effects of aerobic and resistance training on hemoglobin A1c levels in patients with type 2 diabetes: a randomized controlled trial. *JAMA* 2010;304:2253–62.
3. Hordern MD, Dunstan DW, Prins JB, *et al*. Exercise prescription for patients with type 2 diabetes and pre-diabetes: a position statement from Exercise and Sport Science Australia. *J Sci Med Sport* 2012;15:25–31.
4. Kanaley JA, Colberg SR, Corcoran MH, *et al*. Exercise/Physical Activity in Individuals with Type 2 Diabetes: A Consensus Statement from the American College of Sports Medicine. *Med Sci Sports Exerc* 2022;54:353–68.
5. Sabag A, Barr L, Armour M, *et al*. The Effect of High-intensity Interval Training vs Moderate-intensity Continuous Training on Liver Fat: A Systematic Review and Meta-Analysis. *J Clin Endocrinol Metab* 2022;107:862–81.
6. Jelleyman C, Yates T, O'Donovan G, *et al*. The effects of high-intensity interval training on glucose regulation and insulin resistance: a meta-analysis. *Obes Rev* 2015;16:942–61.
7. Rolid K, Andreassen AK, Yardley M, *et al*. High-intensity interval training and health-related quality of life in de novo heart transplant recipients - results from a randomized controlled trial. *Health Qual Life Outcomes* 2020;18:283.
8. Liu J-X, Zhu L, Li P-J, *et al*. Effectiveness of high-intensity interval training on glycemic control and cardiorespiratory fitness in patients with type 2 diabetes: a systematic review and meta-analysis. *Aging Clin Exp Res* 2019;31:575–93.
9. Williams CJ, Gurd BJ, Bonafiglia JT, *et al*. A Multi-Center Comparison of O_{2peak} Trainability Between Interval Training and Moderate Intensity Continuous Training. *Front Physiol* 2019;10:19.
10. Sultana RN, Sabag A, Keating SE, *et al*. The Effect of Low-Volume High-Intensity Interval Training on Body Composition and Cardiorespiratory Fitness: A Systematic Review and Meta-Analysis. *Sports Med* 2019;49:1687–721.
11. Sabag A, Little JP, Johnson NA. Low-volume high-intensity interval training for cardiometabolic health. *J Physiol* 2022;600:1013–26.
12. Madsen SM, Thorup AC, Overgaard K, *et al*. High Intensity Interval Training Improves Glycaemic Control and Pancreatic β Cell Function of Type 2 Diabetes Patients. *PLoS ONE* 2015;10:e0133286.
13. Cox ER, Gajanand T, Keating SE, *et al*. Effect of low-volume combined aerobic and resistance high-intensity interval training on vascular health in people with type 2 diabetes: a randomised controlled trial. *Eur J Appl Physiol* 2024;124:2819–33.
14. Dixit S, Maiya A, Shastry B. Effect of aerobic exercise on quality of life in population with diabetic peripheral neuropathy in type 2 diabetes: a single blind, randomized controlled trial. *Qual Life Res* 2014;23:1629–40.
15. Daly RM, Dunstan DW, Owen N, *et al*. Does high-intensity resistance training maintain bone mass during moderate weight loss in older overweight adults with type 2 diabetes? *Osteoporos Int* 2005;16:1703–12.
16. Dobrosielski DA, Gibbs BB, Ouyang P, *et al*. Effect of exercise on blood pressure in type 2 diabetes: a randomized controlled trial. *J Gen Intern Med* 2012;27:1453–9.
17. Morrato EH, Hill JO, Wyatt HR, *et al*. Physical activity in U.S. adults with diabetes and at risk for developing diabetes, 2003. *Diabetes Care* 2007;30:203–9.
18. Hays LM, Clark DO. Correlates of physical activity in a sample of older adults with type 2 diabetes. *Diabetes Care* 1999;22:706–12.
19. Dunstan DW, Daly RM, Owen N, *et al*. Home-based resistance training is not sufficient to maintain improved glycemic control following supervised training in older individuals with type 2 diabetes. *Diabetes Care* 2005;28:3–9.
20. Egan AM, Mahmood WAW, Fenton R, *et al*. Barriers to exercise in obese patients with type 2 diabetes. *QJM* 2013;106:635–8.
21. Liguori G. *ACSM's guidelines for exercise testing and prescription* 11 ed. Philadelphia, PA: Lippincott Williams & Wilkins, 2021.
22. Borg GA. Psychophysical bases of perceived exertion. *Med Sci Sports Exerc* 1982;14:377–81.
23. Ramos JS, Dalleck LC, Borrani F, *et al*. Low-Volume High-Intensity Interval Training Is Sufficient to Ameliorate the Severity of Metabolic Syndrome. *Metab Syndr Relat Disord* 2017;15:319–28.
24. Tjønna AE, Leinan IM, Bartnes AT, *et al*. Low- and high-volume of intensive endurance training significantly improves maximal oxygen uptake after 10-weeks of training in healthy men. *PLoS ONE* 2013;8:e65382.
25. Francois ME, Durrer C, Pistawka KJ, *et al*. Combined Interval Training and Post-exercise Nutrition in Type 2 Diabetes: A Randomized Control Trial. *Front Physiol* 2017;8:528.
26. Matsuda M, DeFronzo RA. Insulin sensitivity indices obtained from oral glucose tolerance testing: comparison with the euglycemic insulin clamp. *Diabetes Care* 1999;22:1462–70.
27. Stewart A, Marfell-Jones M. *International Society for Advancement of K. International Standards for Anthropometric Assessment*. New Zealand: International Society for the Advancement of Kinanthropometry: Lower Hutt, 2011.
28. Matthews CE, Chen KY, Freedson PS, *et al*. Amount of time spent in sedentary behaviors in the United States, 2003-2004. *Am J Epidemiol* 2008;167:875–81.
29. Troiano RP, Berrigan D, Dodd KW, *et al*. Physical activity in the United States measured by accelerometer. *Med Sci Sports Exerc* 2008;40:181–8.
30. Wang B, Ogburn EL, Rosenblum M. Analysis of covariance in randomized trials: More precision and valid confidence intervals, without model assumptions. *Biometrics* 2019;75:1391–400.
31. Armijo-Olivo S, Warren S, Magee D. Intention to treat analysis, compliance, drop-outs and how to deal with missing data in clinical research: a review. *Phys Ther Rev* 2009;14:36–49.
32. Kahan BC, Forbes AB, Doré CJ, *et al*. A re-randomisation design for clinical trials. *BMC Med Res Methodol* 2015;15:96.
33. Selvin E, Marinopoulos S, Berkenblit G, *et al*. Meta-analysis: glycosylated hemoglobin and cardiovascular disease in diabetes mellitus. *Ann Intern Med* 2004;141:421–31.
34. Zhang Y, Hu G, Yuan Z, *et al*. Glycosylated Hemoglobin in Relationship to Cardiovascular Outcomes and Death in Patients with Type 2 Diabetes: A Systematic Review and Meta-Analysis. *PLoS ONE* 2012;7:e42551.
35. Korkiakangas EE, Alahuhta MA, Laitinen JH. Barriers to regular exercise among adults at high risk or diagnosed with type 2 diabetes: a systematic review. *Health Promot Int* 2009;24:416–27.
36. Gajanand T, Keating SE, Brown WJ, *et al*. Comparing the Efficacy of Supervised and Unsupervised Exercise Training on Glycaemic Control in Type 2 Diabetes: A Systematic Review. *Curr Diabetes Rev* 2020;16:570–9.
37. Ekkekakis P, Biddle SJH. Extraordinary claims in the literature on high-intensity interval training (HIIT): IV. Is HIIT associated

with higher long-term exercise adherence? *Psychol Sport Exerc* 2023;64:102295.

38 Magalhães JP, Júdice PB, Ribeiro R, *et al*. Effectiveness of high-intensity interval training combined with resistance training versus continuous moderate-intensity training combined with resistance training in patients with type 2 diabetes: A one-year randomized controlled trial. *Diabetes Obes Metab* 2019;21:550–9.

39 Sudarsono NC, Tulaar AB, Jusman SWA, *et al*. The Effects of Combined High-Intensity Interval and Resistance Training on Glycemic Control and Oxidative Stress in T2DM. *Asian J Sports Med* 2019;10:e91841.

40 Liu Y, Ye W, Chen Q, *et al*. Resistance Exercise Intensity is Correlated with Attenuation of HbA1c and Insulin in Patients with

Type 2 Diabetes: A Systematic Review and Meta-Analysis. *Int J Environ Res Public Health* 2019;16:140.

41 Keating SE, Johnson NA, Mielke GI, *et al*. A systematic review and meta-analysis of interval training versus moderate-intensity continuous training on body adiposity. *Obes Rev* 2017;18:943–64.

42 Wormgoor SG, Dalleck LC, Zinn C, *et al*. Effects of High-Intensity Interval Training on People Living with Type 2 Diabetes: A Narrative Review. *Can J Diabetes* 2017;41:536–47.

43 Fritschi C, Park H, Richardson A, *et al*. Association Between Daily Time Spent in Sedentary Behavior and Duration of Hyperglycemia in Type 2 Diabetes. *Biol Res Nurs* 2016;18:160–6.