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ORIGINAL ARTICLE

# The effects of low-volume high-intensity interval training and circuit training on maximal oxygen uptake

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## Abstract

**Purpose** High-intensity interval training (HIIT) and circuit training (CT) are popular methods of exercise, eliciting improvements in cardiorespiratory fitness (CRF). However, direct comparisons of these two training methods are limited. We investigated the effects of HIIT and CT on CRF.

**Methods** Thirty-nine apparently healthy middle-aged participants [HIIT; mean age: 42.5 ± 12.3; $\dot{V}O_{2max}$ 31.5 ± 7.1 (ml kg$^{-1}$ min$^{-1}$); 52% males; CT; mean age: 41.2 ± 12.9; $\dot{V}O_{2max}$ 31.4 ± 6.8 (ml kg$^{-1}$ min$^{-1}$); 57% males] were randomly allocated to two sessions per week of HIIT or CT over 8 weeks. HIIT performed ten 1-min cycle-ergometry intervals at > 85% $HR_{max}$, separated by ten 1-min intervals of active recovery. The CT group performed up to 40-min of CT at 60–80% $HR_{max}$. CRF was measured using maximum oxygen uptake ($\dot{V}O_{2max}$), ventilatory anaerobic threshold ($\dot{V}O_2$ at VAT) and maximum oxygen pulse ($\dot{V}O_2$/HR).

**Results** $\dot{V}O_{2max}$ increased by 12% following HIIT (mean difference 3.9 ml kg$^{-1}$ min$^{-1}$; 95% CI: 2.8–4.9; $P < 0.001$), and 3% in CT (mean difference 1.0 ml kg$^{-1}$ min$^{-1}$; 95% CI: −0.4 to 2.0; $P = 0.060$). $\dot{V}O_2$ at VAT increased by 16% following HIIT (mean difference 2.4 ml kg$^{-1}$ min$^{-1}$; 95% CI: 1.6–3.1; $P < 0.001$) and 4% in CT (mean difference 0.7 ml kg$^{-1}$ min$^{-1}$; 95% CI: −0.1 to 1.4; $P = 0.085$). $\dot{V}O_2$/HR increased by 11% following HIIT (mean difference 1.4 ml beat$^{-1}$; 95% CI: 0.9–2.0; $P < 0.001$) and 1% after CT (mean difference 0.3 ml beat$^{-1}$; 95% CI: −0.3 to 0.8; $P = 0.318$).

**Conclusion** Our study demonstrated that HIIT led to greater improvements in CRF when compared to CT.

**Clinical trial registration** ClinicalTrials.gov Identifier: NCT03700671.

**Keywords** Cardiorespiratory fitness · Fidelity · Maximal oxygen consumption · $\dot{V}O_{2max}$ · Ventilatory anaerobic threshold · HIIT

## Abbreviations

| | |
|---|---|
| $\dot{V}O_{2max}$ | Maximal oxygen uptake |
| CPET | Cardiopulmonary exercise test |
| HIIT | High-intensity interval training |
| $HR_{max}$ | Heart rate maximum |
| MICT | Moderate-intensity continuous training |
| CRF | Cardiorespiratory fitness |
| ECG | Electrocardiogram |
| VAT | Ventilatory anaerobic threshold |
| BMI | Body mass index |
| RER | Respiratory exchange ratio |
| $\dot{V}O_2$/HR | Oxygen pulse |
| HR | Heart rate |
| ± | Standard deviation |
| CERT | Consensus on exercise reporting template |
| RPE | Rating of perceived exertion |
| ANOVA | Analysis of variance |
| 95% CI | 95% confidence intervals |
| $\eta_p^2$ | Partial eta squared |
| SV | Stroke volume |
| PPO | Peak power output |
| IQR | Interquartile range |
| AT | Anaerobic threshold |

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## Introduction

Regular exercise is well known to have a positive effect on health [1, 2]. Many of these benefits are associated with improving maximal oxygen uptake ($\dot{V}O_{2max}$) [3, 4]. Increasing $\dot{V}O_{2max}$ through exercise training may improve cardiometabolic health, quality of life and increase life-expectancy [4, 5]. Popular training methods aimed at improving $\dot{V}O_{2max}$ are circuit and high-intensity interval training (HIIT) and are routinely adopted by the general population, health and fitness professionals and researchers [6]. Circuit training (CT) is typically performed at a moderate or high intensity, over a period of 30–50 min and involves a range of aerobic, body weight and resistance exercises with minimal rest [7, 8]. Low-volume HIIT is defined as 'brief, intermittent bursts of vigorous activity, interspersed by periods of rest or low intensity exercise' [9], typically prescribed at a training intensity between 80 and 100% of heart rate maximum ($HR_{max}$) [10].

Whole-body CT and low-volume HIIT consisting of 8–12 1-min interval bouts, interspersed with a similar recovery time have been shown to improve cardiometabolic health and cardiorespiratory fitness (CRF) [8, 11–16]. Increases in $\dot{V}O_{2max}$ and the anaerobic threshold (AT) have been observed following CT; however, published studies are limited to sedentary and older populations, with further markers of CRF not fully explored [8, 17]. Comparable improvements in $\dot{V}O_{2max}$ and the AT have been shown following low-volume HIIT, with increases in maximum oxygen pulse ($\dot{V}O_2$/HR) also observed [16, 18, 19]. However, there is limited evidence directly comparing both training methods across a range of CRF markers, as such it is unknown which approach is most beneficial [20, 21].

Direct comparisons have been made investigating low-volume HIIT and moderate-intensity continuous training (MICT), which is typically 30–60 min in duration adopting the same modality of exercise [14–16]. The results demonstrate low-volume HIIT to be a time-efficient method, eliciting greater improvements in $\dot{V}O_{2max}$, although these findings are not consistently shown [22].

While HIIT and CT are feasible and effective at improving CRF, no study has directly investigated the two. Therefore, the aim of this study was to compare the effect of two weekly sessions of low-volume HIIT and CT over an 8-week period on $\dot{V}O_{2max}$ in apparently healthy middle-aged adults. We also investigated changes in other markers of CRF such as the first ventilatory anaerobic threshold ($\dot{V}O_2$ at VAT) and maximum $\dot{V}O_2$/HR. Intervention fidelity was also evaluated. We hypothesised that HIIT would elicit superior improvements in $\dot{V}O_{2max}$ and additional markers of CRF.

## Methods

### Study design

Participants were enrolled in a randomised control trial at the University of Hull to either 8 weeks of HIIT or CT (two supervised sessions per week, accompanied by an exercise physiologist). A sample size of 38 using G*Power 3.1 software was calculated based on previously published data in which the mean difference between HIIT and MICT was 3.2 ml $kg^{-1}$ $min^{-1}$ with a pooled standard deviation of 3 ml $kg^{-1}$ $min^{-1}$ [19]. Statistical significance was set at $\alpha = 0.05$ and power set to 0.95. To allow for 10% attrition 42 individuals were recruited to the study. To assess the effectiveness of the interventions as determined by $\dot{V}O_{2max}$, a maximal cardiopulmonary exercise test (CPET) to volitional exhaustion on an electronically braked cycle ergometer at baseline (visit one), and following an 8-week exercise intervention of HIIT or CT (visit two) was conducted. When attending the assessments participants were asked not to take part in any strenuous exercise 24 h prior to the appointment, to wear suitable comfortable clothing and avoid a large meal. For visit two, CPET was performed within 6 days of completing the exercise interventions. A thorough warm-up and cool down were before and after each exercise session. All were asked to maintain their habitual physical activity patterns during the intervention. Body mass index (BMI) was calculated by dividing body weight [23] by height in meters squared and was presented as kg $m^{-2}$. Resting blood pressure was measured after 15 min of rest using a sphygmomanometer (A.C. Cossor & Son Ltd, London UK) and stethoscope (3 M Healthcare, St Paul, MN). To provide a comprehensive account of the study the Consensus on Exercise Reporting Template (CERT) was consulted [24].

### Participants

Ethical approval was provided by the School of Life Sciences ethics committee at the University of Hull which was in accordance with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards. A total of 42 apparently healthy men and women between the age of 18–65 years were recruited to the study. Participant characteristics are given in Table 1. Enrolled individuals reported no medical history of cardiometabolic or limiting respiratory disease, were non-smokers, had a body mass index < 30 kg $m^{-2}$, classified as recreationally active [25] and none were taking any medication that would affect heart rate. A condition of enrolment for those over 45 years was to obtain written medical clearance from a general practitioner and undergo resting and exercise 12-lead electrocardiogram (ECG) (GE Healthcare, Chalfont St Giles, United

**Table 1** Baseline characteristics

| Variable | HIIT ($n=21$) | CT ($n=21$) |
|---|---|---|
| Males (%) | 52 | 57 |
| Age (years) | 42.5 ± 12.3 | 41.2 ± 12.9 |
| $\dot{V}O_{2max}$ (l min$^{-1}$) | 2.21 ± 0.61 | 2.38 ± 0.63 |
| $\dot{V}O_{2max}$ (ml kg$^{-1}$ min$^{-1}$) | 31.5 ± 7.1 | 31.4 ± 6.8 |
| VAT (ml kg$^{-1}$ min$^{-1}$) | 15.5 ± 2.7 | 15.6 ± 3.0 |
| BMI (kg m$^{-2}$) | 24.4 ± 2.3 | 24.9 ± 2.7 |
| Systolic blood pressure (mmHg) | 122 ± 14 | 126 ± 11 |
| Diastolic blood pressure (mmHg) | 75 ± 11 | 79 ± 9 |
| Resting HR (bpm) | 68 ± 12 | 67 ± 10 |
| RER at $\dot{V}O_{2max}$ | 1.30 ± 0.12 | 1.31 ± 0.12 |
| $HR_{max}$ (bpm) | 174 ± 12 | 174 ± 14 |
| Maximum $\dot{V}O_2$/HR (ml beat$^{-1}$) | 12.8 ± 3.7 | 13.9 ± 3.9 |
| Peak power output (W) | 191.9 ± 43.7 | 209.8 ± 55.2 |

Values are presented as mean ± SD. No significant differences between groups at baseline

*HIIT* low-volume high-intensity interval training, *CT* circuit training, $\dot{V}O_{2max}$ maximal oxygen consumption, *VAT* ventilatory anaerobic threshold, *BMI* body mass index, *HR* heart rate, *RER* respiratory exchange ratio, $HR_{max}$ maximal heart rate, $\dot{V}O_2/HR$ oxygen pulse

Kingdom). Written informed consent and a pre-exercise medical questionnaire were completed by all.

## Cardiopulmonary exercise testing

Maximal CPETs were conducted in accordance with the American Thoracic Society (ATS) and the American College of Chest Physicians (ACCP) guidelines [26]. An Oxycon pro (Jaeger, Hoechburg, Germany) breath-by-breath metabolic cart was used to collect respiratory gas exchange data. Automatic and manual calibration evaluated ambient temperature, humidity, barometric pressure and altitude. Calibration of the air flow volume was conducted using a 3 l syringe and by automatic calibration. Two-point gas calibration was also conducted to ensure accurate measures of inspired $O_2$ and expired $CO_2$ [27]. Tests were performed on a GE e-bike ergometer (GE Healthcare, Buckinghamshire, UK) using a ramp protocol [26]. The protocol consisted of a 3-min rest phase, 3 min of unloaded cycling, followed by a personalised ramp test [28] (ramp rate ranged between 15 and 30 W) with work rate continually increased every 1–3 s. Participants performed the same ramp rate pre- and post-testing. Participants were asked to pedal at a cadence of 70 rpm until they reached volitional exhaustion at a protocol duration between 8 and 12 min. Self-reported rating of perceived exertion (RPE) scores using the 6–20 scale [29] and heart rate (HR) (FT1 heart rate monitor, Polar Electro, OY, Finland) was recorded during the last 5 s of each minute of the test, at maximum exercise and during the recovery period. Together with verbal encouragement to volitional exhaustion, $\dot{V}O_{2max}$ was attained by participants achieving at least two of the following criteria: $\dot{V}O_2$ plateau as determined by a failure of $\dot{V}O_2$ increase by 150 ml min$^{-1}$ with further increases in workload analysed by breath-by-breath gas exchange data averaged over 15 s [30], respiratory exchange ratio (RER) > 1.10, achieve > 85% age predicated $HR_{max}$ and a RPE > 17 on the 6–20 Borg scale [27]. $\dot{V}O_2$ at VAT was defined using the 'V slope' method [31] and verified using ventilatory equivalents. Peak power output (PPO) (watts) and $HR_{max}$ were defined as the highest value achieved during the CPET with maximum $\dot{V}O_2$/HR determined by the ratio of $\dot{V}O_{2max}$ and $HR_{max}$.

## Training interventions

The HIIT group was asked to perform ten 1-min HIIT intervals, each followed by 1 min of active recovery (AR) (total exercise time 20 min). Resulting from the CPET, HIIT was set at > 85% $HR_{max}$ with a specific HR designated for this criterion. Active recovery was set at a load corresponding to 25–50 W. Sessions were performed on a Wattbike trainer (Wattbike Ltd, Nottingham, UK). The CT group completed a practical seven-station mixed-modality exercise circuit (cycle ergometer, rower, treadmill, sit to stand/squats, knee to elbow and leg kickback with bicep curl) at an intensity of 60–80% $HR_{max}$ (calculated from CPET). No resistance equipment was involved, only body weight. Participants initially performed 20 min of CT with duration increased by 5 min per week until the desired 40 min. Each station was occupied for 3–6 minutes depending on session duration, moving from one station to the next with minimal rest. During both interventions, HR was measured in last 5 s of each station/interval using a FT1 polar heart rate monitor (Polar Electro, OY, Finland) with each CT session timed using a stop watch (Axprod S.L, Guipuzcoa, Spain). Intensity for both interventions was adjusted throughout by the investigator to ensure an appropriate HR range and successful completion of the protocol. Participants were made aware of their HR ranges and verbal encouragement was given by the physiologist to help achieve and maintain these thresholds. Energy expenditure between HIIT and CT was not matched.

To assess the validity of the exercise interventions, participant fidelity to the desired exercise intensity was determined using cut points of > 85% $HR_{max}$ and 60–80% $HR_{max}$ for HIIT and CT, respectively, and reported using previous examples [32, 33]. These values were calculated using the participants' mean heart rate for each individual interval or station over the 16 sessions and was expressed as a percentage of $HR_{max}$ as determined by CPET at visit 1. Specific fidelity thresholds were consulted to determine low (< 50%), moderate (50–70%), and high (> 70%) compliance [34]. Adherence was determined as a percentage of completed sessions, with 14 (> 85%) being the threshold for completion.

### Statistical analysis

Statistical analysis was conducted using SPSS version 24 (IBM, New York, USA). An independent *t* test was used to identify group differences at baseline. Assumptions of normality were verified using the Shapiro–Wilk test. Skewness and kurtosis of distribution were visually examined. Non-normally distributed data were presented as median and interquartile range (IQR). A two-way (condition × time) repeated-measures analysis of variance (ANOVA) was used to compare CRF pre-and post-training. Post-hoc analysis for the main effects and interactions was assessed using a Bonferroni adjustment. Group differences were compared using independent *t* tests. Variables were displayed as mean with 95% confidence intervals (95% CI) or standard deviation (±) where specified. Partial eta squared ($\eta_p^2$) effect sizes were also calculated with 0.01, 0.06 and 0.14 representing small, medium, and large effect sizes, respectively [35].

## Results

Of the 78 CPETs, (pre and post) 95% of participants achieved a plateau in $\dot{V}O_2$ with all achieving at least two of the desired criteria for maximum effort. Three participants dropped out; one from the HIIT group and two from the CT group (work commitments and an injury unrelated to exercise). The mean training intensities for HIIT were 94 ± 4% $HR_{max}$ and 76 ± 3% $HR_{max}$ for CT. The mean exercise duration for the CT group was 32 ± 4 min ($P < 0.001$ versus HIIT) which corresponded to 60% greater training duration. The proportion of intervals/stations achieving the desired intensity criterion was 90% (IQR 10%) for the LV-HIIT group and 86% (IQR 28.5%) for CT (Fig. 1). Overall adherence for HIIT and CT was 95.2% and 90.5%, respectively, with 32 participants having 100% attendance. No adverse events occurred during the exercise sessions.

### Low-volume HIIT versus circuit training

There was a significant main effect for time for $\dot{V}O_{2max}$ (mean difference 2.4 ml kg$^{-1}$ min$^{-1}$; 95% CI: 1.7–3.2; $P < 0.001$; $\eta_p^2 = 0.554$) and interaction effect ($P < 0.001$; $\eta_p^2 = 0.302$). $\dot{V}O_{2max}$ significantly increased (Fig. 2a) in the HIIT group by 12% (mean difference 3.9 ml kg$^{-1}$ min$^{-1}$; 95% CI: 2.8–4.9; $P < 0.001$; $\eta_p^2 = 0.600$) but not in the CT group (3% increase; mean difference 1.0 ml kg$^{-1}$ min$^{-1}$; 95% CI: − 0.4 to 2.0; $P = 0.060$; $\eta_p^2 = 0.092$). HIIT significantly increased $\dot{V}O_{2max}$ to greater extent than CT (mean difference 2.9 ml kg$^{-1}$ min$^{-1}$; 95% CI: 1.4–4.3; $P < 0.001$).

There was a significant main effect for time for $\dot{V}O_2$ at VAT (mean difference 1.5 ml kg$^{-1}$ min$^{-1}$; 95% CI: 1.0–2.1; $P < 0.001$; $\eta_p^2 = 0.474$) and interaction effect ($P < 0.05$; $\eta_p^2 = 0.222$). $\dot{V}O_2$ at VAT significantly increased (Fig. 2b) by 16% after HIIT (mean difference 2.4 ml kg$^{-1}$ min$^{-1}$; 95% CI: 1.6–3.1; $P < 0.001$; $\eta_p^2 = 0.531$) with no notable changes observed in the CT group (4% increase; mean difference 0.7 ml kg$^{-1}$ min$^{-1}$; 95% CI: − 0.1 to 1.4; $P = 0.085$; $\eta_p^2 = 0.078$).

There was a significant main effect for time for maximum $\dot{V}O_2$/HR (mean difference 0.8 ml beat$^{-1}$; 95% CI: 0.5–1.2; $P < 0.001$; $\eta_p^2 = 0.342$) and interaction effect ($P < 0.05$; $\eta_p^2 = 0.189$). Maximum $\dot{V}O_2$/HR significantly increased in the HIIT group by 11% (mean difference 1.4 ml beat$^{-1}$; 95% CI: 0.9–2.0; $P < 0.001$; $\eta_p^2 = 0.428$) but not in CT (1% increase; mean difference 0.3 ml beat$^{-1}$; 95% CI: − 0.3 to 0.8; $P = 0.318$; $\eta_p^2 = 0.027$). Both groups increased PPO, HITT by 14% (mean difference 27 watts; 95% CI: 19.2–34.3; $P < 0.001$; $\eta_p^2 = 0.601$) and CT by 6% (mean difference 11.7 W; 95% CI: 4.2–19.2; $P < 0.01$; $\eta_p^2 = 0.213$). $HR_{max}$ and BMI were unaffected.

## Discussion

The present investigation has evaluated the effects of HIIT and CT in apparently healthy middle-aged adults. Our results show that HIIT performed at 94% $HR_{max}$ elicited a greater increase in $\dot{V}O_{2max}$, $\dot{V}O_2$ at VAT and $\dot{V}O_2$/HR when compared to CT (76% $HR_{max}$), despite 60% less training duration. Further, intervention fidelity was high in both interventions demonstrating excellent delivery of HIIT and CT, as well as its receipt and enactment by the participants.

Our results support previous research highlighting a greater increase in $\dot{V}O_{2max}$ following 1:1 work/rest ratio HIIT, even when performed at lower weekly doses compared to existing literature [14, 16, 36]. As such the results highlight the role of intensity as an important factor to induce CRF adaptation [9]. In contrast, previous studies and meta-analyses have shown that low-volume HIIT is not superior than MICT in improving $\dot{V}O_{2max}$, eliciting similar changes [13, 15, 22, 37, 38]. However, these findings may be explained by the heterogeneous nature of the study populations and HIIT protocols prescribed. Our results are in agreement with previous studies which indicate a total of 64 min per week of MICT may be insufficient to provoke adaptions [39]. However, previous findings have shown increases in $\dot{V}O_{2max}$ following CT when performed at higher doses [8, 20]. Thus, the trivial improvement in $\dot{V}O_{2max}$ in the CT group may be due to the small volume of CT prescribed.

The increase in $\dot{V}O_{2max}$ may be of clinical relevance given that $\dot{V}O_{2max}$ is a strong prognostic marker of

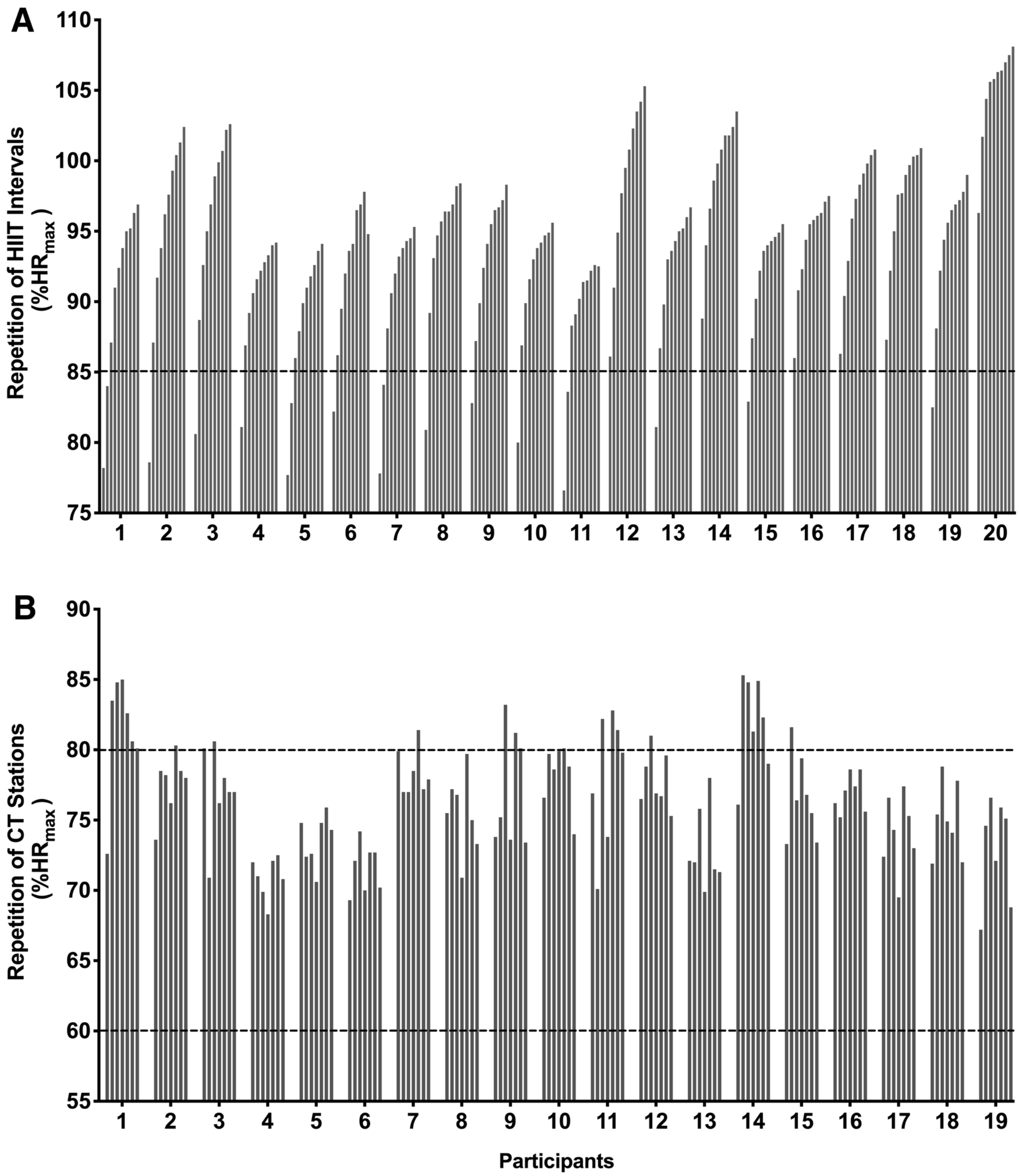


**Fig. 1** Intervention fidelity. HIIT (**a**) and CT (**b**) mean heart rates during each interval or station of the interventions. Error bars have been omitted for figure clarity

all-cause and cardiovascular mortality and improving $\dot{V}O_{2max}$ is associated with a reduction in mortality and cardiometabolic risk [3, 40]. Indeed, for every 3.5 ml kg$^{-1}$ min$^{-1}$ increase in $\dot{V}O_{2max}$ there has been shown an 8–35% reduction in all-cause mortality and cardiovascular disease risk [3, 41]. As such, our findings suggest that HIIT may be a time-efficient and efficacious approach at inducing clinical meaningful benefits when compared to other popular training methods.

The present study showed that HIIT alone, significantly increased $\dot{V}O_2$ at VAT, which is in agreement with previous studies [18]. In contrast, CT has been shown to increase the lactate threshold [17] when performed at higher doses, while a similar low-volume HIIT protocol to the current study reported improvements in $\dot{V}O_2$ at VAT following both HIIT and MICT [37]. While this was time efficient, the relative training intensities of both groups were similar. Thus, the improvements in $\dot{V}O_2$ at VAT in the present study are

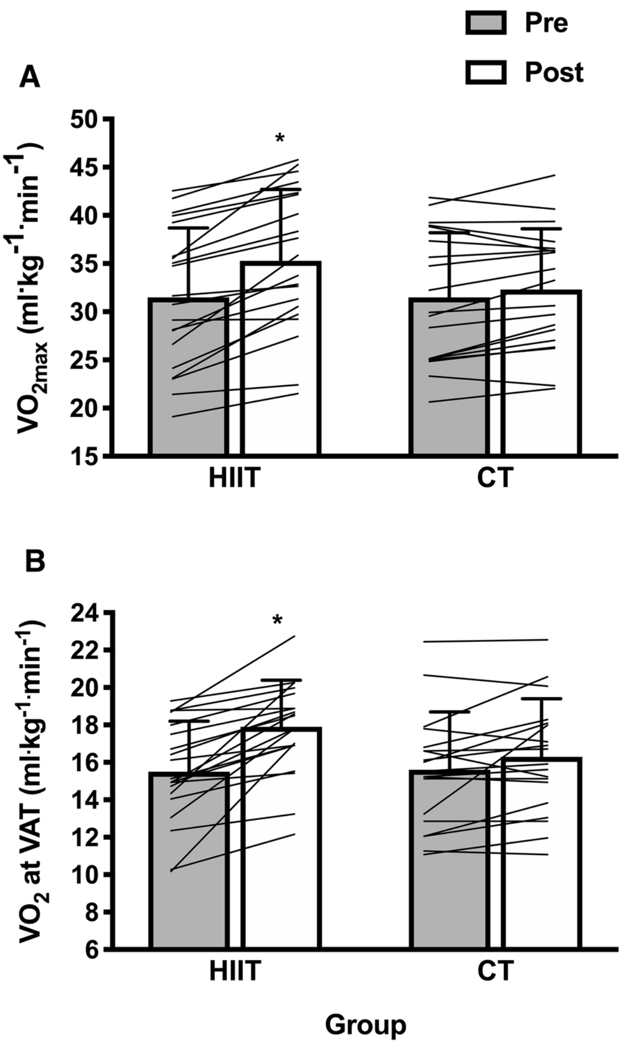


**Fig. 2** Maximal oxygen consumption ($\dot{V}O_{2max}$) (**a**) and VAT (**b**) Δ after 8 weeks of HIIT ($n=20$) and CT ($n=19$). Black lines correspond to individual responses. $\dot{V}O_2$ oxygen uptake, *VAT* ventilatory anaerobic threshold, *HIIT* low-volume high-intensity interval training, *CT* circuit training. *$P<0.001$ versus baseline

likely due to the greater stimulus provided by HIIT. As such, HIIT consisting of two weekly sessions may be sufficient at inducing metabolic adaptations in skeletal muscle, enabling higher doses of exercise to be performed before lactate accumulation, thus becoming 'physiologically efficient' [42].

In agreement with previous research [16] our results showed that HIIT increased maximum $\dot{V}O_2$/HR to a greater extent than CT, a surrogate marker of stroke volume (SV) and arteriovenous $O_2$ difference. This is in contrast to recent findings [15]. Increases in maximum $\dot{V}O_2$/HR are strongly correlated to an increase in SV [43]. While we did not directly measure SV or analyse muscle tissue our findings may support previous data which indicated low-volume HIIT to be an optimal approach for inducing cardiovascular adaptations [44]. Studies adopting a similar low-volume HIIT protocol to the current study have shown increases in mitochondrial oxidative capacity [45, 46], while lower and higher volumes of HIIT have shown to be superior or comparable to MICT at increasing cardiac output and SV [47, 48]. While this is a positive finding from our results, further studies are required to confirm the mechanisms associated with an improvement in $\dot{V}O_{2max}$ following a low-volume HIIT protocol consisting of a 1:1 work/rest ratio.

As well as reporting the attendance and mean exercise data, assessing if participants have performed the exercise training as intended is crucial when evaluating exercise interventions. Indeed, in the absence of evaluating intervention fidelity, incorrect conclusions, positive or negative, may be drawn about the effect of HIIT on a given outcome [49]. Using the pre-specified cut points for exercise intensity, 90% of the HIIT intervals and 86% of the CT stations met the criterion, indicating high fidelity to the interventions. Previous HIIT studies have reported low-to-moderate fidelity with compliance ranging between 23 and 63% [32, 34, 50]. The high levels of fidelity in the present study may be attributed to a number of factors. Firstly, the participants were healthy adults, they were made aware of their target HR each session and were given verbal encouragement to reach these targets. Secondly, the chosen HIIT protocol in the present study may be more practical and less physically demanding [51]. High-volume HIIT protocols, or low-volume HIIT protocols involving 'all out' maximal effort (sprint interval training) may cause psychobiological stress, meaning that high levels of motivation are required to complete the protocol [52].

The failure to report fidelity, and the general inadequate reporting of exercise interventions is a major concern. With exercise intensity typically reported as a ranged based or as a general mean, this has inherent limitations. The authors strongly advocate that the CERT checklist [24] be adopted for future exercise studies as it provides reporting standards that ensures quality and transparency. As a result, exercise interventions may be clearly interpreted, translated, and implemented into practice.

There are a number of limitations that should be considered regarding this study. Not all participants achieved a $\dot{V}O_2$ plateau during CPET as such secondary criteria was used which has established limitations. In addition, participants were not habituated to the CPET or the exercise sessions prior to starting the interventions. This may be relevant to novice or nervous participants in which familiarisation may be beneficial to obtain accurate measures. However, the use of strict criteria (i.e., a $\dot{V}O_2$ plateau and heart rate) was met. Furthermore, laboratory-based studies investigating HIIT and MICT typically adopt the same modality of exercise and a similar or higher volume of training. While this is relevant regarding specificity of training, our aim was to assess two different low-volume training methods.

Finally, for safety and accuracy of exercise prescription a maximal CPET was performed by all participants. However, access to specialised equipment may not always be feasible which may limit HIIT prescription in a "real world" setting. However, the present HIIT protocol appears well tolerated and safe, therefore further studies are required to evaluate the feasibility to adopt this protocol without a prior maximal CPET in healthy adults.

## Conclusion

Our study demonstrated that HIIT is superior to CT, inducing larger improvements in CRF in apparently healthy middle-aged adults. Moreover, the present data provide evidence that 40 min per week of HIIT is sufficient to elicit clinical meaningful increases in $\dot{V}O_2$. Furthermore, 64 min of CT per week appears not to provide sufficient stimulus to evoke CRF adaptation in this population. More broadly, this study provides further indication that HIIT and CT are a practical and effective approach to exercise training in healthy middle-aged adults given the high fidelity.

## Compliance with ethical standards

**Conflict of interest** The authors declare that they have no competing interests.

**Ethical approval** Ethical approval for the study was given by the School of Life Sciences ethics committee at the University of Hull.

**Informed consent** Written consent was obtained by all.



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