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SYSTEMATIC REVIEW

Optimising Exercise Prescription: A Meta-Analysis Examining the Dose Response of Exercise Duration on Cardiorespiratory Fitness Following HIIT and MICT

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Abstract

Background High-intensity interval training (HIIT) is often promoted as a time-efficient alternative to moderate-intensity continuous training (MICT) for improving cardiorespiratory fitness, yet the duration of HIIT sessions varies considerably across studies.

Objective We aimed to characterise the dose–response relationship between exercise session duration and the improvement in cardiorespiratory fitness for HIIT and MICT.

Methods A dose–response meta-analysis of randomised controlled trials comparing exercise duration in HIIT and MICT, following Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) guidelines and registered in PROSPERO (CRD42022335590). Effect sizes were calculated using a random-effects meta-analysis. The primary outcome was maximal oxygen uptake (VO_{2max}). Secondary outcomes included blood pressure, lipid profiles, glucose metabolism markers and body composition measures. A one-stage random-effects dose–response meta-analysis was performed to examine the relationship between exercise duration and adaptations. We searched PubMed and Google Scholar; eligibility criteria for selecting studies were randomised controlled trials in humans, published in English and exercise interventions lasting at least 4 weeks.

Results We identified 69 randomised controlled trials (2387 participants). High-intensity interval training elicited greater improvements in VO_{2max} than MICT (d = 0.38, 95% confidence interval 0.27–0.49, $p < 0.001$). High-intensity interval training demonstrated a non-linear dose–response relationship between exercise session duration and VO_{2max}, with 80% of maximal effect (changes in VO_{2max} = 3.45 mL/kg/min) achieved with only ~11 min/session (95% confidence interval 9.5–40.2). Moderate-intensity interval training showed a linear dose–response relationship between exercise session duration and VO_{2max}, requiring ~52 min/session to achieve 80% of the maximal observed effect (95% confidence interval 30.4–55.8). The dose–response relationship was consistent across populations. High-intensity interval training and MICT had comparable effects in improving cardiometabolic risk factors.

Conclusions High-intensity interval training demonstrated a non-linear dose response, with 80% of maximal effect on VO_{2max} in ~11 min/session, whilst MICT required four to five times longer to reach similar responses. The different types of training had comparable effects on cardiometabolic risk factors.

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Key Points

High-intensity interval training exhibited a non-linear dose–response relationship between exercise session duration and maximal oxygen uptake improvements, achieving 80% of maximal effect (changes in maximal oxygen uptake 3.45 mL/kg/min) in only ~11 min per session, with limited additional gains beyond ~23 min.

Moderate-intensity continuous training showed a linear dose–response pattern within the observed dose range, requiring ~52 min per session to achieve 80% of the maximal observed effect. Because no plateau was reached, further gains at higher doses cannot be excluded.

The dose–response kinetics for maximal oxygen uptake were conserved across the health spectrum, with no statistical difference in the dose–response curve between healthy individuals and those with elevated cardiometabolic risk.

1 Introduction

Exercise is effective in reducing the likelihood of chronic disease, in particular for managing and lowering the risk of first or secondary cardiovascular events [1, 2]. Cardiorespiratory fitness, often measured via maximal oxygen uptake ($\dot{V}O_{2\,max}$), is associated with a reduction in all-cause mortality [3] and cardiovascular disease [4]. Consequently, implementing optimal exercise training programmes in healthy individuals or those with risk factors could help reduce the burden of cardiovascular disease. Despite the well-established benefits of regular physical activity for improving cardiometabolic health, about 35% of adults in developed countries do not meet the recommended guidelines [5]. Lack of time is often cited as a significant barrier for not meeting physical activity requirements [6]. Consequently, time efficacy is a central factor in the growing popularity of high-intensity interval training (HIIT) across research and community settings [7–10].

HIIT is defined as brief (i.e. ≤4 min) high-intensity bursts of exercise interspersed with short active or passive rest periods (full rest) [11]. Previous meta-analyses have shown HIIT to improve cardiorespiratory fitness, as measured by $\dot{V}O_{2\,max}$, to a greater extent than traditional moderate-intensity continuous training (MICT) [12, 13]. However, the broad definition of HIIT means that exercise duration, intensity and rest periods can all be manipulated leading to almost endless combinations. Indeed, some HIIT protocols take nearly as long as a typical MICT session [14, 15]. Consequently, little is known about potential differences in the dose–response relationship between the time spent exercising and the benefits of HIIT versus MICT in improving cardiorespiratory fitness.

A recent meta-analysis has compared ultra-low-volume HIIT, higher-volume HIIT and MICT [16] and found no significant differences in cardiorespiratory fitness improvements between low-volume HIIT and either MICT or higher-volume HIIT, despite requiring only 14–47% of the time commitment. Intriguingly, they also found longer total session durations to be associated with smaller improvements in $\dot{V}O_{2\,max}$. These findings suggest that minimal effective doses for HIIT may be substantially lower than traditionally prescribed. However, this previous work was limited to ultra-low-volume protocols (≤ 15 min total session time). Furthermore, while participants included both healthy individuals and those with cardiometabolic conditions, potential differences in dose–response relationships between these populations were not explicitly examined.

Therefore, this study aimed to conduct a comprehensive dose–response meta-analysis comparing HIIT and MICT across all training durations, using restricted cubic spline models to characterise the shape of dose–response curves and identify the minimal effective, near-maximal and maximal effective doses, and formally test whether dose–response relationships differ between healthy individuals and those with elevated cardiometabolic risk (pre-hypertension, overweight/obesity, metabolic syndrome, pre-diabetes mellitus) using moderator analysis. Secondly, we compared the effects of HIIT and MICT on markers of cardiometabolic health. We hypothesised that HIIT and MICT would present distinct dose–response relationships. Moreover, we expected that HIIT and MICT would lead to more favourable outcomes in cardiorespiratory fitness in those with elevated cardiometabolic risk compared with a healthy population because of lower baseline fitness, though the relative dose–response curve shapes would be similar between populations. A secondary hypothesis is that the differences in cardiorespiratory fitness will result in distinct changes in markers of cardiometabolic health.

2 Methods

This article is an expansion and further analysis of the dataset published by Mattioni Maturana et al. [12], which investigated the effects of HIIT versus MICT on cardiometabolic endpoints. We expanded the dataset by conducting a new systematic search of randomised controlled trials, which was initiated in April 2021 and completed in February 2025 and these additional studies added to

the initial meta-analysis. The meta-analysis protocol was based on Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) guidelines [17], and registered in PROSPERO under the ID CRD42022335590. The search was conducted in PubMed and supported by grey literature from Google Scholar. The search criteria are available in Appendix 1 of the Electronic Supplementary Material (ESM).

The eligibility criteria included the following: (i) the study reported at least one of the following outcomes: $\dot{V}O_{2\,max}$, body mass index (BMI), body mass, percentage body fat, systolic blood pressure, diastolic blood pressure, high-density lipoprotein cholesterol, low-density lipoprotein cholesterol, triglycerides, total cholesterol, fasting insulin, fasting glucose, or homeostatic model assessment of insulin resistance; (ii) the study was a randomised controlled trial with an exercise training programme of at least 4 weeks, with participants randomly assigned to either HIIT or MICT; (iii) the group in the study involved only HIIT or MICT interventions, that is, groups in studies that involved any nutritional or resistance training intervention were not considered; (iv) we excluded studies with patients with diagnosed cardiovascular disease (including cardiac rehabilitation), insulin-dependent diabetes mellitus, or other conditions requiring ongoing medical treatment or rehabilitation. Studies including participants with cardiometabolic risk factors (obesity, metabolic syndrome, pre-diabetes, pre-hypertension) were eligible; and (v) the study was conducted in humans and published in English.

2.1 Outcomes

We considered $\dot{V}O_{2\,max}$ as the primary outcome. Maximal oxygen uptake was extracted as reported by the original authors, irrespective of whether it was designated as a true $\dot{V}O_{2\,max}$ or peak oxygen uptake. Secondary outcomes included BMI, body mass, percentage body fat, systolic blood pressure, diastolic blood pressure, high-density lipoprotein cholesterol, low-density lipoprotein cholesterol, triglycerides, total cholesterol, fasting insulin, fasting glucose and homeostatic model assessment for insulin resistance.

2.2 Participants

Healthy subjects were defined as individuals who were free from diagnosed cardiovascular or metabolic disease and did not use any medications. The cardiometabolic group included individuals who the authors reported as having metabolic syndrome, pre-hypertension, pre-diabetes and were obese/overweight.

2.3 Exercise Training Intervention

In line with international standards, we have classified HIIT as performance of repeated bouts of relatively hard work interspersed with recovery periods of easier work or rest [18]. Interventions were classified according to the characteristics of the prescribed protocol rather than the terminology used by the original authors, given the inconsistent nomenclature across the literature [12] (see Appendix 2 of the ESM). Under the HIIT umbrella, we grouped both protocols using near-maximal efforts interspersed with recovery periods (high-intensity bouts typically prescribed at >80% $\dot{V}O_{2\,max}$ or >85% maximal heart rate, HR_{max}) and those using maximal or supra-maximal "all-out" sprint efforts of short duration ($\leq$30 s) interspersed with recovery periods. This differs from our previous analysis [12], in which near-maximal interval (HIIT) and all-out sprint protocols were examined as separate modalities; here they were combined to maximise the dose range available for the dose–response models. In all included studies, the HIIT group was compared against a MICT group performing continuous exercise at a pre-defined intensity consistently lower than the HIIT comparator. By definition, MICT should be performed within the moderate-intensity domain (i.e. below the lactate/gas exchange threshold); however, the majority of studies prescribed intensity relative to maximal anchors (percentage of $\dot{V}O_{2\,max}$ or HR_{max}) rather than to a physiological threshold, which limited our ability to confirm that the prescribed intensity truly fell within the moderate domain. Across the included studies, MICT was most commonly prescribed at ~50–80% $\dot{V}O_{2\,max}$ or ~65–80% HR_{max} (Appendix 4 of the ESM), a range for which the upper end may extend into the heavy-intensity domain, particularly in less fit participants. All MICT prescriptions, as defined by the original authors, were therefore retained. Finally, although studies frequently described their HIIT and MICT groups as "matched" or "work-equated", this was rarely supported by reported training data; we therefore did not exclude studies on this basis and instead extracted the prescribed exercise dose as reported.

2.4 Bias Assessment

We assessed the risk of bias in the included studies using the most recent Cochrane risk of bias for randomised trials guidelines [19]. The bias was assessed according to five categories: (i) bias arising from the randomisation process; (ii) bias due to deviations from the intended intervention; (iii) bias due to missing outcome data; (iv) bias in the measurement of the outcome; and (v) bias in selection of the reported result.

The judgement was then made according to three categories: "low", "some concerns" or "high". The phenomenon

in which smaller studies may present different (often larger) treatment effects than larger sample sizes (i.e. small-study effects) was also assessed for publication bias control.

2.5 Meta-Analysis

We extracted the mean, standard deviation and sample size reported for each group (HIIT and MICT) pre- and post-intervention. When the standard error was reported instead of the standard deviation, we then converted it using the formula:

$$SD = SEM \times \sqrt{N},$$

where *SD* is the standard deviation, *SEM* is the standard error of the mean and *N* is the group sample size [20]. When the study reported CIs, it was then converted to standard deviation using the formula:

$$SD = \sqrt{N} \times \frac{CI_{high} - CI_{low}}{2 \times t},$$

where *SD* is standard deviation, *N* is the group sample size, CI_{high} is the upper limit of the CI, CI_{low} is the lower limit of the CI and *t* is the t distribution of *N-1* for a given *alpha* (e.g. $a = 0.05$) [20]. We then utilised both the raw mean difference (MD) as well as the standardised mean difference (i.e. Cohen's *d*) in the meta-analysis, which was calculated with the random-effects model through the DerSimonian-Laird estimator [21] for the estimation of the between-study variance. Effect sizes were considered as trivial ($d < 0.2$), small ($d = 0.2$–0.5), medium ($d = 0.5$–0.8) or large ($d > 0.8$).

2.6 Sensitivity Analysis

For each meta-analysis, a sensitivity analysis was performed to determine the robustness of the outcomes to the assumptions made while performing the analysis. The leave-one-out cross-validation method was applied, consisting of performing the meta-analysis on each subset of the included studies by leaving out one study at a time [22]. The leave-one-out cross-validation method investigates how each individual study affects the overall estimate of the meta-analysis. When the leave-one-out cross-validation showed that the mean effect was relying on a single study (i.e. outlier), the study was then removed from the overall analysis and the meta-analysis was run again. The significance level was set at $p < 0.05$.

2.7 Dose–Response Meta-Analysis

For the endpoints that there was a significant effect of HIIT over MICT (or vice-versa), we then performed a dose–response meta-analysis to investigate the dose–response relationship in each exercise training group. The dose of exercise was determined as minutes per session (min/session, within-session dose), minutes per week (min/week, weekly training volume) and total minutes (cumulative dose). We analysed all the exercise training prescriptions as follows: (i) warm-up and cool-down periods were excluded from the duration calculation as these were kept similar between HIIT and MICT protocols within studies (and thus unlikely to explain potential differences between exercise modes); (ii) all the high-intensity and recovery periods were considered; (iii) as HIIT is defined as a period of high-intensity exercise followed by a recovery period, in case after the last high-intensity bout there was no recovery period reported, we then "added" a last recovery period to the calculation; and (iv) in case the exercise duration was inconsistent throughout the intervention (e.g. training progression from once a week to three times per week throughout the weeks of training), we have considered the median as the study's exercise duration.

A one-stage random-effects dose–response meta-analysis was then performed to examine the relationship between exercise dose and the delta response induced by the exercise training programme, and to test whether this relationship differed between HIIT and MICT [23, 24]. We modelled the exercise dose, as described elsewhere [24], using the following linear mixed model:

$$y_i = X_i\beta + Z_i b_i + \epsilon_i,$$

where y_i represents the mean differences in VO_{2max} for the non-referent dose levels in study I, X_i is the study-specific design matrix containing the dose transformations and their interaction with intervention type, β represents the fixed-effect coefficients defining the shape of the dose–response curve, b_i is the random-effects coefficients allowing for between-study heterogeneity and ϵ_i represents the within-study error term. We used restricted maximum likelihood estimation to obtain the model parameters. Between-study heterogeneity was quantified using the variance partition coefficient, which represents the proportion of total variance attributable to between-study heterogeneity at each exposure level. The goodness of fit was assessed using deviance statistics and examination of de-correlated residuals.

To characterise the dose response, we conducted an effective dose (ED) analysis. We calculated the doses required to achieve 50%, 80% and 100% of the maximal observed effect (ED50, ED80 and ED100, respectively). The analysis was performed by identifying the dose that corresponded to each targeted percentage of the maximum predicted effect. For each ED value, we computed 95% CIs using bootstrapping methods. To prevent extrapolation beyond the observed dose range, the analysis was truncated at the dose corresponding to the maximum predicted effect.

2.7.1 Work-Time Sensitivity Analysis

As a sensitivity analysis quantifying the contribution of recovery to the session dose, the HIIT dose–response models (min/session, min/week, total minutes) were refitted using active high-intensity work time only (i.e. the product of the number and duration of high-intensity bouts) excluding recovery, warm-up and cool-down.

2.7.2 Moderator Analyses

We conducted random-effects meta-regressions of the HIIT versus MICT effect size on baseline $\dot{V}O_{2\,max}$ (continuous, and by age- and sex-adjusted fitness-percentile category) and on participant age. We additionally examined whether prescribed MICT intensity (anchored to $\%\dot{V}O_{2\,max}$ and, separately, $\%HR_{max}$) moderated the within-group $\dot{V}O_{2\,max}$ response.

2.8 Data Conversion

Because we were performing a meta-analysis on the difference in means between two interventions, it was necessary to have the following: (i) the difference in means (raw difference) and (ii) the standard deviation of the difference between pre- and post-intervention. The raw mean difference was calculated as:

$$M_{diff} = M_{post} - M_{pre},$$

where M_{diff} is the raw mean difference, M_{post} is the reported mean post-intervention and M_{pre} is the reported mean pre-intervention. However, more steps were required for calculating the standard deviation of the difference between pre- and post-intervention. It is necessary to have the Pearson correlation coefficient (r) between the pre- and post-intervention values for each study [25, 26]. As this is rarely reported in exercise training studies, an r value of *0.85* was chosen, and a sensitivity analysis was performed with $r = 0.80$, $r = 0.85$ and $r = 0.90$, as previously suggested [27]. Once the r coefficient was defined, the standard deviation of the difference in means was calculated as:

$$SD_{diff} = \sqrt{SD_{pre}^2 + SD_{post}^2 - 2 \times r \times SD_{pre} \times SD_{post}},$$

where SD_{diff} was the standard deviation of the difference in means, SD_{pre} was the standard deviation from pre-intervention, SD_{post} was the standard deviation from post-intervention and N was the sample size of the intervention group. For performing the meta-analysis using raw differences, we converted each endpoint to a common unit according to the *American Medical Association Manual of Style* [27]. High-density lipoprotein cholesterol, low-density lipoprotein cholesterol and total cholesterol were converted from mg/dL to mmol/L according to the formula:

$$\frac{mg/dL}{38.6},$$

and triglycerides were converted from mg/dL to mmol/L according to the formula:

$$\frac{mg/dL}{88.5}.$$

Fasting glucose was converted from mg/dL to mmol/L according to the formula:

$$\frac{mg/dL}{18.018018}.$$

Fasting insulin was converted from uIU/mL to pmol/L according to the formula:

$$uIU/mL \times 6.945.$$

All data analyses and visualisations were performed in R Version 4.4.2 [28] with the packages tidyverse [29], meta [30], metafor [31], dosresmeta [32], robvis [33] and metabolic [12].

3 Results

Figure 1 displays the flow diagram of study selection. Two reviewers (NHAZ and EAD) independently screened the titles and abstracts of the 4085 articles that were searched and retrieved 577 eligible articles for a full-text assessment; an additional 23 studies were identified through Google Scholar and the reference lists of relevant reviews. After applying the eligibility criteria, 69 articles were included in this study [8, 34–101]. There were 2387 participants in the articles examined (see Appendix 5 of the ESM). In total, HIIT had 1199 participants and MICT had 1188 participants. The mean ± standard deviation sample size for all groups was 29 ± 17 participants. The men ratio (i.e. total number of male individuals divided by sample size) was 55 ± 36%. The session duration (excluding warm-up and cool-down) was 25.3 ± 11.6 min for HIIT and 43.2 ± 11.8 min for MICT. The duration of exercise training per week was 74.4 ± 35.4 min for HIIT, and 130 ± 36 min for MICT. Total minutes was 716 ± 469 min for HIIT and 1306 ± 589 min for MICT. The average exercise training intervention was 10 ± 6 weeks across the included studies. The distribution of exercise dose metrics is displayed in Fig. 2. The high-intensity bouts of HIIT were most often prescribed at 80–95% HR_{max} (or 75–170% $\dot{V}O_{2\,max}$), whereas MICT was prescribed at 65–80% HR_{max} (or 50–80% $\dot{V}O_{2\,max}$); the full

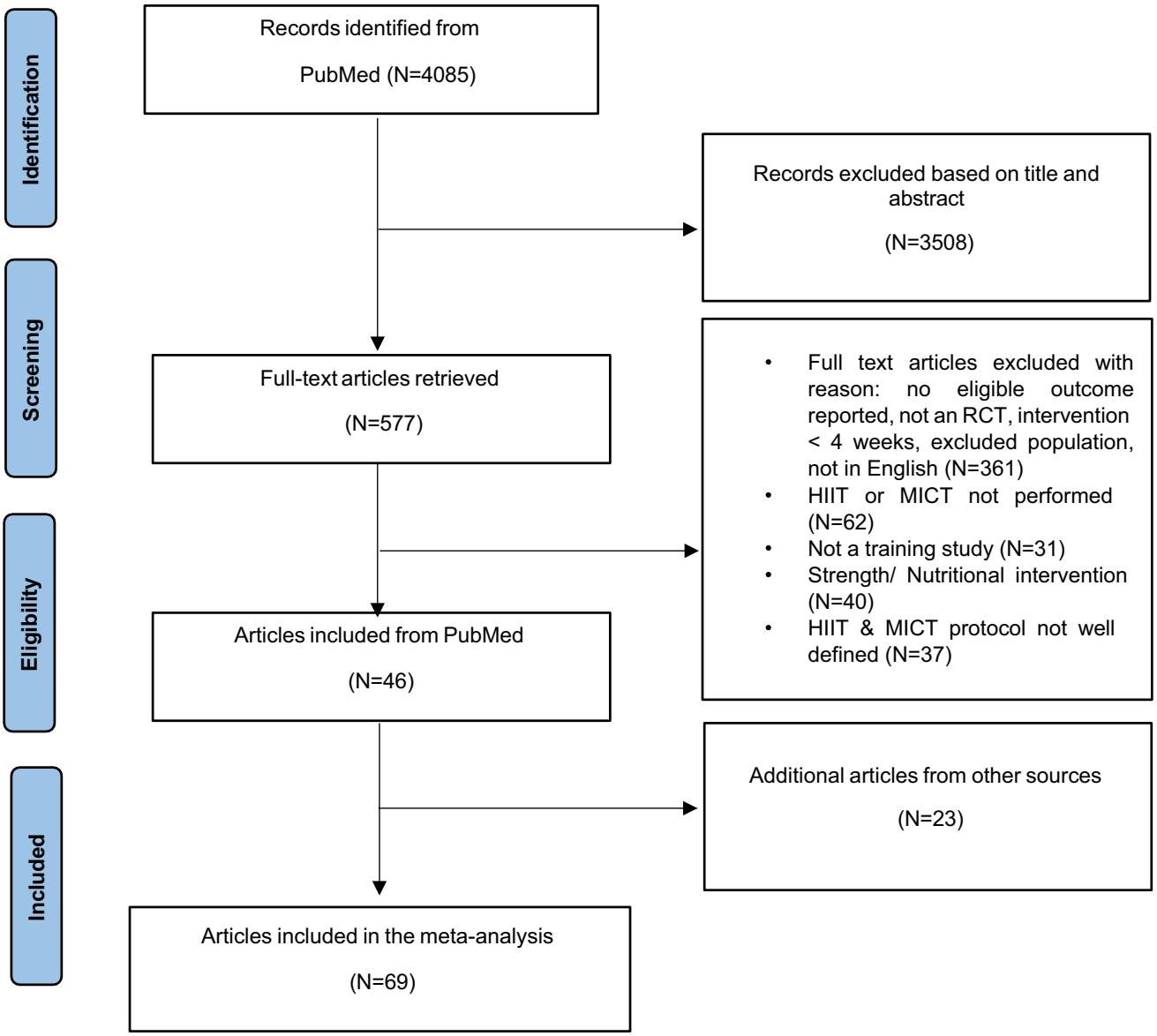

Fig. 1 Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) flow diagram illustrating the study selection process. Records were identified through a PubMed database search (N = 4085) and supplemented by studies from other sources (reference lists of relevant reviews and Google Scholar, N = 23). Following title and abstract screening (N = 3508 excluded) and a full-text assessment, 46 studies from the database search and 23 from other sources met the eligibility criteria, yielding 69 studies included in the final meta-analysis. *HIIT* high-intensity interval training, *MICT* moderate-intensity continuous training, *RCT* randomised controlled trial

set of anchors used (heart rate, oxygen uptake, threshold and power output based) is presented in Appendix 4 of the ESM. Additionally, the distribution of prescribed intensities based on anchors are summarised in 10% bins in Appendix 6 of the ESM. The total sessions during the intervention were 2382 sessions for HIIT and 2532 sessions for MICT. The compliance (i.e. adherence to the number of prescribed exercise sessions) with the exercise training was 89.4 ± 9.4% for HIIT and 89.1 ± 10.5% for MICT.

Appendix 3 of the ESM displays the overall risk of bias of the included studies using the Cochrane bias assessment [20]. This revealed that 59 out of the 69 studies presented a "low" risk of bias, and the remaining ten studies presented "some concerns" in the bias related to the randomisation process (domain 1). In the bias related to deviations from the intended intervention (domain 2), 46 studies presented a "low" bias, and 23 studies presented "some concerns". Regarding bias related to missing outcome data (domain 3), and measurement of the outcome (domain 4), all the included studies presented a "low" risk of bias. Finally, for the reported result (domain 5), 65 studies presented a "low" risk of bias, and the remaining 4 presented "some concerns".

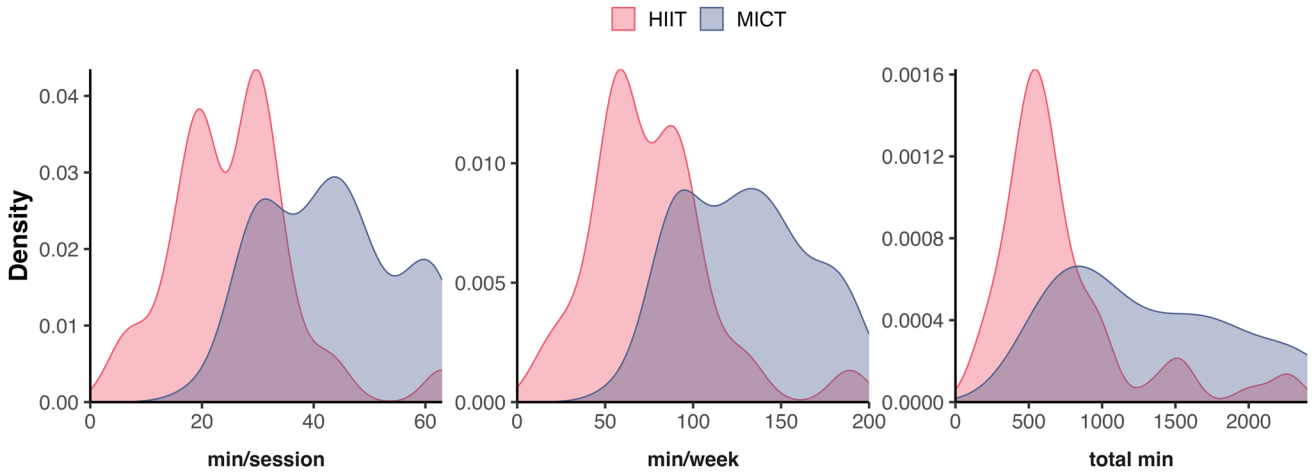

Fig. 2 Distribution of exercise doses across training interventions and dose metrics. Probability density distributions showing the range and frequency of exercise doses examined in included studies for high-intensity interval training (HIIT, *red*) and moderate-intensity continuous training (MICT, *blue*). Three dose metrics are presented: min/session (within-session exercise time), min/week (session duration × weekly frequency) and total minutes (weekly dose × intervention duration in weeks). Each panel shows kernel density estimates with the height of the curve representing the relative frequency of studies at each dose level. High-intensity interval training studies predominantly employed lower doses with distributions skewed toward shorter durations, while MICT studies showed more uniform distributions across higher dose ranges. The *shaded regions* represent the probability density, with a greater overlap between interventions observed for total program minutes compared with per-session or weekly doses

3.1 Dose–Response Meta-Analysis for Cardiorespiratory Fitness ($\dot{V}O_{2\,max}$)

Within-group analyses (i.e. pre-post training for HIIT or MICT only) indicated that both HIIT (MD = 4.36 ± 0.29 mL/kg/min, d = 0.83 ± 0.07, $p < 0.001$) and MICT presented a significant increase in $\dot{V}O_{2\,max}$ (MD = 2.59 ± 0.27 mL/kg/min, $d = 0.48 \pm 0.06$, $p < 0.001$). Between-group analyses (i.e. HIIT vs MICT) indicated a significantly greater effect for HIIT over MICT (MD = 1.20 mL/kg/min 95% CI 0.83–1.57, $d = 0.38$ 95% CI 0.27–0.49, $p < 0.001$); see Fig. 3 for more details.

As a significant difference was found between HIIT and MICT, we performed a dose–response meta-analysis on $\dot{V}O_{2\,max}$, with the exercise dose defined as min/session, min/week and total minutes. High-intensity interval training demonstrated a significant non-linear dose–response relationship (second spline term = − 2.643, $p < 0.001$), while MICT showed a linear pattern (combined second spline term = 0.149); see Fig. 4 for graphical representation. Predicted maximal effects varied substantially by dose metric: for HIIT, the maximal predicted improvement in $\dot{V}O_{2\,max}$ was 4.31 mL/kg/min when modelled by min/session, 4.32 mL/kg/min for min/week and 6.64 mL/kg/min for total minutes. For MICT, maximal effects were 4.13, 3.27 and 3.70 mL/kg/min, respectively. These differences reflect variation in the maximum observed doses across studies and the distinct aspect of training stimulus captured by each dose metric. To achieve 80% of maximal effect (ED80), HIIT required only 11.4 min/session compared with 52.4 min/session for MICT ($p < 0.001$), representing a 4.6-fold time saving. At ED50 (50% of the maximal effect), HIIT required 5.8 min/session versus 36.0 min/session for MICT (6.2-fold difference, $p < 0.001$). For the maximal observed effect (ED100), HIIT required 23.2 min/session compared with 63.0 min/session for MICT (2.7-fold difference, $p < 0.001$); see Table 1 for a summary of these estimations, including all the other dose metrics.

When the HIIT dose was expressed as active high-intensity work time rather than total session time, 80% of the maximal $\dot{V}O_{2\,max}$ gain was attained with approximately 5 min of work per session (ED80 5.2 min/session [95% CI 4.5–7.5]) and approximately 15 min of work per week (ED80 14.7 min/week [95% CI 12.8–19.0]), with the response plateauing at approximately 10 min of work per session. Across HIIT interventions, recovery comprised a median of 50% of each session (range 17–90%) and the per-interval work-to-rest ratio ranged from 1:9 to 5:1 (median 1:1; Appendix 7 of the ESM), underscoring that an identical session duration can represent markedly different amounts of high-intensity work.

Prescribed MICT intensity did not significantly moderate the within-group $\dot{V}O_{2\,max}$ response ($\beta = -0.02$ mL·kg/min/per $\%\dot{V}O_{2\,max}$, $p = 0.80$; $\beta = -0.11$ per $\%HR_{max}$, $p = 0.25$). Baseline $\dot{V}O_{2\,max}$ likewise did not moderate the HIIT versus MICT effect, whether modelled continuously ($\beta = -0.003$ per mL·kg/min, $p = 0.64$) or by fitness-percentile category (< 30th vs ≥30th: $d = 0.36$ vs 0.40, p

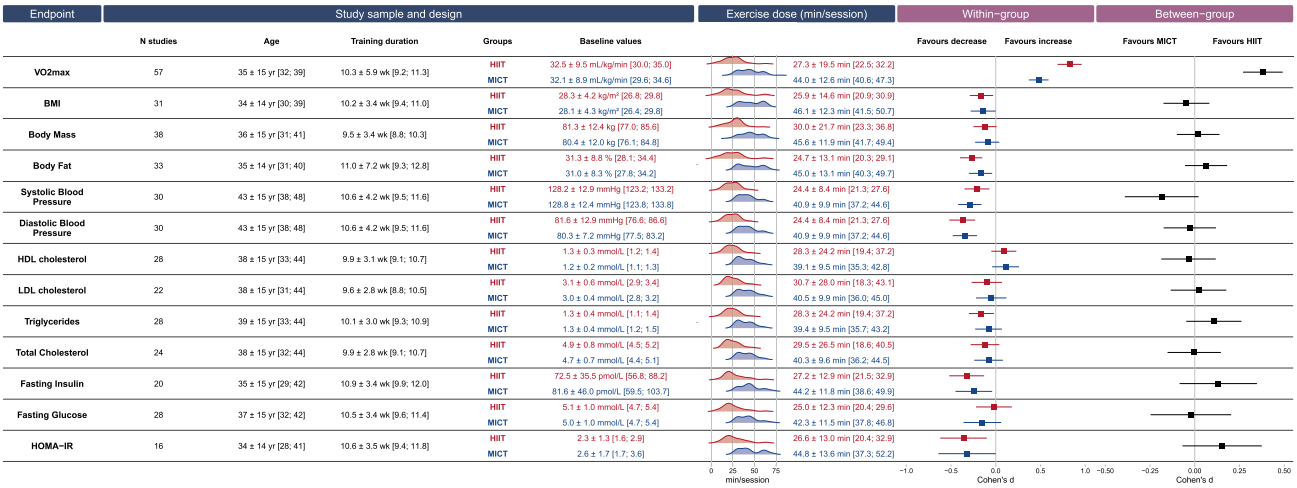

Fig. 3 Study characteristics and meta-analysis results for primary and secondary outcomes. Summary of included studies and pooled effect estimates for high-intensity interval training (HIIT) and moderate-intensity continuous training (MICT) interventions. Study characteristics include number of studies, participant age, training duration, group allocation and baseline values (mean ± standard deviation [95% confidence interval]). The within-group meta-analysis shows pre-post changes for each exercise modality, with forest plots indicating direction of effect (favours decrease vs favours increase). Between-group meta-analysis compares HIIT versus MICT effects, with forest plots showing comparative effectiveness (favours MICT vs favours HIIT). Effect estimates are presented as mean differences with 95% confidence intervals. Statistical significance is indicated by confidence intervals not crossing the line of no effect. *BMI* body mass index, *HDL* high-density lipoprotein, *HIIT* high-intensity interval training, *HOMA-IR* homeostatic model assessment for insulin resistance, *LDL* low-density lipoprotein, *MICT* moderate-intensity continuous training, *min* minutes, $\dot{V}O_{2\,max}$ maximal oxygen uptake, *wk* week, *yr* years

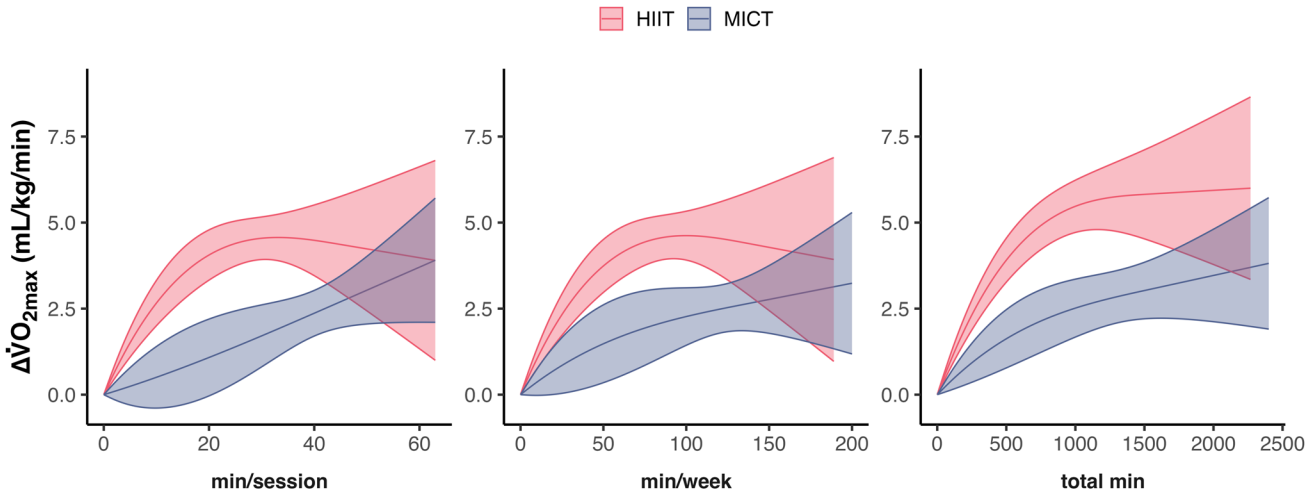

Fig. 4 Dose–response curves for maximal oxygen uptake ($\dot{V}O_{2\,max}$) improvements by exercise modality and dose metrics. Dose–response relationships between exercise dose (min/session, min/week and total minutes) and predicted changes in $\dot{V}O_{2\,max}$ ($\Delta\dot{V}O_{2\,max}$) for high-intensity interval training (HIIT, *red*) and moderate-intensity continuous training (MICT, *blue*). Curves were derived from a one-stage random effects dose–response meta-analysis using restricted maximum likelihood estimation. *Shaded areas* represent 95% confidence intervals around the predicted dose–response curves. Exercise dose includes high-intensity and recovery periods but excludes warm-up and cool-down phases

= 0.73), and within-group gains were unrelated to baseline in both groups (HIIT $\beta = 0.016$, $p = 0.61$; MICT $\beta = 0.014$, $p = 0.66$). Participant age did not significantly moderate the effect (continuous $\beta = 0.005$ per year, $p = 0.19$; categorical $p = 0.63$), although the continuous estimate trended toward a larger HIIT advantage at older ages.

Table 1 ED analysis for maximal oxygen uptake improvements comparing HIIT and MICT across three dose metrics

Dose metric	% of maximal effect	HIIT		MICT		MICT/HIIT ratio (fold difference)
		Dose	Response (mL/kg/min)	Dose	Response (mL/kg/min)	
Min/session						
	50%	5.8 [4.9–14.4]	2.16	36.0 [14.8–44.5]	2.06	6.2
	80%	11.4 [9.5–40.2]	3.45	52.4 [30.4–55.8]	3.30	4.6
	100%	23.2 [18.6–63.0]	4.31	63.0 [63.0–63.0][a]	4.13	2.7
Min/week						
	50%	16.9 [14.4–38.3]	2.16	63.5 [27.0–125.0]	1.64	3.8
	80%	33.1 [28.0–112.0]	3.46	133.0 [50.8–170.0]	2.62	4.0
	100%	66.7 [54.4–189.0]	4.32	200.0 [97.3–200.0][a]	3.27	3.0
Total minutes						
	50%	332 [180–660]	3.32	667 [306–1306]	1.85	2.0
	80%	1170 [358–1617]	5.31	1498 [589–1964]	2.96	1.3
	100%	2268 [776–2268][a]	6.64	2400 [1156–2400][a]	3.70	1.1

Values represent the exercise dose required to achieve ED50, ED80 and ED100. Response values indicate the predicted improvement in maximal oxygen uptake (mL/kg/min) at each effective dose level. Values in brackets represent 95% confidence intervals calculated using parametric bootstrapping (10,000 iterations). The MICT/HIIT ratio quantifies time efficiency, with values >1 indicating HIIT requires less time than MICT to achieve equivalent effects. All between-intervention differences were statistically significant ($p < 0.001$)

ED effective dose, *ED50* 50% of the maximal predicted effect, *ED80* 80% of the maximal predicted effect, *ED100* 100% of the maximal predicted effect, *HIIT* high-intensity interval training, *MICT* moderate-intensity continuous training, *min* minutes

[a]Upper confidence bound equals maximum observed dose, indicating dose–response curve did not plateau; estimate represents lower bound

3.2 Dose Response for Cardiorespiratory Fitness: Healthy Versus Cardiometabolic Risk

Formal statistical testing using Wald tests revealed no significant differences in dose–response curves between healthy individuals and those with elevated cardiometabolic risk for both HIIT ($\chi^2 = 1.87$, $p = 0.39$) and MICT ($\chi^2 = 3.73$, $p = 0.16$). Despite the lack of statistical significance, descriptive analyses showed some variation in point estimates. For HIIT, healthy individuals showed a stronger non-linear response pattern (second spline term = −5.44, $p < 0.001$) compared with those with an elevated cardiometabolic risk (second spline term = −0.76, $p = 0.025$). Point estimates for ED80 were 10.1 min/session [95% CI 8.9–16.7] in healthy individuals versus 12.9 min/session [95% CI 9.6–49.2] in those with cardiometabolic risk, though the wide overlapping CIs precluded definitive conclusions. Similarly, for MICT, point estimates for ED80 were 26.2 min/session [95% CI 16.4–54.2] in healthy individuals versus 53.7 min/session [95% CI 24.9–56.2] in those with cardiometabolic risk (Wald test, $p = 0.16$).

Substantial between-study heterogeneity was observed across all analyses, with the strongest heterogeneity in the elevated cardio-metabolic risk group (HIIT: between-study SD = 0.18 for first spline term, 1.01 for second spline term; MICT: SD = 0.01 for first spline term, 0.04 for second spline term). This heterogeneity likely reflects the diverse nature of cardiometabolic conditions included (obesity, metabolic syndrome, pre-diabetes, pre-hypertension) and variable baseline fitness levels, limiting statistical power to detect population-specific differences. Given the non-significant formal tests and wide CIs, we interpret these subgroup results as exploratory and focus our primary conclusions on the overall dose–response patterns that combine both populations.

3.3 Dose Response for Cardiometabolic Risk Factors

Within-group analyses revealed that HIIT produced significant improvements in BMI (MD = −0.46 ± 0.18 kg·m^{-2}, $d = -0.16 \pm 0.07$, $p = 0.018$), body fat (MD = −1.52 ± 0.26%, $d = -0.27 \pm 0.06$, $p < 0.001$), systolic blood pressure (MD = −2.31 ± 0.83 mmHg, $d = -0.21 \pm 0.07$, $p = 0.004$), diastolic blood pressure (MD = −2.93 ± 0.51 mmHg, $d = -0.37 \pm 0.07$, $p < 0.001$), triglycerides (MD = −0.09 ± 0.04 mmol/L, $d = -0.16 \pm 0.07$, $p = 0.028$) and fasting insulin (MD = −8.34 ± 1.85 pmol/L, $d = -0.32 \pm 0.10$, $p = 0.001$). Moderate-intensity continuous training produced significant improvements in body fat (MD = −1.04 ± 0.31%, $d = -0.17 \pm 0.07$, $p = 0.010$), systolic blood pressure (MD = −3.44 ± 0.78 mmHg, $d = -0.29 \pm 0.07$, $p < 0.001$), diastolic blood pressure (MD = −2.85 ± 0.50 mmHg, $d = -0.34 \pm 0.07$, $p < 0.001$) and fasting insulin (MD = −6.43 ± 2.62 pmol/L, $d = -0.24 \pm 0.11$, $p = 0.022$), but not BMI (MD = −0.44 ± 0.21, $d = -0.14 \pm 0.07$, $p = 0.055$) or triglycerides (MD = −0.03 ± 0.04 mmol/L, $d = -0.08 \pm 0.08$,

$p = 0.295$). No between-group (HIIT vs MICT) differences were observed for the effect of the exercise training intervention on BMI, body fat, systolic blood pressure, diastolic blood pressure, triglycerides and fasting insulin (Fig. 3). Accordingly, no dose-response analyses on these outcomes were performed.

4 Discussion

We found that both HIIT and MICT were effective in improving cardiorespiratory fitness ($\dot{V}O_{2\,max}$), with HIIT showing superior effects compared with MICT ($d = 0.38$, $p < 0.001$). High-intensity interval training achieved 80% of its maximal effect (i.e. $\Delta\dot{V}O_{2\,max} = 3.45$ mL/kg/min) with ~11 min per session, following a non-linear kinetics. In contrast, MICT exhibited a linear volume-dependent relationship, requiring ~52 min to achieve comparable effects — a nearly five-fold greater time commitment compared with HIIT. The HIIT versus MICT differences were robust across prescribed intensity, baseline fitness, age and population, supporting the generalisability of the observed dose response. Despite the distinct dose–response curves of HIIT and MICT on cardiorespiratory fitness, we observed no significant differences between exercise types in improvements in cardiometabolic endpoints. This suggests that while HIIT may be more beneficial in improving cardiorespiratory fitness, both modes of exercise resulted in improvements in cardiovascular disease risk factors.

Our findings provide evidence for the time-efficiency advantage of HIIT, with near-maximal $\dot{V}O_{2\,max}$ adaptations achieved in substantially less time than required for MICT. Previous work suggests that brief HIIT protocols of approximately 20 min (i.e. 10×1 min intervals with 1-min recovery periods) of intense exercise can improve aerobic capacity, skeletal muscle oxidative capacity and markers of cardiovascular risk after only a few weeks in both healthy individuals and those with cardiometabolic disorders [14]. Equally, a previous meta-analysis that included 18 randomised controlled trials confirmed that short-term low-volume HIIT is as effective as long-term high-volume HIIT in improving cardiorespiratory fitness [102]. Our dose–response meta-analysis goes well beyond these findings by defining the "point of diminishing returns". The non-linear plateau observed at ~20–30 min/session implies that extending HIIT beyond this duration provides minimal additional stimulus for improving $\dot{V}O_{2\,max}$. Conversely, the linear response of MICT confirms that moderate-intensity adaptations rely on the accumulation of volume, necessitating the traditional 45–60 min/session prescription to match the efficiency of HIIT [5]. However, future work is needed to further examine the individualised components of exercise duration, intensity and overall exercise dose, as these may affect the duration of exercise bouts to achieve maximum effect sizes.

Contradicting our hypothesis, we did not find a statistical difference in the dose–response curves between healthy individuals and those with cardiometabolic risk in $\dot{V}O_{2\,max}$ when comparing the same intervention between populations. The interaction term for population status was non-significant, indicating that the shape of the adaptation curve is remarkably comparable across the health spectrum. This finding is evidence that the primary driver of the adaptive curve is the nature of the stimulus (i.e. exercise intensity), and not the nature of the recipient (i.e. health status). From a clinical perspective, this is a highly encouraging finding: it implies that the time-efficient benefits of HIIT are not reserved for healthy and fit individuals only, but are equally accessible to patients with cardiometabolic risk factors. Both populations ultimately achieved comparable magnitudes of improvement through both training modalities, suggesting that both HIIT and MICT remain effective training strategies when appropriately prescribed.

In contrast to the distinct effects of HIIT and MICT on cardiorespiratory fitness, we found comparable effects of both types of exercise training on various cardiometabolic risk factors. Although previous studies, including meta-analyses, have also confirmed comparable effects of HIIT and MICT on selected cardiovascular risk factors [103, 104], a unique element in our meta-analysis was the ability to link changes in cardiorespiratory fitness to adaptations in cardiometabolic risk factors. The dissociation between cardiorespiratory and cardiometabolic adaptations may stem from the fact that $\dot{V}O_{2\,max}$ is centrally limited by cardiac output [105], which appears particularly responsive to the high cardiac preload and the elevated peak cardiac output and wall shear stress imposed during high-intensity efforts [106], while the repeated exposure to elevated vascular shear stress contributes to peripheral and endothelial adaptation [107]. Metabolic adaptations are largely driven by peripheral adaptations such as glycogen depletion and total caloric expenditure, which can be achieved via either high intensity (HIIT) or long duration (MICT) [108]. Whilst future studies are warranted to better understand this relation, our observations suggest that the choice between modalities should be guided not only by physiological adaptation but also by individual preferences and practical considerations [109, 110].

Although exercise enjoyment was not an outcome of this meta-analysis, it is an important determinant of long-term adherence. The evidence is mixed and appears to depend on exercise intensity and protocol structure. Acute affective responses during higher-intensity bouts tend to be less positive than during moderate-intensity exercise, but in interval protocols this in-task decline is typically followed by a pronounced positive affective rebound, with post-exercise affect returning to or rising above pre-exercise levels — unlike

continuous exercise of equivalent intensity, where it may remain depressed [110]. In a cohort of inactive adults, both measured and perceived fitness improved with HIIT and MICT, with a tendency to favour HIIT but with substantial inter-individual variability [109]. These observations reinforce that the work-to-rest structure of HIIT (see Appendix 7 of the ESM) shapes not only its physiological stimulus but also its perceived tolerability, and that modality choice should account for individual preference alongside physiological efficiency.

We classified interventions as HIIT or MICT according to the definitions used in the original studies; however, recent efforts to standardise exercise-intensity terminology highlight that these labels map imperfectly onto the underlying physiological intensity domains [18, 111]. Within the bioenergetic framework, the moderate-intensity domain is below the first metabolic threshold (approximated by the gas exchange or lactate threshold), the heavy domain lies between the first and second thresholds, and the severe domain extends above the second threshold up to $\dot{V}O_{2\,max}$ [112]. Notably, MICT as commonly prescribed may frequently fall within the heavy domain rather than the moderate domain, whereas interval-based protocols typically fall within the severe domain (or, for all-out sprint efforts, the extreme domain) [111]. Because the included studies almost universally anchored intensity to percentages of maximal references (% $\dot{V}O_{2\,max}$ or % HR_{max}) rather than to physiological thresholds, the precise domain of each prescription cannot be confirmed; the same relative intensity is known to elicit markedly different metabolic responses across individuals [60, 113], with a several-fold range in muscle lactate reported at a fixed 70% $\dot{V}O_{2\,max}$ and roughly half of individuals exercising above and half below their first metabolic threshold at 80% HR_{max} [111]. This intensity heterogeneity, and the likelihood that a proportion of MICT was in fact performed within the heavy domain, may attenuate the apparent contrast between modalities and contribute to the volume-dependent linear dose response we observed for MICT. Future dose–response work should, where feasible, anchor intensity to physiological thresholds to allow clear classification across the moderate, heavy and severe domains.

Several caveats qualify the interpretation of these duration estimates. They are population-level averages derived by pooling protocols that varied substantially in prescribed intensity and work-to-rest structure (Appendices 6 and 7 of the ESM). Because session duration includes recovery, a given nominal duration can represent very different amounts of high-intensity work: expressing the HIIT dose as active work time alone shifted the ED80 from 11 to 5 min/session (Table 2). Moreover, the HIIT and MICT labels each span more than one physiological intensity domain. Although the dose response was statistically conserved across population, baseline fitness and age, we did not perform a fully intensity- or fitness-stratified analysis. The estimated durations should therefore be regarded as the average minimal effective and near-maximal doses for the conventional modality categories, rather than as universally optimal prescriptions applicable to every population or individual.

Table 2 Sensitivity analysis, high-intensity interval training effective doses for maximal oxygen uptake expressed as total session time (work + recovery; reproduced from Table 1) vs active high-intensity work time (excluding recovery, warm-up and cool-down)

Dose metric	% of maximal effect	Total session time	Active work time
min/session			
	50%	5.8 [4.9–14.4]	2.6 [2.3–3.6]
	80%	11.4 [9.5–40.2]	5.2 [4.5–7.5]
	100%	23.2 [18.6–63.0]	10.2 [8.7–36.0]
min/week			
	50%	16.9 [14.4–38.3]	7.5 [6.6–9.5]
	80%	33.1 [28.0–112.0]	14.7 [12.8–19.0]
	100%	66.7 [54.4–189.0]	28.8 [24.7–41.1]
Total minutes[a]			
	50%	332 [180–660]	96 [83–214]
	80%	1170 [358–1617]	193 [164–773]
	100%	2268 [776–2268][b]	422 [329–1296]

Values are min [95% confidence interval]

min minutes

[a]For the cumulative (total minutes) metric, the dose–response curve is nearly flat at high doses, so the dose corresponding to a given fraction of the maximal effect is estimated with low precision (wide confidence intervals, as in Table 1). The active-work proportion for this metric consequently differs from the within-session and weekly metrics and should not be over-interpreted

[b]Upper confidence bound equals the maximum observed dose (curve did not plateau); the estimate represents a lower bound

From a practical standpoint, these findings do not imply that HIIT should be performed to the exclusion of other modalities. Because HIIT and MICT produced equivalent improvements in cardiometabolic risk factors despite their contrasting time requirements for $\dot{V}O_{2\,max}$, the two modalities are better viewed as complementary than as competing. A flexible periodised approach, in which the balance of HIIT and MICT is adjusted to time availability and individual preference, and varied across the training cycle, may therefore be more sustainable than a single fixed prescription. When time is limited, the steep early portion of the HIIT dose response (with the majority of the $\dot{V}O_{2\,max}$ gain attainable from only a few minutes of high-intensity work per session) offers an efficient stimulus; when time is less constrained, the accumulation of moderate-intensity volume provides a lower-strain route to comparable adaptation. There is also preliminary evidence that the sequence in which modalities are combined can influence

both physiological and perceived fitness outcomes [109], suggesting that how HIIT and MICT are periodised, and not only their relative volumes, may be worth considering. These considerations reinforce an individualised approach to exercise prescription rather than a uniform recommendation of any single modality.

4.1 Limitations

Some limitations should be discussed. Although we compared groups with versus without cardiometabolic risk, we were unable to control for subject characteristics. This correction should be considered for future studies. We were also unable to resolve the dose response by further fitness stratification (recreationally trained, well trained, elite) because the included samples were predominantly sedentary to a low fitness level, leaving under-represented the well-trained end of the spectrum — where a reduced trainability ("ceiling") might be expected; however, neither baseline $\dot{V}O_{2\,max}$ nor age moderated the effect, indicating the dose response is broadly generalisable across the represented range. Additionally, our primary outcome relied on $\dot{V}O_{2\,max}$/peak oxygen uptake values as reported by the original studies, the majority of which did not document verification of a true maximum via a VO2 plateau or supramaximal verification bout [114]. However, the usefulness of such verification trials is highly debatable, as recent evidence suggests that distinct $\dot{V}O_2$ plateaus are often absent and that verification phases add little to no value in confirming true $\dot{V}O_{2\,max}$ [115–117]. Because each trial assessed both groups under identical testing conditions and we analysed the between-group contrast within a random-effects framework, this non-specific measurement variability is largely shared between modalities and is unlikely to systematically bias the HIIT versus MICT comparison. We were unable to correct for the time between the last exercise session and post-training evaluations, which is relevant as single exercise bouts can have long-lasting effects due to acute plasma volume shifts. Examining dose–response relationships ideally requires within-subject comparisons of different 'doses'. To date, only a few studies implemented repeated measures throughout an exercise intervention (i.e. only pre- and post-training measures are usually performed) or within-subject comparisons of distinct exercise duration to understand the temporal aspects of the dose–response relationship. Finally, our analysis examined two components of the FITT (Frequency, Intensity, Time, Type) principle: time and frequency. Exercise intensity and protocol type varied substantially across studies but were not systematically modelled. The observed non-linear HIIT dose response may reflect intensity modulation in longer protocols or heterogeneity in protocol design rather than duration per se. The independent and interactive effects of all FITT components warrant investigation. Despite these limitations, the current work represents a major step forward in understanding the dose–response relationship across the full spectrum of exercise intensities and session durations.

5 Conclusions

Our dose–response meta-analysis demonstrated HIIT triggered a distinct dose–response curve compared with MICT in improving $\dot{V}O_{2\,max}$. High-intensity interval training achieved 80% of its maximal effect ($\Delta\dot{V}O_{2\,max}$ = 3.45 mL/kg/min) in only 11 min/session with a plateau at ~23 min/session, whereas MICT followed a linear pattern requiring ~52 min/session (4.6-fold difference) for comparable effects. Using restricted cubic splines in a large one-stage dose–response analysis, we provided the first quantitative characterisation of these contrasting dose–response relationship between distinct exercise intensity prescriptions. We provide evidence-based estimates of the minimal effective and near-maximal exercise durations associated with clinically meaningful $\dot{V}O_{2\,max}$ improvements. These estimates represent population-level averages and should not be read as optimal individualised prescriptions. Although HIIT is markedly more time efficient for enhancing cardiorespiratory fitness, both exercise modalities yield equivalent cardiometabolic benefits, supporting low-volume HIIT as a powerful exercise prescription option while reaffirming the continued value of longer-duration MICT for overall cardiometabolic health.

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Consent to Participate Not applicable.

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Availability of Data and Material All the data related to the present article are presented in the tables and figures. Additional data can be provided upon reasonable request.

Code Availability Not applicable.

Authors' Contributions FMM and NHAZ contributed equally to this work. FMM and NHAZ conceived and designed the study. NHAZ and EAD screened the titles, abstracts, and full texts and selected the studies for inclusion. FMM performed the statistical analyses and prepared the figures and tables. FMM and NHAZ wrote the first draft of the manuscript. MC, AMN, DHJT and EAD critically revised the manuscript and supervised the work. All authors read and approved the final version of the manuscript.

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