

Effectiveness of High-Intensity Interval Training (HIT) and Continuous Endurance Training for $\text{VO}_{2\text{max}}$ Improvements: A Systematic Review and Meta-Analysis of Controlled Trials

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Abstract

Background Enhancing cardiovascular fitness can lead to substantial health benefits. High-intensity interval training (HIT) is an efficient way to develop cardiovascular fitness, yet comparisons between this type of training and traditional endurance training are equivocal.

Objective Our objective was to meta-analyse the effects of endurance training and HIT on the maximal oxygen consumption ($\text{VO}_{2\text{max}}$) of healthy, young to middle-aged adults.

Methods Six electronic databases were searched (MEDLINE, PubMed, SPORTDiscus, Web of Science, CINAHL and Google Scholar) for original research articles. A search was conducted and search terms included ‘high intensity’, ‘HIT’, ‘sprint interval training’, ‘endurance training’, ‘peak oxygen uptake’, and ‘ $\text{VO}_{2\text{max}}$ ’. Inclusion criteria were controlled trials, healthy adults aged 18–45 years, training duration ≥ 2 weeks, $\text{VO}_{2\text{max}}$ assessed pre- and post-training. Twenty-eight studies met the inclusion criteria and were included in the meta-analysis. This resulted in 723 participants with a mean $\pm$ standard deviation (SD) age and initial fitness of 25.1 ± 5 years and $40.8 \pm 7.9 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$, respectively. We made probabilistic magnitude-based inferences for meta-analysed effects based on standardised thresholds for small, moderate and large changes (0.2, 0.6

and 1.2, respectively) derived from between-subject SDs for baseline $\text{VO}_{2\text{max}}$.

Results The meta-analysed effect of endurance training on $\text{VO}_{2\text{max}}$ was a possibly large beneficial effect ($4.9 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$; 95 % confidence limits $\pm 1.4 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$), when compared with no-exercise controls. A possibly moderate additional increase was observed for typically younger subjects ($2.4 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$; $\pm 2.1 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) and interventions of longer duration ($2.2 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$; $\pm 3.0 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$), and a small additional improvement for subjects with lower baseline fitness ($1.4 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$; $\pm 2.0 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$). When compared with no-exercise controls, there was likely a large beneficial effect of HIT ($5.5 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$; $\pm 1.2 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$), with a likely moderate greater additional increase for subjects with lower baseline fitness ($3.2 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$; $\pm 1.9 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) and interventions of longer duration ($3.0 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$; $\pm 1.9 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$), and a small lesser effect for typically longer HIT repetitions ($-1.8 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$; $\pm 2.7 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$). The modifying effects of age ($0.8 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$; $\pm 2.1 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) and work/rest ratio ($0.5 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$; $\pm 1.6 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) were unclear. When compared with endurance training, there was a possibly small beneficial effect for HIT ($1.2 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$; $\pm 0.9 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) with small additional improvements for typically longer HIT repetitions ($2.2 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$; $\pm 2.1 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$), older subjects ($1.8 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$; $\pm 1.7 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$), interventions of longer duration ($1.7 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$; $\pm 1.7 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$), greater work/rest ratio ($1.6 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$; $\pm 1.5 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) and lower baseline fitness ($0.8 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$; $\pm 1.3 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$).

Conclusion Endurance training and HIT both elicit large improvements in the $\text{VO}_{2\text{max}}$ of healthy, young to middle-

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aged adults, with the gains in $\text{VO}_{2\text{max}}$ being greater following HIT when compared with endurance training.

Key Points

When compared with no exercise, endurance training and high-intensity interval training elicit large improvements in maximal oxygen uptake.

Endurance training and high-intensity interval training elicit additional benefit for individuals with lower pre-training fitness.

In healthy, young to middle-aged adults, high-intensity interval training improves maximal oxygen uptake to a greater extent than traditional endurance training.

1 Introduction

Improving or maintaining cardiovascular fitness can reduce the risk of all-cause and cardiovascular diseases [1]. Indeed, when compared with other well established risk factors such as hypertension, diabetes mellitus, smoking and obesity, cardiovascular fitness is a more powerful predictor of mortality [2, 3]. Fitness training programmes aimed at the improvement of cardiovascular fitness therefore have broad appeal to the general population.

The fitness industry has recently seen a surge of interest in high-intensity interval training (HIT)—a burst-and-recover cycle that is suggested to be a viable alternative to the traditional approach to enhancing aerobic fitness, namely continuous endurance training [4]. However, specifying an optimal training regimen for improving fitness in the general community requires knowledge of how these different types of training influence adaptations in physiological parameters [5]. Consequently, there has been a substantial amount of research examining which modality of training, endurance or HIT, is superior for aerobic fitness improvements.

Endurance training and HIT both increase aerobic fitness [6] and thus relate to benefits in cardiovascular risk factors, fitness and all-cause mortality [7]. Some studies, however, have suggested that HIT leads to improvements in both aerobic and anaerobic fitness [8] and improves endurance performance to a greater extent than endurance training alone [9]. For example, Daussin et al. [10] found that maximal oxygen uptake ($\text{VO}_{2\text{max}}$) increases were

higher for untrained men and women who participated in an 8-week HIT programme (15 %) than they were for untrained participants undertaking an endurance training programme (9 %). High-intensity interval training has also been reported to be more effective than continuous, steady-state exercise training for inducing fat loss in men and women, despite requiring considerably less total energy expenditure during training [11, 12]. Recent studies have demonstrated that the cardiovascular adaptations occurring following HIT are similar, and in some cases superior, to those following endurance training [5, 13], and further beneficial effects of HIT were provided by the Nord-Trøndelag Health Study [13], which indicated that just a single weekly bout of HIT reduced the risk of cardiovascular disease in both men and women (relative risk: 0.61 and 0.49, respectively).

It is therefore not surprising that recent meta-analyses [14–17] have confirmed HIT to be an appropriate training stimulus to improve cardiorespiratory fitness and reduce metabolic risk factors in patient populations. Using similar inclusion criteria to the aforementioned reviews, Bacon et al. [18] meta-analysed the effect of HIT on $\text{VO}_{2\text{max}}$ but only calculated an overall effect size, irrespective of the type of control group (no-exercise or endurance training). Consequently, we cannot conclude that HIT is better than endurance training because the effect of HIT is, naturally, much higher in comparison with no-exercise control groups than the effect when compared with endurance training controls. A separate analysis (HIT vs endurance training; HIT vs no exercise) is therefore necessary to determine more precise effects of HIT. Gist et al. [19] reported a moderate effect (0.69) of sprint interval training (SIT)—classified as a form of HIT at the highest end of the intensity spectrum [20]—on $\text{VO}_{2\text{max}}$ in comparison with no-exercise control groups; yet a trivial effect (0.04) when compared with endurance training controls. However, this meta-analysis [19], as well as the recent meta-analyses performed by Weston et al. [21] and Sloth et al. [20], only addressed the effect of SIT on $\text{VO}_{2\text{max}}$. In doing so, these reviews excluded HIT research utilizing longer interval durations and shorter recovery periods. While there have been meta-analyses on longer duration HIT repetitions in patient populations [14–17], to the best of the authors' knowledge there is no systematic review and meta-analysis examining the effect of longer duration HIT repetitions in comparison with either endurance training or no-exercise controls. Therefore, our aim was to meta-analyse the effects on $\text{VO}_{2\text{max}}$ of endurance training and HIT in healthy, young to middle-aged adults, when compared with no-exercise controls and also when the two types of training were compared with one another. A further aim was to examine the modifying effects of study and subject characteristics.

2 Methods

2.1 Search Strategy

Electronic database searches were performed using MEDLINE, PubMed, SPORTDiscus, Web of Science, CINAHL and Google Scholar using all available records up to 28 February 2014. The search terms covered the areas of high-intensity interval training, continuous endurance training and $\text{VO}_{2\text{max}}$ using a combination of the following key words: high-intensity interval training, high-intensity intermittent training, sprint interval training, endurance training, continuous endurance training, aerobic exercises, maximal oxygen uptake, peak oxygen uptake, cardiorespiratory fitness, $\text{VO}_{2\text{max}}$, young adults. The literature search, quality assessment and data extraction were conducted independently by two authors (ZM and GS). Papers that were clearly not relevant were removed from the database list before assessing all other titles and abstracts using our pre-determined inclusion and exclusion criteria. Inter-reviewer disagreements were resolved by consensus opinion or arbitration by a third reviewer. Full papers, including reviews, were then collected and when not available the corresponding author was contacted by mail. Reference lists of the selected manuscripts were also examined for any other potentially eligible papers. This systematic review and meta-analysis was undertaken in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement [22].

2.2 Inclusion Criteria

2.2.1 Type of Study

Our meta-analysis included randomised and non-randomised controlled trials, written in English. Uncontrolled and cross-sectional studies were excluded from analysis and only studies published in the last 20 years (after 1995) were included in our review.

2.2.2 Type of Participants

The type of participants included in our meta-analysis were healthy, untrained, sedentary, recreational and non-athletic men and women aged between 18 and 45 years, who were not suffering from any kind of acute or chronic diseases. No exclusion criteria were applied to participant baseline fitness; however, studies with overweight and obese participants were excluded from our review due to confusion over the proper expression of $\text{VO}_{2\text{max}}$

data when comparing obese and normal weight individuals.

2.2.3 Type of Interventions

To be included in our meta-analysis, training programmes had to last at least a minimum of 2 weeks, with participants allocated to endurance training, HIT or a no-exercise control group. Endurance training intensity was classified as moderate intensity (60–85 % maximum heart rate [HR_{max}]), with HIT intensity classified as ‘all-out’, ‘supramaximal’, ‘maximal’ or ‘high (90–95 % HR_{max})’. Studies involving nutritional interventions were only included if the intervention was used by all participants, and studies were excluded if training was combined with strength training.

2.2.4 Type of Outcome Measure

The outcome measure for this meta-analysis was maximal oxygen uptake ($\text{VO}_{2\text{max}}$).

2.3 Final Study Selection

Following database examination, 804 potential manuscripts were identified with another 17 selected on the basis of the reference lists of the potential manuscripts (Fig. 1). After removal of duplicates and elimination of papers based on title and abstract screening, 84 studies remained. The full texts of the remaining papers were examined in more detail. According to our eligibility criteria, 56 did not meet the inclusion criteria leaving 28 studies that met our inclusion criteria and were therefore included in the meta-analysis (Table 1).

2.4 Data Extraction

Cochrane Consumers and Communication Review Group’s data extraction protocol was used to extract participant information including age, health status and sex, sample size, description of the intervention (including type of exercises, intensity, duration and frequency), study design and study outcomes. This was undertaken by one author (ZM) while GS checked the extracted data for accuracy and completeness. Disagreements were resolved by consensus or by a third reviewer. Reviewers were not blinded to authors, institutions or manuscript journals. In those studies where the data were shown in figures or graphs, either the corresponding author was contacted to get the numerical data to enable analysis or graph digitizer software was used to extract the necessary data (DigitizerZelt, Germany).

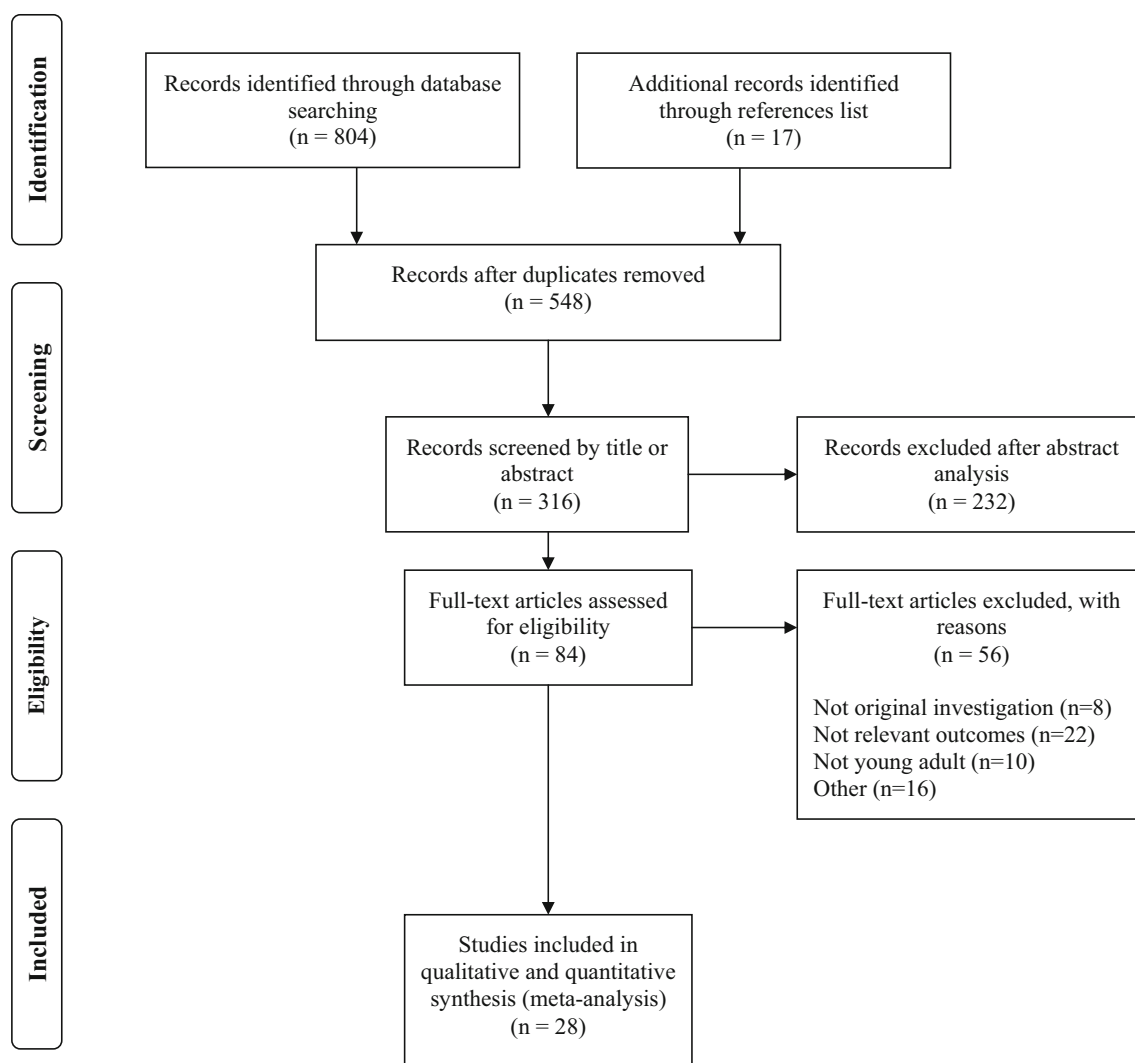


Fig. 1 Flow diagram of the study selection process

2.5 Assessment of Bias

Risk of bias was evaluated according to the PRISMA recommendation [23] and two independent reviewers assessed the risk of bias. Agreement between the two reviewers was assessed using k statistics for full-text screening, and rating of relevance and risk of bias. When there was disagreement about the risk of bias, a third reviewer checked the data and took the final decision on it. The k agreement rate between reviewers was $k = 0.95$.

2.6 Statistical Analysis

A random effects meta-analysis was conducted to determine the pooled effect size of HIT and endurance training on VO_{2max} , using Comprehensive Meta-Analysis software, Version 2 for Windows (Biostat company, Englewood, NJ,

USA). We performed separate analyses to determine the pooled effect of the change in VO_{2max} for endurance training vs no exercise, HIT vs no exercise, and HIT vs endurance training. The precision of the pooled effect was reported as 95 % confidence limits (CL) and also as probabilities that the true value of the effect was trivial, beneficial or harmful in relation to threshold values for benefit and harm. These probabilities were then used to make a qualitative probabilistic inference about the overall effect [24]. Given that enhanced aerobic functioning has clear clinical applications [21], our meta-analysed effects were assessed via clinical inferences. Here, the effects were considered unclear if the chance of benefit (improved VO_{2max}) was high enough to warrant use of the intervention but with an unacceptable risk of harm (reduced VO_{2max}). An odds ratio of benefit to harm of <66 was used to identify such unclear effects. Inferences were then subsequently

Table 1 Summary of characteristics of all studies meeting the inclusion criteria

Study	Population, age (year), no. of subjects, groups (n)	Duration (weeks)	Total sessions	Group	Exercise intensity	No. of reps		Reps duration (s)	Work/rest ratio	Δ $\text{VO}_{2\text{max}}$ (%)	Outcomes and results
						Start	End				
Astorino et al. [26]	Recreational active men ($n = 16$) and women ($n = 13$), age 25.3 ± 4.5 years HIT ($n = 20$), CON ($n = 9$)	3	6	HIT	All-out	4	6	30	0.10	6.1	HIT $\uparrow$ $\text{VO}_{2\text{max}}$, oxygen pulse and power output NC in resting BP, HR and force production
Nybo et al. [27]	Untrained inactive men ($n = 36$), age 20–43 years HIT ($n = 8$), END ($n = 9$), CON ($n = 11$), STR ($n = 8$)	12	36	HIT	95–100 % HR_{max} 80 % HR_{max}	5	5	180	2.0	14.0	HIT was less efficient than END for resting HR, fat percentage and ratio between total and HDL cholesterol. END $\downarrow$ body mass and fat percentage
Osei-Tutu and Campagna [28]	Healthy Caucasian sedentary men and women ($n = 40$), age 20–40 years END ($n = 15$), CON ($n = 10$)	8	40	END	60–79 % HR_{max}			1800		7.2	NC in total bone mass and lean body mass in HIT and END groups $\text{VO}_{2\text{max}}$ $\uparrow$ in END, END $\downarrow$ fat percentage (–6.7 %), tension and total mood disturbance
Trapp et al. [11]	Healthy nonsmoking, inactive women ($n = 45$), age 18–30 years HIT ($n = 15$), END ($n = 15$), CON ($n = 15$)	15	45	HIT	95–100 % HR_{max} 75 % HR_{max}	60	60	2700	0.67	26.4	HIT and END $\uparrow$ $\text{VO}_{2\text{max}}$ compared with CON group; only HIT $\downarrow$ total body mass, fat mass, trunk fat and insulin level
Gormley et al. [29]	Healthy young men and women ($n = 61$), age 18–44 years HIT ($n = 13$), END ($n = 13$), CON ($n = 14$)	6	18 24	HIT END	100 % HRR 75 % HRR	5	5	90 2400	1	20.2 9.6	NC in adiponectin levels in HIT and END groups HIT and END $\uparrow$ $\text{VO}_{2\text{max}}$ NC in resting HR and BP in any group
Ciolac et al. [30]	Healthy young college women ($n = 44$), age 20–30 years HIT ($n = 16$), END ($n = 16$), CON ($n = 12$)	16	48 48	HIT END	80–90 % $\text{VO}_{2\text{max}}$ 60–70 % $\text{VO}_{2\text{max}}$	14	14	672 2400	0.5	15.7 8.0	HIT and CON were equally $\downarrow$ ambulatory blood pressure and $\downarrow$ insulin
Bayati et al. [31]	Young active males ($n = 16$), age 25.0 ± 0.8 years HIT ($n = 8$), CON ($n = 8$)	4	12	HIT	125 % P_{max}	6	10	96	0.25	9.7	HIT $\uparrow$ power at $\text{VO}_{2\text{max}}$ (+16.1 %) and peak power output (+7.4 %); blood lactate recovery $\uparrow$ in HIT compared with CON
Metcalfe et al. [32]	Healthy sedentary young men and women ($n = 29$), age 22.5 ± 2.0 years HIT ($n = 15$), CON ($n = 14$)	6	18	HIT	All-out	1	2	35		13.4	NC in mean power output HIT $\uparrow$ insulin sensitivity by 28 % in men
Ziemann et al. [33]	Recreationally active men ($n = 21$), age 21.3 ± 1.0 years HIT ($n = 10$), CON ($n = 11$)	6	18	HIT	80 % $\text{pVO}_{2\text{max}}$	6	6	108	0.5	11.0	HIT $\uparrow$ anaerobic threshold (3.8 $\text{mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$), work output (12.5 $\text{J} \cdot \text{kg}^{-1}$), glycolytic work (11.5 $\text{J} \cdot \text{kg}^{-1}$), mean power (0.3 $\text{W} \cdot \text{kg}^{-1}$), peak power (0.4 $\text{W} \cdot \text{kg}^{-1}$), and max power (0.4 $\text{W} \cdot \text{kg}^{-1}$)
Ben Abderrahman et al. [34]	Male physical education students ($n = 15$), age 20.6 ± 0.7 years HIT ($n = 9$), CON ($n = 6$)	7	21	HIT	105–110 % MAS	8	10	66	1	5.9	NC in time spent above 95 % of $\text{VO}_{2\text{max}}$ in absolute and relative values
Burgomaster et al. [35]	Healthy young men ($n = 10$) and women ($n = 10$), age 23.56 ± 1.0 years HIT ($n = 10$), END ($n = 10$)	6	18 30	HIT END	All-out 65 % $\text{VO}_{2\text{peak}}$	4	6	30 2400–3600	0.11	7.3 9.8	HIT and END $\uparrow$ in mitochondrial markers for skeletal muscle and lipid oxidation; both groups $\uparrow$ $\text{VO}_{2\text{max}}$ compared with control group without changes between training groups
Chara et al. [36]	Male physical education students ($n = 48$), age 21.4 ± 1.3 years HIT ($n = 10$), CON ($n = 9$)	12	24	END	100 % $\text{vVO}_{2\text{max}}$	5	5	120		9.8	NC in percentage of body fat and energy intake in all groups HIT $\uparrow$ in $\text{vVO}_{2\text{max}}$ 10.38 %

Table 1 continued

Study	Population, age (year), no. of subjects, groups (n)	Duration (weeks)	Total sessions	Group	Exercise intensity	No. of reps Start End	Total reps	Reps duration (s)	Work/rest ratio	Δ $\text{VO}_{2\text{max}}$ (%)	Outcomes and results
Hottenrott et al. [6]	Recreational endurance men ($n = 15$) and women ($n = 15$), age 43.4 ± 6.9 years HIT ($n = 14$), END ($n = 16$)	12	36 24	HIT END	All-out 75–85 % V_{LT}	4 10	936	30 1800–7200	0.33	18.5 7.0	HIT and END $\uparrow\uparrow$ peak oxygen uptake, resting HR, V_{LT} and visceral fat, body mass; END $\uparrow$ total body fat and fat-free mass compared with HIT
Lo et al. [37]	Healthy nonathletic men ($n = 34$), age 20.4 ± 1.36 years HIT ($n = 10$), STR ($n = 10$), CON ($n = 14$)	24	72	END	75–85 % HRR			1800		20.5	NC in maximal lactate for both groups END and STR $\uparrow \text{VO}_{2\text{max}}$ and lower body strength; STR $\uparrow$ upper body strength, lean mass and body size of arm and calf compared with END and CON groups
McKay et al. [38]	Young adult men ($n = 12$), age 25.0 ± 4.0 years HIT ($n = 6$), END ($n = 6$)	3	8 8	HIT END	120 % WR_{max} 65 % $\text{VO}_{2\text{max}}$	8 12	60	60 5400–7200	1	4.3 7	HIT and END $\uparrow \text{VO}_{2\text{max}}$ after training programme; HIT and END $\downarrow$ time constant for VO_2 response by ~ 20 % after only 2 days of training and by ~ 40 % post-training, with no difference between groups
Tabata et al. [39]	Young male students ($n = 14$), age 23.0 ± 1.0 years HIT ($n = 7$), END ($n = 7$)	6	30 30	HIT END	170 % $\text{VO}_{2\text{max}}$ 70 % $\text{VO}_{2\text{max}}$	7 8	225	20 3600	2	14.6 9.4	END did not increase anaerobic capacity but $\uparrow\uparrow$ in $\text{VO}_{2\text{max}}$ HIT $\uparrow\uparrow \text{VO}_{2\text{max}}$ by $7 \text{ mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ and anaerobic capacity by 28 %
Cocks et al. [40]	Young sedentary men ($n = 16$), age 21.0 ± 0.7 years HIT ($n = 8$), END ($n = 8$)	6	18 30	HIT END	All-out 65 % $\text{VO}_{2\text{peak}}$	4 5	85	30 2400–3600	0.11	7.6 15.6	HIT and END $\uparrow \text{VO}_{2\text{peak}}$ and maximal power output (END 16 %, HIT 9 %); both groups $\downarrow$ in HRR, mean and diastolic BP with no difference between groups; NC in systolic BP in both groups
Dunham and Harms [41]	Physically active, healthy, untrained subjects ($n = 15$), age 21.3 ± 2.3 years HIT ($n = 8$), END ($n = 7$)	4	12 12	HIT END	90 % $\text{VO}_{2\text{max}}$ 60–70 % $\text{VO}_{2\text{max}}$	5 5	60	60 2700	0.33	9.6 5.5	HIT and END $\uparrow \text{VO}_{2\text{max}}$ and time trials following training with no differences between groups; HIT $\uparrow$ in maximum inspiratory pressure compared with END
Edge et al. [42]	Recreationally female students ($n = 16$), age 20.0 ± 1.0 years HIT ($n = 8$), END ($n = 8$)	5	15 15	HIT END	120–140 % LT 80–95 % LT	2 10	100	120	2	14.0 14	NC in expiratory flow rates in both groups HIT and END $\uparrow$ in $\text{VO}_{2\text{peak}}$ and the LT (7–10 %), with no significant differences between groups
Esfarjani and Laursen [43]	Healthy recreational men ($n = 17$), age 20.0 ± 2.0 years HIT1 ($n = 6$), HIT2 ($n = 6$), END ($n = 5$)	10	20 20 40	HIT HIT END	75 % $\text{vVO}_{2\text{max}}$ 130 % $\text{vVO}_{2\text{max}}$ 75 % $\text{vVO}_{2\text{max}}$	5 8 7 12	130 190	200 30 3600	1 0.11	9.2 6.2 2.1	NC in percentage of $\text{VO}_{2\text{peak}}$ at which LT occurred HIT1 $\uparrow$ in $\text{VO}_{2\text{max}}$, $\text{vVO}_{2\text{max}}$ (+6.4 %), T_{max} (5 %) and V_{LT} (+11.7 %); HIT2 $\uparrow$ in $\text{VO}_{2\text{max}}$, $\text{vVO}_{2\text{max}}$ (+7.8 %), T_{max} (32 %), and V_{LT} (+11.7 %) but not V_{LT} ; NC in these variables were found in END
Macpherson et al. [44]	Healthy young recreationally active men ($n = 12$) and women ($n = 8$), age 24.0 ± 3.0 years HIT ($n = 6$), END ($n = 5$)	6	18 18	HIT END	All-out 65 % $\text{VO}_{2\text{max}}$	4 6	90	30 1800–3600	0.11	11.5 12.5	HIT1 $\uparrow$ in $\text{VO}_{2\text{max}}$ and T_{max} compared with END HIT and END $\uparrow$ body composition, 2000-run time trial performance and $\text{VO}_{2\text{max}}$; fit mass $\downarrow$ by 12.4 % with HIT and 5.8 % with END; lean mass $\uparrow$ 1 % in both groups. None of these improvements differed between groups
Shepherd et al. [45]	Healthy sedentary men ($n = 16$), age 21.5 ± 1.0 years HIT ($n = 8$), END ($n = 8$)	6	18 30	HIT END	All-out 65 % $\text{VO}_{2\text{peak}}$	4 6	90	30 2400–3600	0.11	7.6 15.6	HIT and END $\uparrow\uparrow \text{VO}_{2\text{peak}}$, fat-free mass, and maximum workload; NC in relative fat mass

Table 1 continued

Study	Population, age (year), no. of subjects, groups (<i>n</i>)	Duration (weeks)	Total sessions	Group	Exercise intensity	No. of reps		Total reps	Reps duration (s)	Work/rest ratio	Δ VO _{2max} (%)	Outcomes and results
						Start	End					
Helgerud et al. [5]	Healthy nonsmoking men (<i>n</i> = 24), age 24.6 ± 3.8 years HIT1 (<i>n</i> = 6), HIT2 (<i>n</i> = 6), END1 (<i>n</i> = 6), END2 (<i>n</i> = 6)	8	24	HIT1	90–95 % HR _{max}	47	47	1128	15	1	6.4	HIT1 and HIT 2 ↑↑ VO _{2max} compared with END1 and END 2; percentage increases in VO _{2max} for the HIT1 and HIT 2 groups were 5.5 and 7.2 %, respectively. Stroke volume of the heart ↑ in HIT1 and HIT2
		24	24	HIT2	90–95 % HR _{max}	4	4	96	240	1.33	8.8	
		24	24	END1	70 % HR _{max}			2700			1.8	
		24	24	END2	85 % HR _{max}			1455			2.0	NC in blood volume, high-density lipoprotein and low-density lipoprotein in any groups after training programme
Warburton et al. [46]	Healthy untrained men (<i>n</i> = 20), age 30 ± 4 years HIT (<i>n</i> = 6), END (<i>n</i> = 6), CON (<i>n</i> = 8)	12	36	HIT	90 % VO _{2max}	8	12	384	120	1	22.2	HIT and END ↑↑ VO _{2max} and peak stroke volume, blood volume compared to CON; no differences between HIT and END in any parameters
			36	END	65 % VO _{2max}			1800–2880			23	
Berger et al. [47]	Healthy sedentary men (<i>n</i> = 11) and women (<i>n</i> = 12), age 24 ± 5 years HIT (<i>n</i> = 8), END (<i>n</i> = 8), CON (<i>n</i> = 7)	6	22	HIT	90 % VO _{2max}	15	20	445	60	1	21.0	HIT and END ↑↑ VO _{2max} and pulmonary VO _{2max} kinetics, compared with CON
			22	END	60 % VO _{2max}			1800			20.0	
Matsuo et al. [48]	Sedentary men (<i>n</i> = 42), age 26.5 ± 6.2 years HIT (<i>n</i> = 14), END (<i>n</i> = 14)	8	40	HIT	80–85 % VO _{2max}	3	3	120	180	1.5	22.5	HIT and END ↑↑ VO _{2max} , HIT ↑↑ VO _{2max} compared with END; only HIT ↑↑ left ventricular mass, stroke volume and resting HR
			40	END	60–65 % VO _{2max}			2400			10.0	
O'Donovan et al. [49]	Sedentary men (<i>n</i> = 42), age 41 ± 4 HIT (<i>n</i> = 13), END (<i>n</i> = 14), CON (<i>n</i> = 15)	24	72	HIT	80 % VO _{2max}						15.7	HIT and END ↑↑ VO _{2max} , HIT ↑ HDL and ↓ LDL, NC in END for HDL and LDL
			72	END	60 % VO _{2max}						22.5	
Sandvei et al. [50]	Healthy young men (<i>n</i> = 8) and women (<i>n</i> = 15), age 25.2 ± 0.7 years HIT (<i>n</i> = 11), END (<i>n</i> = 12)	8	24	HIT	100 % HR _{max}	5	10	189	30	0.16	5.3	HIT and END ↑ VO _{2max} , HIT ↑ insulin sensitivity and cholesterol profile while NC for END
			24	END	70–80 % HR _{max}			1800–3600			3.8	

BBP blood pressure, *CON* control group, *END* continuous endurance training, *HDL* high-density lipoprotein, *HIT* high-intensity interval training, *HR* heart rate, *HRR* heart rate reserve, *LT* lactate threshold, *MMAS* maximal aerobic speed, *max* maximal, *NC* no changes $p > 0.05$, *P_{max}* power at $\text{VO}_{2\text{max}}$, *pVO_{2max}* maximal aerobic power, *rep* repetitions, *STR* strength training, *T_{max}* time to exhaustion at $\text{vVO}_{2\text{max}}$, *V_{LT}* velocity of the lactate threshold, *VO_{2max}* maximal oxygen uptake, *VO_{2peak}* peak rate of oxygen consumption, *vVO_{2max}* maximal aerobic power, *vVO_{2max}* running speed at $\text{VO}_{2\text{max}}$, *WR_{max}* work rate at maximal O_2 uptake, $\uparrow$ indicates significant increase $p < 0.05$, $\uparrow\uparrow$ indicates significant increase $p < 0.01$, $\downarrow$ indicates significant decreases $p < 0.05$, $\downarrow\downarrow$ indicates significant decreases $p < 0.01$

based on standardised thresholds for small, moderate and large changes of 0.2, 0.6 and 1.2 standard deviations (SDs), respectively [24] and derived by averaging appropriate between-subject variances for baseline $\text{VO}_{2\text{max}}$. Magnitude thresholds were 0.8, 2.4 and $4.7 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ (endurance vs no exercise), 0.8, 2.3 and $4.7 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ (HIT vs no exercise) and 0.9, 2.6 and $5.3 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ (HIT vs endurance training). The chance of the true effect being trivial, beneficial or harmful was then interpreted using the following scale: 25–75 %, possibly; 75–95 %, likely; 95–99.5 %, very likely; >99.5 %, most likely [24]. Random variation in the effect from study to study was expressed as an SD, with the SD doubled to interpret its magnitude [25]. Publication bias was assessed by examining asymmetry of funnel plots using Egger's test, and a significant publication bias was considered if the $p < 0.10$.

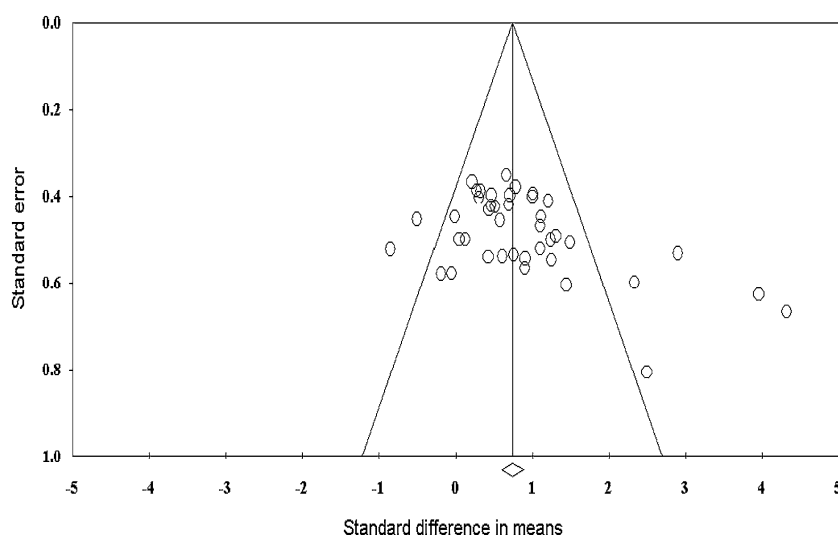
2.7 Meta-Regression Analysis

Meta-regression analyses were conducted to explore the effect of putative moderator variables on the pooled effect. Here, we selected five moderator variables that could reasonably influence the overall effect of training on $\text{VO}_{2\text{max}}$ and these were age, baseline fitness, intervention duration, work:rest ratio and HIT repetition duration. The modifying effects of these five variables were calculated as the effect of two SDs (i.e. the difference between a typically low and a typically high value) [24].

3 Results

The Egger's test was performed to provide statistical evidence of funnel plot asymmetry (Fig. 2) and the results indicated publication bias for all analyses ($p < 0.10$).

Fig. 2 Funnel plot of standard difference in means vs standard error; the aggregated standard difference in means is the random effects mean effect size weighted by degrees of freedom



3.1 Endurance Training vs No-Exercise Controls

The meta-analysed effect of endurance training, when compared with controls, was a possibly large beneficial effect on $\text{VO}_{2\text{max}}$ ($4.9 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$; 95 % CL $\pm 1.4 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) (Fig. 3; Table 2). Meta-regression analysis revealed a greater beneficial effect (possibly moderate) for typically younger vs older subjects and interventions of longer duration, and a greater beneficial improvement (possibly small) for subjects with typically lower baseline fitness. The random variation in the overall pooled effect from study to study, expressed as an SD, was $1.3 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$.

3.2 High-Intensity Interval Training (HIT) vs No-Exercise Controls

The meta-analysed effect of HIT, when compared with controls, was a likely large beneficial effect on $\text{VO}_{2\text{max}}$ ($5.5 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$; $\pm 1.2 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) (Fig. 4; Table 3). Meta-regression analysis revealed a likely moderate greater beneficial improvement in $\text{VO}_{2\text{max}}$ for subjects with typically lower baseline fitness and interventions of longer duration and a likely small lesser effect for longer HIT repetitions. The effects of all other putative modifiers were unclear. Random variation in the effect from study to study was $1.3 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$.

3.3 HIT vs Endurance Training

When compared with endurance training, there was a possibly small beneficial effect of HIT on $\text{VO}_{2\text{max}}$ ($1.2 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$; $\pm 0.9 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) (Fig. 5; Table 4). The modifying effects of typically longer HIT repetitions, older and less fit subjects, longer interventions

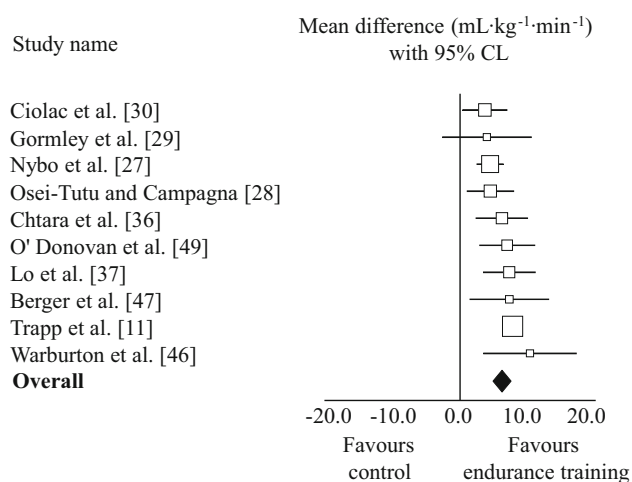


Fig. 3 Effects of endurance training vs no-exercise controls on maximal oxygen uptake. *CL* confidence limits

and a greater work:rest ratio were possibly to likely small increased beneficial improvements in VO_{2max} . Random variation in the effect from study to study was $0.8 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$.

4 Discussion

This study presents a quantitative evaluation of HIT and endurance training models for VO_{2max} improvements in healthy adults aged 18–45 years. Our results show that when compared with no-exercise controls, both types of training elicit large improvements in VO_{2max} . In studies where HIT and endurance were directly compared, there was a small beneficial effect for HIT.

The results of our systematic review and meta-analysis confirm the conclusions of previous studies [11, 27–30, 36, 37, 51] that continuous aerobic endurance training is an effective method for VO_{2max} improvement in young adults. The training effect was greater for less fit adults, which is

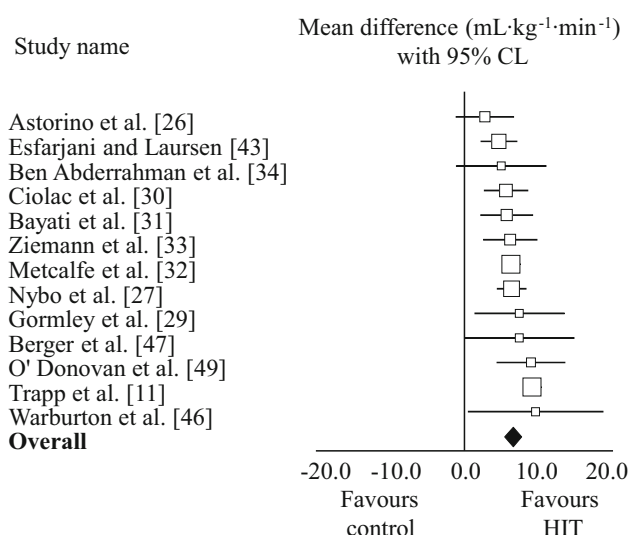


Fig. 4 Effects of HIT vs no-exercise controls on maximal oxygen uptake. *CL* confidence limits, *HIT* high-intensity interval training

consistent with previous work demonstrating that aerobic training has an adaptive effect that favours the less fit [21]. Further to this, the beneficial effect of continuous endurance training on VO_{2max} is greater for younger subjects and with interventions of longer duration. Most of the studies in this particular analysis undertook three moderate-intensity sessions per week lasting 40–60 min, yet the American College of Sports Medicine (ACSM) recommends to undertake moderate-intensity continuous exercises for a minimum of 30 min on 5 days each week or 20 min of vigorous exercises 3 days each week, or a combination of the two [52]. As such, it is clear from the findings of this review that substantial gains in aerobic fitness can be obtained with a moderate-intensity training session frequency lower than that currently recommend [2].

When compared with no-exercise controls, HIT elicits a likely large substantial improvement in the VO_{2max} of healthy adults. The size of this effect was greater than that

Table 2 Effects of endurance training on VO_{2max}

	Effect on VO _{2max} (mL·kg ⁻¹ ·min ⁻¹)		Inference
	Mean	±95 % CL	
Main effect			
Endurance training vs control	4.9	±1.4	Possibly large ↑
Modifying effects ^a			
Age lower by 13.7 years	2.4	±2.1	Possibly moderate ↑
Intervention duration longer by 13 weeks	2.2	±3.0	Possibly moderate ↑
Baseline VO _{2max} lower by 12.6 mL·kg ⁻¹ ·min ⁻¹	1.4	±2.0	Possibly small ↑

CL confidence limits, VO_{2max} maximal oxygen uptake, $\uparrow$ indicates increase

^a Modifying effects are presented as the effect of two standard deviations of the numerical covariates (i.e. a typically high value minus a typically low value)

Table 3 Effects of HIT on VO_{2max}

	Effect on VO _{2max} (mL·kg ⁻¹ ·min ⁻¹)		Inference
	Mean	±95 % CL	
Main effect			
HIT vs control	5.5	±1.2	Likely large ↑
Modifying effects ^a			
Baseline VO _{2max} lower by 18.5 mL·kg ⁻¹ ·min ⁻¹	3.2	±1.9	Likely moderate ↑
Intervention duration longer by 13 weeks	3.0	±1.9	Likely moderate ↑
Age higher by 11.7 years	0.8	±2.1	Unclear
Work:rest ratio higher by 1.1	0.5	±1.6	Unclear
HIT repetition duration longer by 161 s	-1.8	±2.7	Likely small ↓

CL confidence limits, HIT high-intensity interval training, VO_{2max} maximal oxygen uptake, $\uparrow$ indicates increase, $\downarrow$ indicates decrease

^a Modifying effects are presented as the effect of two standard deviations of the numerical covariates (i.e. a typically high value minus a typically low value)

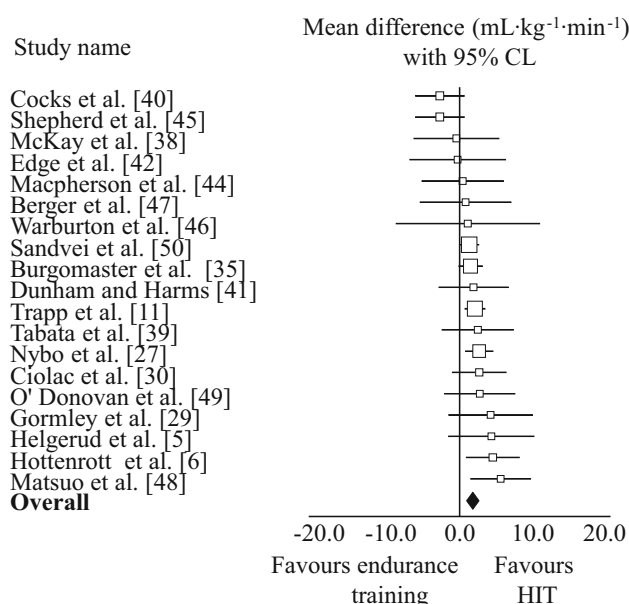


Fig. 5 Effects of HIT vs endurance training on maximal oxygen uptake. CL confidence limits, HIT high-intensity interval training

reported by Gist et al. [19], who reported a moderate effect (effect size 0.69) for low-volume HIT when compared with no-exercise controls, with differences in the overall dose of exercise possibly accounting for these inconsistent results. Irrespective of dose, HIT has a clear beneficial effect on the aerobic fitness of healthy young adults when compared with no exercise. This effect is moderated by initial fitness as the training benefits individuals with lower initial fitness—a finding consistent with low-volume HIT programmes [21]. With regard to HIT programming, a moderating beneficial effect for longer intervention

duration is consistent with the subgroup analysis performed by Bacon et al. [18]. Here, the authors reported that the largest increases in VO_{2max} were following longer intervention durations ($p = 0.004$). Additionally, we found an unclear effect on VO_{2max} with an increased work:rest ratio (e.g. greater recovery between HIT repetitions), a finding consistent with that reported by Weston et al. [21]. Future studies are therefore needed to resolve this unclear effect, although the prescription of an 'optimal' work:rest ratio is challenging as variables such as age, sex, baseline fitness and training experience may need to be considered when designing HIT programmes. We also found an unclear modifying effect of age on HIT and consistent with previous HIT meta-analyses [18, 19, 21], the demographic of participants in the studies analysed was mainly young adults. As such, we suggest that more HIT studies need to be undertaken in older populations, especially given the recent encouraging findings reported by Adamson et al. [53] and Knowles et al. [54] whereby HIT elicited substantial improvements in VO_{2max} and also measures of functional fitness and quality of life.

When compared with endurance training controls, HIT had a possibly small beneficial effect on VO_{2max} . Previous comparisons between HIT and endurance training yielded either an unclear effect [19, 21] or a significantly higher increase in VO_{2peak} after HIT compared with endurance training ($3.03 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$; ± 2.0 to $4.1 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) [21]. Discrepancies in the overall training dose (e.g. low-volume HIT vs HIT) and study participants (e.g. healthy participants vs patient populations) no doubt account for the inconsistency in these findings. The difference in the training effect between HIT and endurance was enhanced for older and less fit subjects, suggesting

Table 4 Effects of HIT vs endurance training on VO_{2max}

	Effect on $\text{VO}_{2\text{max}}$ ($\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$)		Inference
	Mean	$\pm 95\%$ CL	
Main effect			
HIT vs endurance training	1.2	± 0.9	Possibly small $\uparrow$
Modifying effects ^a			
HIT repetition duration longer by 164 s	2.2	± 2.1	Likely small $\uparrow$
Age higher by 12.9 years	1.8	± 1.7	Likely small $\uparrow$
Intervention duration longer by 10.3 weeks	1.7	± 1.7	Likely small $\uparrow$
Work:rest ratio higher by 1.4	1.6	± 1.5	Likely small $\uparrow$
Baseline $\text{VO}_{2\text{max}}$ lower by $14.5\text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$	0.8	± 1.3	Possibly small $\uparrow$

CL confidence limits, HIT high-intensity interval training, VO_{2max} maximal oxygen uptake, $\uparrow$ indicates increase

^a Modifying effects are presented as the effect of two standard deviations of the numerical covariates (i.e. a typically high value minus a typically low value)

HIT to have appeal for those involved in the fitness programming of older adults and patient populations, especially given that the safety concerns associated with HIT are unfounded [55, 56]. Our supposition is supported by recent evidence whereby HIT induced substantial improvements in cardiovascular (e.g. VO_{2max}), functional fitness (e.g. sit-to-stand test) and health-related quality of life/physical functioning following short (3 weeks) [53] and long duration (13 weeks) [54] interventions. Our findings of enhanced beneficial effects for HIT with longer repetitions, greater work:rest ratios and longer training interventions provides valuable information to those involved in the design and implementation of HIT programmes.

While information on the physiological mechanisms subtending the improvements in VO_{2max} following either endurance training or HIT helps to explain changes in VO_{2max} , a discussion of physiological adaptations is beyond the scope of our review. In this instance, we direct readers to the articulate and comprehensive reviews of Jones and Carter [57], Gibala et al. [58] and Sloth et al. [20] for a detailed discussion of the underlying physiological adaptations to endurance training and HIT.

Finally, the observed magnitude of the between-study variation in the mean effect was moderate for endurance training vs control and HIT vs control, and small for HIT vs endurance training. As such, the mean effect, when compared with control, lies typically between $3.6 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ (very likely moderate) and $6.2 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ (very likely large) for endurance training, between $4.2 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ (most likely moderate) and $6.8 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ (very likely large) for HIT, and between $-0.4 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ (most likely trivial) and $2.0 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ (likely small) for HIT compared with endurance training.

5 Conclusion

Our meta-analysis confirms that endurance training and HIT both elicit large improvements in the VO_{2max} of healthy, young to middle-aged adults with the effects being greater for the less fit. Furthermore, when comparing the two modes of training, the gains in VO_{2max} are greater following HIT. Given the well established link between aerobic fitness and mortality, further investigations into the manipulations of the HIT dose (e.g. repetition intensity, duration, work:rest ratio etc.) are therefore recommended to enhance our understanding of the beneficial effects of HIT.

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