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Effects of high-intensity interval training (HIIT) and sprint interval training (SIT) on fat oxidation during exercise: a systematic review and meta-analysis

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ABSTRACT

Objective To investigate the effects of high-intensity interval training (HIIT) and sprint interval training (SIT) on fat oxidation during exercise (FatOx) and how they compare with the effects of moderate-intensity continuous training (MICT).

Design Systematic review and meta-analysis.

Data sources Academic Search Ultimate, CINAHL, Networked Digital Library of Theses and Dissertations, Open Access Theses and Dissertations, OpenDissertations, PubMed/MEDLINE, Scopus, SPORTDiscus and Web of Science.

Eligibility criteria for selecting studies Studies using a between-group design, involving adult participants who were not trained athletes, and evaluating effects of HIIT or SIT on FatOx (vs no exercise or MICT) were included.

Results Eighteen studies of fair-to-good quality were included; nine comparing HIIT or SIT with no exercise and eleven comparing HIIT or SIT with MICT. A significant pooled effect of these types of interval training on FatOx was found (mean difference in g/min (MD)=0.08; 95% confidence interval (CI) 0.04 to 0.12; $p<0.001$). Significant effects were found for exercise regimens lasting ≥4 weeks, and they increased with every additional week of training ($\beta=0.01$; 95% CI 0.00 to 0.02; $p=0.003$). HIIT and/or SIT were slightly more effective than MICT (MD=0.03; 95% CI 0.01 to 0.05; $p=0.005$). The effects on FatOx were larger among individuals with overweight/obesity.

Conclusion Engaging in HIIT or SIT can improve FatOx, with larger effects expected for longer training regimens and individuals with overweight/obesity. While some effects seem small, they may be important in holistic approaches to enhance metabolic health and manage obesity.

WHAT IS ALREADY KNOWN

⇒ High-intensity interval training (HIIT) and sprint interval training (SIT) seem to increase fat oxidation during exercise (FatOx), but it is unclear what is the magnitude of their effect on FatOx and whether they are more effective for improving FatOx than moderate-intensity continuous training (MICT).

WHAT ARE THE NEW FINDINGS

⇒ HIIT and SIT are effective for improving FatOx even when applied for only 4 weeks, with the mean effect ranging from 0.05 g/min for short training regimens to 0.13 g/min for training regimens lasting more than 12 weeks.

⇒ Compared with MICT, HIIT and SIT are only slightly more effective in improving FatOx (on average 0.03 g/min), but they usually require almost two times lower time commitment.

⇒ Significantly greater improvements in FatOx following HIT and SIT can be expected among individuals with overweight or obesity, compared with individuals with 'normal' weight.

INTRODUCTION

In recent years, effects of high-intensity interval training (HIIT) and sprint interval training (SIT) on cardio-metabolic outcomes have been widely investigated.[1 2] A large number of adults engage in this type of exercise to improve their health and fitness.[3] Both HIIT and SIT involve short bursts of high-intensity exercise interspersed with rest intervals.[4–6] HIIT is usually performed at intensities below or at maximal oxygen uptake (VO_{2max}) or peak power output (PPO), while SIT requires 'all-out' efforts at supramaximal work rates.[4 5] For brevity, when referring to both HIIT and SIT hereafter, we used the term 'interval training', unless stated otherwise. It should be noted that there are other modes of interval training, such as Fartlek, CrossFit style exercise and various high-intensity functional training workouts. However, they are likely to elicit different acute responses compared with HIIT and SIT, and they were therefore beyond the scope of this review.

Studies performed among athletes and in the general population show that HIIT and SIT induce various adaptations such as improvements in VO_{2max}, body composition, mitochondrial biogenesis, exercise performance and fat oxidation during exercise (FatOx).[7–10] Increased whole-body FatOx with a concomitant reduction of carbohydrate utilisation during exercise or at rest is a hallmark adaptation observed following endurance training.[11 12] This adaptation occurs mostly in skeletal muscles and results in an increased whole-body FatOx capacity.[13] Higher FatOx capacity is associated with better metabolic health, especially in individuals with obesity and metabolic disorders of fatty acid oxidation.[14 15] A high resting respiratory exchange

ratio, an indicator of reduced FatOx, is associated with increased fat mass in adults.[16] Individuals with obesity may have impaired FatOx, in turn facilitating accumulation of body fat.[13 17] Some studies have also shown that a reduced capacity to oxidise fat is associated with insulin resistance and type 2 diabetes.[18 19]

Previous research has investigated the effects of different regimens of interval training on FatOx.[20–24] A narrative review[25] concluded that HIIT and SIT lead to increases in FatOx. Previous systematic reviews have examined effects of HIIT and SIT on different cardiometabolic outcomes.[8 10 26] However, a systematic review and meta-analysis of the effect of HIIT and SIT (compared with no exercise) on FatOx have not yet been performed.

Evidence suggests that moderate-intensity continuous training (MICT) produces similar effects on some outcomes as HIIT and SIT.[27 28] However, studies comparing the effects of these types of interval training and MICT on FatOx reported inconsistent results,[29–34] and they have also never been systematically reviewed and pooled in a meta-analysis.

Therefore, our aim was to conduct a systematic review and meta-analysis of studies that examined the effects of HIIT and SIT on FatOx among adults. We also aimed to compare the effects of interval training and MICT on FatOx.

METHODS

This review was performed in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines[35] and preregistered in the PROSPERO database (ID: CRD42020215994). Discrepancies from the protocol are described in online supplemental file 1.

Search strategy

Academic Search Ultimate, CINAHL, Networked Digital Library of Theses and Dissertations, Open Access Theses and Dissertations, OpenDissertations, PubMed/MEDLINE, Scopus, SPORTDiscus and Web of Science (Core Collection) were searched from the database inception to 31 December 2021. We searched through titles, abstracts and keywords of publications for any mentions of English terms related to FatOx, HIIT and SIT (online supplemental file 2).

Two reviewers (MMA and YG) independently assessed the identified publications for eligibility. In the secondary search, we additionally examined our personal databases and the reference lists of all included publications.

Study selection

A study was included if it satisfied the following criteria: (a) used a between-group design that included adult human participants who were not trained athletes; (b) the training intervention lasted a minimum of 2 weeks or six sessions; (c) the training intervention was supervised, consisted of HIIT or SIT eliciting intensities of approximately ≥75% of VO_{2max}, peak oxygen uptake (VO_{2peak}), PPO, maximal heart rate (HR_{max}), peak heart rate or heart rate reserve, and it did not include other types of exercise; (d) before and after the training intervention, total FatOx or maximal FatOx was assessed by means of indirect calorimetry during a continuous submaximal or an incremental graded exercise test, as these procedures yield comparable estimates[36–38] and (e) evaluated the effects of HIIT or SIT on FatOx (during exercise) in comparison with a non-exercising control group and/or MICT. Despite some attempts to provide a standardised definition of HIIT,[7 26 39 40] a wide consensus has still not been reached. To be as inclusive as possible, in the eligibility criteria we used a relatively low-intensity threshold. We did not include studies involving trained athletes, because trained athletes have high FatOx that is associated with their improved muscle oxidative capacity,[41–43] and their further improvements in FatOx would therefore be less likely than among untrained individuals.

Data extraction

From the included studies, the following data were extracted by one author (MMA) and checked by two other authors (YG and ZP): lead author name, year of publication, study population, study design, participant characteristics, training protocol, type of exercise testing used to measure FatOx, type of exercise, means and standard deviations of FatOx (in g/min) at baseline and follow-up, and correlations of FatOx between baseline and follow-up. For studies that reported FatOx at more than one submaximal intensity, we considered the intensity eliciting the highest FatOx rate. We asked the corresponding authors of seven papers[31 44–49] to provide us additional relevant data, or where possible, we extracted data from figures using a web application.[50]

Methodological quality of included studies and certainty of evidence

Study quality was appraised independently by two authors (MMA and YG) using the 11-item Physiotherapy Evidence Database (PEDro) scale.[51] Based on the summary scores on the scale, the studies were classified as being excellent (9–10 points), good (6–8 points), fair (4–5 points) and poor (≤3 points) quality.[52]

The Grading of Recommendations Assessment, Development and Evaluation (GRADE) approach was used to rate the certainty of evidence as 'high', 'moderate', 'low' or 'very low'.[53]

Statistical analysis

Separate random-effects meta-analyses were conducted to summarise the effects of interval training (HIIT and/or SIT) on FatOx, in comparison with a non-exercising control group and MICT. Subgroup and moderation analyses were performed by: (a) training modality, (b) type of exercise, (c) body mass index (BMI) category, (d) sex and (e) definition of exercise workload during FatOx assessment.

To explore dose–response effects of interval training (HIIT and/or SIT) on FatOx we conducted a set of random-effects meta-regression analyses with restricted maximum likelihood estimation, each including a predictor related to an exercise session or to the training regimen. When assessing the shape of dose–response relationships, we fitted linear, quadratic and cubic functions and selected the model with the lowest value of bias-corrected Akaike information criterion (AICc).

The categorical moderators in subgroup analyses and numerical predictors in the meta-regression analyses were selected because: (a) they are commonly considered for exercise prescription purposes; (b) information on them is commonly reported when describing HIIT and SIT intervention protocols; and/or (c) they may have affected effect sizes.

The effects were presented as mean difference (MD) and their 95% confidence interval (CI) in grams per minute. Missing correlations between baseline and follow-up FatOx were replaced by a weighted pooled correlation ($r=0.70284$) calculated from seven available correlations.[32 46 54 55] We also conducted sensitivity analyses in which missing correlations

were replaced with extreme correlations (ie, 1 for the effects favouring no exercise or MICT and 0 for the effects favouring interval training), simulating the most conservative estimation of the pooled effect. Furthermore, for each of the two studies that included more than one interval training group,[33 56] in the main meta-analysis we included a pooled effect from all their interval training groups, while in a sensitivity analysis we considered them separately. An additional sensitivity analysis was conducted including two studies that were closely related to the topic of the review but did not fully meet the eligibility criteria; in one study,[49] not all training sessions were supervised, while in another study,[48] exercise intensity was not assessed objectively in all training sessions.

Low, moderate, substantial and high heterogeneity were deemed to be represented by I^2 values in the range of 0%–40%, 30%–60%, 50%–90% and 75%–100%, respectively.[57] Contour-enhanced funnel plot and Egger's asymmetry test were used to examine publication bias.[58] The analyses were performed using the 'metafor' package[59] in R (R Foundation for Statistical Computing, Vienna, Austria).

RESULTS

Search results

We screened a total of 2089 references (online supplemental figure 1). In the primary search, we identified 691 publications, and 15 of them were considered eligible for inclusion in the review. In the secondary search, we screened 1395 references of included studies, and three additional studies[30 34 55] were included from the authors' personal databases. In total, 18 studies met the eligibility criteria and were included in the review.[29–34 44–47 54–56 60–64]

Study characteristics

A total of 511 individuals (224 men and 287 women; age range: 20–63 years) participated in the included studies. Nine studies[29 31 32 34 45 46 54 62 63] compared the effects of interval training versus effects of MICT. Seven studies[33 44 47 55 56 60 61] assessed the effects of interval training against a non-exercising control group. Two studies[30 64] included both MICT and non-exercising control groups. Fourteen studies[29 30 32 33 44–46 54–56 60 62–64] used HIIT, while five studies[31 33 34 47 61] used SIT protocols. Other characteristics of the studies, including a detailed description of their samples, designs, exercise protocols, ways of controlling for diet and physical activity, and methods for the assessment of FatOx are presented in online supplemental file 3.

Methodological quality of included studies

The PEDro scale score of the included studies ranged from 4 to 6, suggesting a fair-to-good methodological quality of the included studies. A summary of methodological quality assessment and a table with individual scores for each included study are provided in online supplemental file 4.

Effects of interval training (HIIT and/or SIT) on FatOx compared with no exercise

Main and sensitivity analyses

In the meta-analysis including results from nine studies, we found a significant pooled effect of interval training on FatOx (MD=0.08; 95% CI 0.04 to 0.12; $p<0.001$; figure 1). Heterogeneity between the studies was substantial ($I^2=77.1\%$; $p<0.001$). All three sensitivity analyses confirmed that interval training improves FatOx compared with no exercise (MD=0.07 and $p<0.01$ for all; online supplemental figures 2–4).

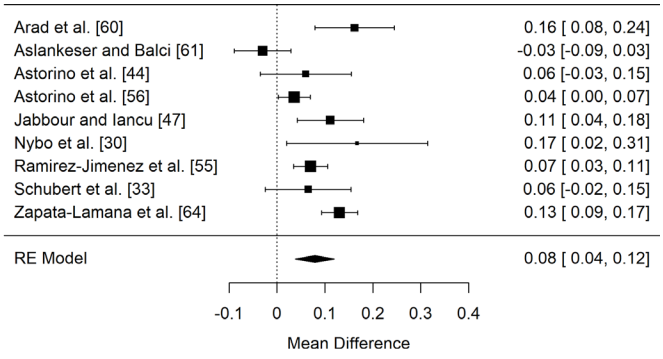

Figure 1 The effect of interval training (high-intensity interval training and/or sprint interval training) on fat oxidation (g/min). The effects are presented as mean difference (95% CI) in grams per minute. The effects are presented as mean difference (95% CI) in grams per minute. A positive value indicates a larger increase in fat oxidation as a result of interval training compared with no exercise. RE model, pooled mean difference between the observed effects of interval training and no exercise from a random-effects meta-analysis model.

Subgroup and moderation analyses by training modality

In a meta-analysis including seven studies,[30 33 44 55 56 60 64] we found a significant pooled effect of HIIT on FatOx (MD=0.09; 95% CI 0.05 to 0.13; $p<0.001$; $I^2=56.4\%$; table 1). The pooled effect of SIT on FatOx calculated from the results of three studies[33 47 61] was not found to be significant ($p=0.263$). We did not find a significant moderation effect for training modality ($p=0.270$).

Subgroup and moderation analyses by type of exercise

In a meta-analysis including eight studies,[33 44 47 55 56 60 61 64] we found a significant pooled effect of interval cycling on FatOx (MD=0.07; 95% CI 0.03 to 0.12; $p<0.001$; $I^2=78.9\%$). The pooled effect of interval running on FatOx could not be calculated and the moderation analysis could not be conducted, due to an insufficient number of studies.

Subgroup and moderation analyses by BMI category

In a meta-analysis including four studies,[47 55 60 64] we found a significant pooled effect of interval training on FatOx among individuals with overweight/obesity (MD=0.11; 95% CI 0.07 to 0.15; $p<0.001$; $I^2=57.1\%$). Among individuals with 'normal' weight, the pooled effect of interval training on FatOx calculated from the results of five studies[30 33 44 56 61] was not found to be significant ($p=0.108$). BMI ('normal' weight vs overweight/obesity) was found to be a significant moderator of the effects of interval training on FatOx ($p=0.014$).

Subgroup and moderation analyses by sex

In a meta-analysis including three studies,[30 33 55] we found a significant pooled effect of interval training on FatOx among men (MD=0.07; 95% CI 0.04 to 0.11; $p<0.001$; $I^2=0.3\%$). We also found a significant pooled effect of interval training on FatOx among women (MD=0.08; 95% CI 0.01 to 0.15; $p=0.027$; $I^2=80.0\%$), calculated from the results of five studies.[33 44 60 61 64] We did not find a significant moderation effect for sex ($p=0.972$).

Subgroup and moderation analyses for absolute versus relative exercise workload during FatOx assessment

In a meta-analysis including eight studies that assessed FatOx at the same absolute exercise workload before and after the

Table 1 The effect of high-intensity interval training (HIIT) and sprint interval training (SIT) on fat oxidation (g/min): subgroup and moderation meta-analyses

	MD*	95% CI†	p_d‡	I^2 (%)§	p_h¶	p_a**	p_m††
Training modality							
HIIT	0.09	0.05 to 0.13	<0.001	56.4	0.032	0.669	0.270
SIT	0.05	−0.04 to 0.14	0.263	77.7	0.006	0.480	
Type of exercise							
Cycling	0.07	0.03 to 0.12	<0.001	78.9	<0.001	0.745	n/a
Running	n/a	n/a	n/a	n/a	n/a	n/a	
BMI category‡‡							
'Normal' weight	0.04	−0.01 to 0.09	0.108	53.2	0.079	0.141	0.014
Overweight/obese	0.11	0.07 to 0.15	<0.001	57.1	0.062	0.327	
Sex							
Men	0.07	0.04 to 0.11	<0.001	0.3	0.384	0.646	0.972
Women	0.08	0.01 to 0.15	0.027	80.0	<0.001	0.962	
Exercise workload during fat oxidation assessment							
Absolute	0.07	0.03 to 0.11	0.001	72.5	0.004	0.154	n/a
Relative	n/a	n/a	n/a	n/a	n/a	n/a	

*Pooled mean difference (g/min) between the observed effects of interval training and no exercise. A positive value indicates a larger increase in fat oxidation as a result of interval training compared with no exercise
†95% confidence interval for pooled mean difference
‡p value for pooled mean difference
§I^2 measure of heterogeneity between studies expressed as percentage
¶p value from the test of heterogeneity
**p value for funnel plot asymmetry
††p value for the test of moderation effect
‡‡Body mass index classified as 'normal weight' (average BMI of participants between 18.5 kg/m^2 and 25 kg/m^2) or 'overweight/obese' (average BMI of participants greater than 25 kg/m^2)

intervention,[30 33 44 47 55 56 60 61] we found a significant pooled effect of interval training on FatOx (MD=0.07; 95% CI 0.03 to 0.11; p=0.001; I^2=72.5%). Only one study[64] assessed FatOx at the same relative exercise workload before and after the intervention, hence, we could not conduct the respective subgroup and moderation analyses.

Dose–response effects

In all meta-regression analyses, AICc indicated that the linear model provided the best balance between goodness of fit and simplicity of the model (figures 2 and 3, online supplemental table 1).

A significant dose–response relationship was found between the length of training regimen (expressed in weeks) and the effect of interval training on FatOx (β=0.01; 95% CI 0.00 to 0.02; p=0.003), showing that longer training regimens are associated with larger effects (figure 3). Significant effects on FatOx were apparent for training protocols lasting four weeks or longer.

A significant inverse dose–response relationship was found between the number of exercise sessions per week and the effects of interval training on FatOx (β=−0.06; 95% CI −0.10 to −0.01; p=0.010; figure 3). We did not find a significant association between any other type of exercise dose and the effects of interval training on FatOx (p>0.050 for all).

Differences between effects of interval training (HIIT and/or SIT) and MICT on FatOx

Main and sensitivity analyses

In a meta-analysis including 11 studies, we found that interval training is more effective than MICT in improving FatOx (MD=0.03; 95% CI 0.01 to 0.05; p=0.005; figure 4). Heterogeneity between the studies was low (I^2=11.0%; p=0.057). A sensitivity analysis did not confirm that interval training is more effective than MICT in improving FatOx (p=0.983; online supplemental figure 5).

Subgroup and moderation analyses by training modality

In a meta-analysis including nine studies,[29 30 32 45 46 54 62–64] we found that HIIT is more effective than MICT in improving FatOx (MD=0.03; 95% CI 0.02 to 0.05; p<0.001; I^2=0.0%; table 2). A subgroup meta-analysis for SIT and moderation analysis could not be conducted, due to an insufficient number of studies.

Subgroup and moderation analyses by type of exercise

In a meta-analysis including seven studies,[29 31 32 34 45 62 64] we found that interval cycling is more effective than moderate-intensity continuous cycling in improving FatOx (MD=0.02; 95% CI 0.00 to 0.05; p=0.047; I^2=10.7%). In a meta-analysis including four studies,[30 46 54 63] the difference between effects of interval running and moderate-intensity continuous running was not found to be significant (p=0.102). We did not find a significant moderation effect for the type of exercise (p=0.541).

Subgroup and moderation analyses by BMI category

In a meta-analysis including eight studies,[29 32 45 46 54 62–64] we found that interval training is more effective than MICT in improving FatOx in individuals with overweight or obesity (MD=0.03; 95% CI 0.02 to 0.05; p<0.001; I^2=0.0%). In a meta-analysis including three studies,[30 31 34] we did not find a significant difference between the effects of interval training and MICT on FatOx in individuals with 'normal' weight (p=0.405). BMI ('normal' weight vs overweight/obesity) was found to be a significant moderator of the effects of interval training on FatOx (p=0.016).

Subgroup and moderation analyses by sex

In a meta-analysis including four studies,[54 62–64] we found that interval training is more effective than MICT in

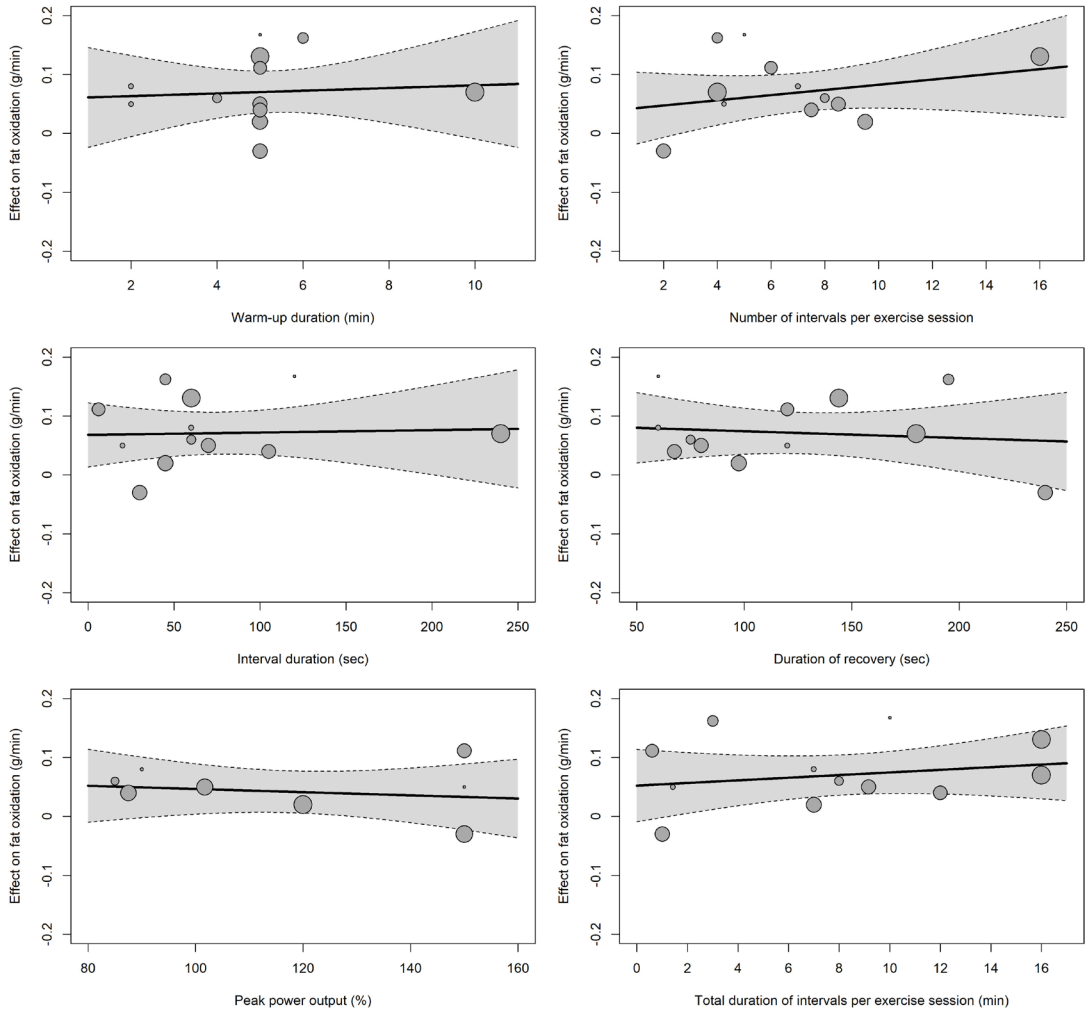

Figure 2 Dose–response effects of interval training (high-intensity interval training and/or sprint interval training) on fat oxidation: results of meta-regression analysis for predictors related to an exercise session. The effects are presented as mean difference in grams per minute. The circle sizes are proportional to the precision of effect(s) observed in each study. A positive value indicates a larger increase in fat oxidation as a result of interval training compared with no exercise. The dashed line represents the 95% CI of the regression line.

improving FatOx in women (MD=0.04; 95% CI 0.01 to 0.07; p=0.004; I^2=28.4%). In a meta-analysis including five studies,[29 30 32 34 54] we did not find a significant difference between the effects of interval training and MICT on FatOx in men (p=0.806). We did not find a significant moderation effect for sex (p=0.383).

Subgroup and moderation analyses for absolute versus relative exercise workload during FatOx assessment

We did not find a significant difference between the effects of interval training and MICT on FatOx in a meta-analysis of five studies[30 32 45 46 63] that assessed FatOx at the same absolute exercise workload before and after the intervention (p=0.206) and in a meta-analysis of six studies[29 31 34 54 62 64] that assessed FatOx at the same relative exercise workload before and after the intervention (p=0.658). We did not find a significant moderation effect for absolute versus relative exercise workload during FatOx assessment (p=0.515).

Publication bias

The Egger's test did not suggest publication bias for studies comparing the effects of interval training and no exercise (p=0.364; online supplemental figure 6) and for studies comparing the effects of interval training and MICT (p=0.051; online supplemental figure 7).

DISCUSSION

Main findings

The main finding of this systematic review and meta-analysis is that interval training (HIIT and/or SIT) is effective for increasing FatOx among adults, with the expected mean increase in FatOx ranging between 0.04 and 0.12 g/min. Significant effects were found among individuals with 'normal' weight and among individuals with overweight/obesity. However, significantly larger effects of interval training on FatOx were found among individuals with overweight/obesity. Furthermore, a significant effect on FatOx can be expected with completion of interval training regimens lasting ≥4 weeks. The magnitude of effects increases with greater length of training regimen, with every additional week of interval training expected to further increase FatOx on average by 0.004–0.017 g/min. However, we could not determine the probable ceiling effect, given that the longest duration of interval training in the included studies was 14 weeks. Results also reveal that interval training (HIIT and/or SIT) is generally more effective than MICT in increasing

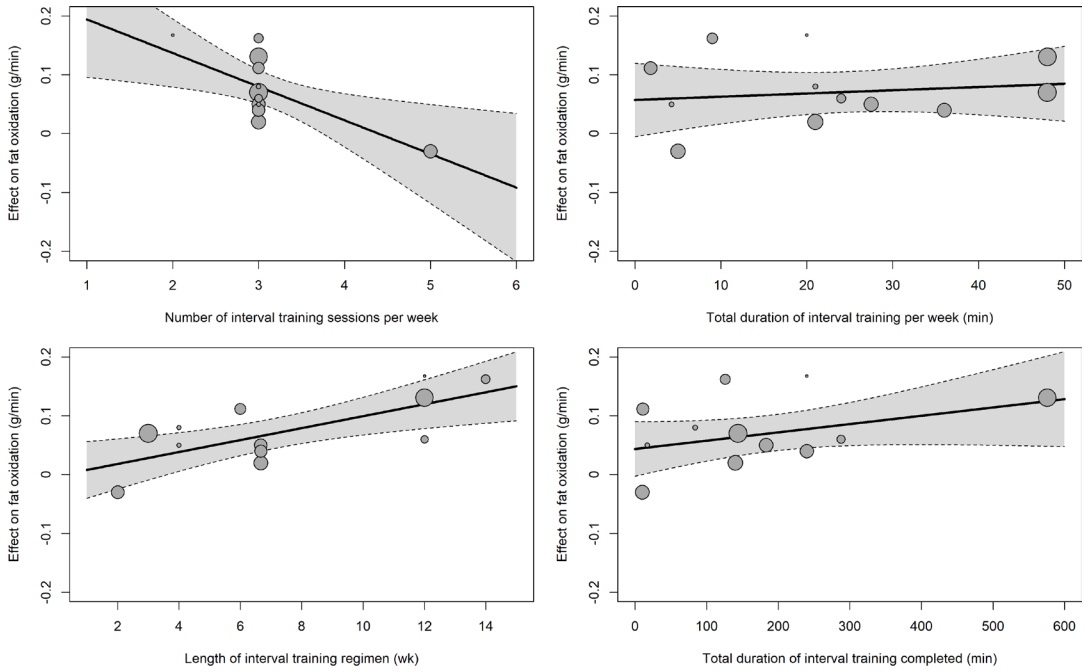

Figure 3 Dose–response effects of interval training (high-intensity interval training and/or sprint interval training) on fat oxidation: results of meta-regression analysis for predictors related to the training regimen. The effects are presented as mean difference in grams per minute. The circles sizes are proportional to the precision of effect(s) observed in each study. A positive value indicates a larger increase in fat oxidation as a result of interval training compared with no exercise. The dashed line represents the 95% CI of the regression line.

FatOx. However, a significant difference between the effects of interval training and MICT was found among individuals with overweight/obesity but not among individuals with 'normal' weight.

Effects of interval training (HIIT and/or SIT) on FatOx

Size of the effects

When expressed in relative terms, the pooled effect of interval training (HIIT and/or SIT vs no exercise) on FatOx (Cohen's d=0.24) found in our main meta-analysis can be categorised as small, according to Cohen's classification.[65] This small effect is comparable to the pooled effects of interval training on body weight, visceral and abdominal fat mass, total body fat mass and cardiorespiratory fitness found in previous meta-analyses.[66–68] However, in a meta-analysis including only studies in which interval training lasted ≥12 weeks (data not shown), we found a large effect size (Cohen's d=0.90). In comparison, the effect size for shorter regimens (data not shown) was very small (Cohen's d=0.16), according to Sawilowsky.[69] Similarly, in our subgroup meta-analysis for individuals with overweight/obesity, we found a medium effect size (Cohen's d=0.54), while for individuals with 'normal' weight the effect size was very small (Cohen's d=0.13).[65 69] This suggests that the magnitude of effects of HIIT or SIT on FatOx may significantly vary, depending on the length of training regimen and participant characteristics, such as obesity status.

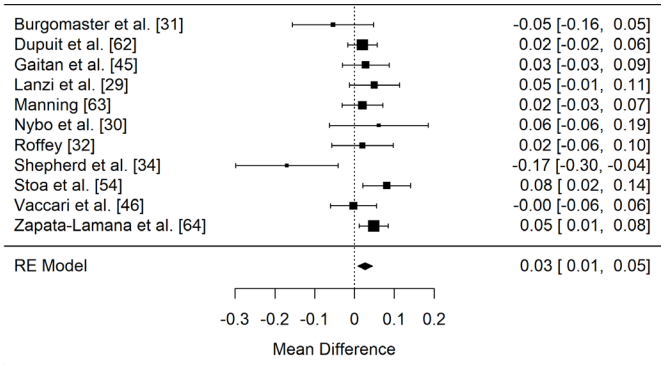

Figure 4 The difference between effects of interval training (high-intensity interval training and/or sprint interval training) and moderate-intensity continuous training (MICT) on fat oxidation (g/min). The effects are presented as mean difference (95% CI) in grams per minute. A positive value indicates a larger increase in fat oxidation as a result of interval training compared with MICT. RE Model, pooled mean difference between the observed effects of interval training and MICT from a random-effects meta-analysis model.

There are no widely accepted thresholds for interpreting training-induced increases in FatOx in terms of their practical or clinical significance. To facilitate easier interpretation of findings in this area, based on our meta-analyses, we propose that any increase greater than 0.07 g/min can be interpreted as a practically significant increase in FatOx. In our main meta-analysis, this value roughly corresponds to the lower threshold for small effect size (Cohen's d=0.20) suggested by Cohen.[65] It should be noted, however, that this threshold may not necessarily apply to other types of exercise or other population groups.

Moderators

Our results support findings from previous studies suggesting that the obesity status moderates the effects of interval training.[70–72] Individuals with obesity generally have higher FatOx during exercise than individuals with 'normal' weight,[73 74] which may be attributed to higher resting intramuscular triglyceride, resting non-esterified fatty acids[75] and basal plasma fatty acid oxidation concentrations.[73 76] Larger effects of HIIT and SIT observed in individuals with overweight or obesity, compared with

Table 2 The difference between effects of high-intensity interval training (HIIT) / sprint interval training (SIT) and moderate-intensity continuous training (MICT) on fat oxidation (g/min): subgroup and moderation meta-analyses

	MD*	95% CI†	p_d‡	I^2 (%)§	p_h¶	p_a**	p_m††
Training modality							
HIIT	0.03	0.02 to 0.05	<0.001	0.0	0.657	0.792	n/a
SIT	n/a	n/a	n/a	n/a	n/a	n/a	
Type of exercise							
Cycling	0.02	0.00 to 0.05	0.047	10.7	0.042	0.008	0.541
Running	0.03	−0.01 to 0.08	0.102	36.8	0.226	0.605	
BMI category‡‡							
'Normal' weight	−0.05	−0.18 to 0.07	0.405	70.7	0.040	0.872	0.016
Overweight/obese	0.03	0.02 to 0.05	<0.001	0.0	0.572	0.979	
Sex							
Men	0.01	−0.06 to 0.08	0.806	63.2	0.044	0.264	0.383
Women	0.04	0.01 to 0.07	0.004	28.4	0.146	0.158	
Exercise workload during fat oxidation assessment							
Absolute	0.02	−0.01 to 0.05	0.206	0.0	0.898	0.531	0.515
Relative	0.01	−0.04 to 0.07	0.658	81.9	0.006	0.014	

*Pooled mean difference between the observed effects of interval training and moderate-intensity exercise. A positive value indicates a larger increase in fat oxidation as a result of interval training compared with moderate-intensity exercise.
†95% confidence interval for pooled mean difference.
‡*p* value for pooled mean difference.
§I^2 measure of heterogeneity between studies expressed as percentage.
¶*p* value from the test of heterogeneity.
***p* value for funnel plot asymmetry.
††*p* value for the test of moderation effect.
‡‡Body mass index classified as 'normal weight' (average BMI of participants between 18.5 kg/m^2 and 25 kg/m^2) or 'overweight/obese' (average BMI of participants greater than 25 kg/m^2).

individuals with 'normal' weight, may be explained by greater increases in the oxidation of non-plasma fatty acids, presumably derived from intramuscular triglyceride.[74]

Only one study[30] compared interval running with no exercise, so the respective meta-analysis could not be performed. The CI for the pooled effect for interval cycling from our meta-analysis largely overlapped with the CI for the effect reported in the Nybo *et al* study,[30] providing no clear indication that the type of exercise moderates the effects of interval training on FatOx. Similarly, only one study[64] used relative intensities in the exercise protocol used for FatOx assessment. Although the effect of HIIT (vs no exercise) on FatOx found in this study (MD=0.13; 95% CI 0.09 to 0.17) appears to be somewhat higher than the pooled effect found in the studies that used absolute exercise intensities for FatOx assessment, this potential moderator needs to be further explored.

Dose–response effects

Our results showed that a longer length of interval training (HIIT and/or SIT) is associated with greater increases in FatOx. Although the average weekly increase in FatOx equal to 0.01 g/min may seem trivial per se, a cumulative increase in FatOx over a long period of time may actually be substantial. This would indicate that interval training should preferably be performed for a long period of time, to reap its full benefits in regard to FatOx. Previous meta-analyses found similar effects of the length of interval training regimen on changes in vascular function, markers of glucose regulation and insulin resistance, VO_{2max}, BMI, body fat and waist circumference.[8 66 77–80]

A significant inverse dose–response relationship was found between the number of interval training sessions per week and the magnitude of effects on FatOx. However, this finding should be interpreted with caution, because in all but two studies, the participants exercised three times per week. Additional studies examining effects of varying frequencies of HIIT or SIT on increases in FatOx are needed to draw a conclusion about this relationship.

Differences between effects of interval training (HIIT or SIT) and MICT on FatOx

Size of the effects

When expressed in relative terms, the pooled difference between the effects of interval training (HIIT and/or SIT) and MICT on FatOx (Cohen's d=0.18) found in our meta-analysis can be categorised as very small, according to Sawilowsky.[69] However, in the studies included in this meta-analysis, the interval training regimens required on average almost two times lower time commitment than the MICT regimens. Therefore, it may be concluded that interval training is likely to result in a slightly larger increase in FatOx compared with MICT, while saving a significant amount of time to participants. Given that a lack of time is one of the most commonly perceived barriers to exercise,[81] this finding may encourage many individuals who feel that they do not have enough time to exercise to consider engaging in interval training. The very small difference between the effects of interval training and MICT on FatOx corroborates findings for outcomes such as body composition, total cholesterol, and blood pressure.[10 67 80]

Moderators

We found that interval training (HIIT and/or SIT) is more effective than MICT for improving FatOx among individuals with overweight/obesity, while this was not found among individuals with 'normal' weight. This suggests that in exercise

programmes that aim to improve FatOx in individuals with overweight/obesity, priority may be given to interval training. However, based on our systematic review, no conclusions can be made in regard to other potential moderators of the differential effects of interval training and MICT on FatOx.

Methodological quality of included studies

Although all included studies were of fair-to-good methodological quality, several of their limitations should be taken into account when interpreting the findings of our meta-analysis. First, participants in five studies[29–31 54 61] were not randomly allocated to the intervention and control groups, potentially leading to bias. Second, in most studies, participants were only instructed to abstain from physical activity for 24 hours before testing instead of assessing their physical activity levels. While it may be important to assess participants' physical activity, a recent study did not find a significant association between habitual physical activity recorded 48 hours before repeated testing of FatOx and subsequent FatOx estimates.[82] Third, only one[63] of the included studies standardised participants' food intake before FatOx testing, despite the fact that short-term changes in diet can exert a profound effect on substrate availability and oxidation in working skeletal muscle.[25 83] Hence, future studies should consider adopting more detailed and comprehensive monitoring of physical activity and dietary intake before the FatOx assessment. Fourth, additional limitations of the included studies were not blinding participants, investigators who delivered the intervention, and assessors to group allocation. Given the obvious challenges in blinding participants and investigators who deliver the intervention to group allocation in intervention trials that include exercise, further studies should consider including assessor blinding. Finally, of the 13 studies involving women, only 3 studies[33 47 60] considered the menstrual cycle, which may have affected some of the findings[84] by reducing the validity of FatOx estimates. While some studies did not find a significant effect of menstrual cycle on estimates of FatOx,[85–87] future studies assessing the effects of interval training on FatOx may want to consider this potentially relevant factor, especially when small effects are anticipated.

Certainty of evidence

Based on the GRADE assessment, certainty of evidence for the effects of interval training (HIIT and/or SIT) on FatOx can be considered as 'low' (online supplemental table 2). The reasons why certainty of the evidence was downgraded include: (a) issues with the methodological quality of individual studies included in the meta-analysis; (b) substantial heterogeneity between the studies and (c) a relatively wide CI for the pooled effect covering a range of both practically unimportant and important effects. However, we upgraded certainty of the evidence, due to the significant dose–response relationship between the length of the interval training regimen and its effects on FatOx.

Certainty of evidence for the difference between effects of interval training and MICT on FatOx can be considered as 'moderate'. Although individual studies in this meta-analysis had issues with methodological quality, heterogeneity between the studies was low and the CI of the pooled effect size covered only practically unimportant effects.

Practical implications

When recommending HIIT and SIT regimens longer than 12 weeks, medical and exercise practitioners can expect their clients to achieve improvements in FatOx larger than 0.13 g/min. However, even shorter HIIT and SIT regimens lasting more than four weeks are expected to increase FatOx. As a result of engagement in HIIT or SIT, higher FatOx may facilitate improvements in obesity status and metabolic health. Effects of HIIT and SIT on FatOx (especially in some subgroup analyses) may not seem very large per se. However, they can be considered practically important in a context of a holistic approach to the management of obesity and metabolic health, where exercise represents only one important component of the overall intervention and potentially contributes to the cumulative effect. They are also practically important if considered long-term. For example, for a 'typical' adult who engages in 150 min of moderate-to-vigorous physical activity per week, a training-mediated increase in FatOx of 0.13 g/min (ie, the expected effect for engaging in ≥12 weeks of HIIT or SIT) may lead to ~1 kg of additional fat burned in a year or ~10 kg in a decade.

When deciding whether to recommend HIIT/SIT or MICT to their clients, medical and exercise practitioners should consider that slightly larger improvements in FatOx are expected for HIIT or SIT (on average 0.03 g/min). It should also be emphasised that HIIT and SIT typically require less time than MICT, which may be important to some clients.

Greater overall benefits from HIIT and SIT (as well as a larger effect in comparison with MICT) can be expected for individuals with overweight or obesity, compared with individuals with 'normal' weight. This is an encouraging finding, because improvements in FatOx may be especially important among individuals with overweight or obesity.

When prescribing or promoting HIIT and SIT, it is important to acknowledge that the nature of these exercise modalities may be aversive for some individuals.[88] While some of the training regimens used in the included studies (particularly some of the SIT regimens) are likely inappropriate for most adults, there is a variety of HIIT and SIT protocols to choose from, and an appropriate one may be found for different population groups.[88]

Strengths and limitations of the review

The key strengths of this review are the comprehensive literature search conducted in nine bibliographic databases, rigorous checking of the extracted data performed by two independent authors (in addition to the author who extracted the data), and consideration of five potential effect moderators in subgroup analyses and ten predictors in dose–response meta-regression analyses.

This review was subject to limitations. First, the studies included in the meta-analyses used different interval training and study protocols, and they were conducted in different population groups. While this enabled us to conduct the moderation and dose–response analyses, it may have contributed to the substantial heterogeneity between studies in some meta-analyses and it made the interpretation of findings more challenging. Second, several subgroup and moderation analyses could not be conducted due to an insufficient number of suitable studies. Third, as there are no widely accepted thresholds for interpreting changes in FatOx in terms of their practical or clinical significance, while assessing certainty of evidence we used the effect size classification proposed by Cohen.[65] This generic classification of effect sizes may not necessarily be valid for classifying changes in FatOx. Certainty of evidence regarding the effects of interval training on FatOx was downgraded based on the comparison of the effect size with the Cohen's threshold.[65] We

may have, therefore, underestimated certainty of the evidence. Fourth, due to a relatively small number of studies included in the meta-analyses, heterogeneity may have been overestimated or underestimated.[89] Fifth, the probability of type I error may be increased, due to a range of subgroup, moderator and dose–response analyses. However, even after applying the Holm-Šidák correction for multiple comparisons, 12 out of 15 significant effects remained significant. The only effects that did not remain significant were: (a) the effect of interval cycling on FatOx; (b) the effect of interval training on FatOx among women and (c) the dose–response effect of the number of interval training sessions per week on FatOx. These three effects should, therefore, be interpreted with caution. Finally, as suggested in a recent review,[90] a range of measurement-related factors such as ergometer type, metabolic cart and warm-up protocol, may affect FatOx estimates. These factors varied across the included studies, which might have increased between-study heterogeneity.

CONCLUSION

Our systematic review and meta-analysis that included 18 studies of fair-to-good methodological quality with a total of 511 participants show that HIIT and SIT are effective for improving FatOx. While HIIT and SIT regimens of any duration longer than four weeks are likely to increase FatOx, greater improvements in FatOx can be expected with longer training programmes. HIIT and SIT are effective for improving FatOx among both individuals with 'normal' weight and individuals with overweight or obesity; however, larger benefits can be expected in the latter population group. We also found that interval training (HIIT and/or SIT) is generally more effective than MICT in increasing FatOx. Based on these findings, medical and exercise practitioners can provide evidence-based recommendations to their clients to engage in HIIT and SIT, with the aim to increase FatOx, and in turn improve their metabolic health.

More research is needed on potential moderators of the effects, dose–response relationships and underlying mechanisms explaining these increases in FatOx. To improve certainty of the evidence on the effects of HIIT and SIT on FatOx, more studies with similar protocols and good methodological quality are needed. Future studies should also consider monitoring physical activity and dietary intake before the assessment of FatOx, blinding of assessors to group allocation, and considering the stage of menstrual cycle.

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Contributors MMA conceived the idea for the study, performed the literature search, study selection, data extraction, and risk of bias assessment, and participated in drafting the manuscript. YG participated in study selection, data extraction and risk of bias assessment. NS provided methodological guidance on the study design and performed the GRADE assessment. ŞNK, HHT, TAA and JG contributed to writing the manuscript. ZP provided methodological guidance on the study design, participated in the data extraction and study selection, performed the statistical analysis, interpreted the results, participated in drafting the manuscript, and led the correspondence with journal editors and reviewers. All authors revised the draft manuscript, contributed to its revisions and approved its final version.

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