Systematic Review

Is Low-Volume High-Intensity Interval Training a Time-Efficient Strategy to Improve Cardiometabolic Health and Body Composition? A Meta-Analysis

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ABSTRACT

The present meta-analysis aimed to assess the effects of low-volume high-intensity interval training (LV-HIIT; i.e., ≤5 min high-intensity exercise within a ≤15-min session) on cardiometabolic health and body composition. A systematic search was performed in accordance with PRISMA guidelines to assess the effect of LV-HIIT on cardiometabolic health and body composition. Twenty-one studies (moderate to high quality) with a total of 849 participants were included in this meta-analysis. LV-HIIT increased cardiorespiratory fitness (CRF, SMD=1.19 [0.87, 1.50]) while lowering systolic blood pressure (SMD=-1.44 [-1.68, -1.20]), diastolic blood pressure (SMD=-1.51 [-1.75, -1.27]), mean arterial pressure (SMD=-1.55 [-1.80, -1.30]), MetS z-score (SMD=-0.76 [-1.02, -0.49]), fat mass (kg) (SMD=-0.22 [-0.44, 0.00]), fat mass (%) (SMD=-0.22 [-0.41, -0.02]), and waist circumference (SMD= -0.53 [-0.75, -0.31]) compared to untrained control (CONTROL). Despite a total time-commitment of LV-HIIT of only 14-47% and 45-94% compared to moderate-intensity continuous training and HV-HIIT, respectively, there were no statistically significant differences observed for any outcomes in comparisons between LV-HIIT and moderate-intensity continuous training (MICT) or high-volume HIIT. Significant inverse dose–responses were observed between the change in CRF with LV-HIIT and sprint repetitions (β=−0.52 [-0.76, -0.28]), high-intensity duration (β=−0.21 [-0.39, -0.02]), and total duration (β=−0.19 [-0.36, -0.02]), while higher intensity significantly improved CRF gains. LV-HIIT can improve cardiometabolic health and body composition and represent a time-efficient alternative to MICT and HV-HIIT. Performing LV-HIIT at a higher intensity drives higher CRF gains. More repetitions, longer time at high-intensity, and total session duration did not augment gains in CRF.

PROSPERO registration: CRD42023422518.

Keywords: Low-volume HIIT; CRF; cardiometabolic health; body composition

NOVELTY

1. LV-HIIT is efficacious in improving **cardiometabolic health and** body composition **and may represent a time-efficient alternative to MICT and HV-HIIT**.
2. Performing LV-HIIT at a higher intensity drives higher CRF gains, and more repetitions, longer duration high-intensity, and total session duration did not augment gains in CRF.

INTRODUCTION

Cardiorespiratory fitness (CRF) has emerged as a clinical vital sign in recent years (Ross *et al.*, 2016), as low CRF is linked to an increased risk of metabolic disease (Haapala *et al.*, 2022), cardiovascular disease (CVD), and cancer (Laukkanen *et al.*, 2004). The mortality risk for individuals with the lowest CRF (20th percentile) was 4-fold higher compared with individuals with the highest CRF. (Kokkinos *et al.*, 2022). Physical activity, including exercise, is acknowledged as a fundamental therapy for improving CRF (Pérez-Martínez *et al.*, 2017). Guidelines from the World Health Organization (WHO) advocate that adults should partake in at least 150-300 minutes (min) of moderate-intensity exercise or 75-150 min of vigorous-intensity exercise per week, or an equivalent combination of both (Piercy *et al.*, 2018; Bull *et al.*, 2020).

However, current surveys based on self-reported data indicate that 23.3% of adults worldwide (Sallis *et al.*, 2016) and 35% (Guthold *et al.*, 2018) of adults in developed countries fail to meet the prescribed physical activity criteria due to various factors, including perceived time constraints (Kimm *et al.*, 2006; Reichert *et al.*, 2007; Garne-Dalgaard *et al.*, 2019). A typical 30 min exercise session involves preparation, warm-up, and cool-down, often performed after commuting to a fitness facility, thereby requiring a substantial time commitment.

To address the barrier of perceived lack of time, recent guideline recommendations (Piercy *et al.*, 2018) and cohort studies (Ahmadi *et al.*, 2022; Stamatakis *et al.*, 2022) have emphasized the cardiometabolic health benefits of low-volume (<10 min) vigorous exercise. This style of exercise can be easily performed multiple times throughout the day, thus serving as interruptions to sedentary activity and counteracting the detrimental effects of prolonged sitting on cardiometabolic health (Dunstan *et al.*, 2021). Consequently, the explorations of the health benefits of such brief exercise sessions have become a burgeoning research area.

High-intensity interval training (HIIT) refers to brief bouts of high-intensity exercise interspersed with intervals of recovery (Gillen *et al.*, 2014). HIIT has gained increasing popularity in the realms of fitness enthusiasts, sports competitors, and even public health (Buchheit *et al.*, 2013). This approach is valued for its time efficiency and induces various health benefits, including improved body composition (Batacan *et al.*, 2017; Maillard *et al.*, 2018), CRF (Milanović *et al.*, 2015), and vascular function (Costa *et al.*, 2018). Adaptations to HIIT appear comparable, or even superior, to moderate-intensity continuous training (MICT) (Milanović *et al.*, 2015; Su *et al.*, 2019; Sultana *et al.*, 2019). Nonetheless, traditional HIIT protocols are not particularly time-efficient, typically requiring 25 to 40 min per session (Gillen *et al.*, 2014). Even sprint interval training (SIT), a version of HIIT involving 'all-out' or 'supramaximal' sprints, is not as time efficient as often claimed; the 'classic' Wingate-based training entails 4-6 × 30-second (s) sessions interspersed with 4-5 min of recovery resulting in a total time commitment of ~25-30 min (Gibala *et al.*, 2020).

Therefore, to move HIIT from a laboratory "magic bullet" to a "practical strategy" for impacting public health (Gray *et al.*, 2016; Nassis, 2017), it has been proposed to shift focus to more time-efficient, low-volume high-intensity interval training (LV-HIIT) interventions (Vollaard *et al.*, 2017). LV-HIIT requires a minimal time commitment and may be associated with more acceptable perceptual responses (Songsorn *et al.*, 2019; Metcalfe *et al.*, 2022). A recent meta-analysis including 67 HIIT interventions reported that longer HIIT time per session or week predicted greater dropout (Reljic *et al.*, 2019). Crucially, initial evidence suggests that there is not a positive dose–response between HIIT volume and increases in CRF (Vollaard *et al.*, 2017; Vollaard *et al.* 2017). Together, the lack of associations between greater HIIT volume and lower CRF gain, and the higher dropout with greater HIIT volume, suggest the need to further verify and explore the feasibility and efficacy of LV-HIIT and attempt to uncover the minimum effective dose for LV-HIIT protocols and health improvements.

There is currently no consensus on the definition of LV-HIIT, primarily due to disagreement regarding whether it should be quantified in terms of metabolic equivalent min or exercise duration. Sultana et al. (2019) meta-analyzed the effect of LV-HIIT on body composition and cardiorespiratory fitness, and defined LV-HIIT as "≤500 metabolic equivalent min per week". However, this approach may not satisfy exercise participants who attach greater importance to the total exercise time, which affects their decision to continue or increase their frequency of participation (Harris *et al.*, 2019). Additionally, 71% of the HIIT sessions included in the study by Sultana et al. (2019) lasted longer than 15 min, questioning the appropriateness of their definition.

Considering the aim to provide a time-efficient alternative to MICT, defining LV-HIIT based on exercise duration may be more practical. However, the existing definitions of LV-HIIT using exercise duration are inconsistent. While Taylor (2019) and Sabag et al. (2022) defined LV-HIIT as the total time spent in active intervals, excluding rest periods, not exceeding 15 min, Gibala and Little (2020) defined LV-HIIT as intervals of vigorous exercise with a maximum duration of 5 min for the session (e.g., 5 × 1min intervals), and overall session duration, including warm-up, cool-down, and recovery periods, of no more than 15 min. To address the perceived barrier of lack of time, total exercise session duration is more relevant than the volume of high-intensity bouts per se and therefore we interpret the latter definition as being more relevant to the issue of addressing physical inactivity in the general population.

To the best of our knowledge, no systematic reviews or meta-analyses have been conducted on the cardiometabolic health benefits of LV-HIIT protocols with a total session duration of ≤15 min. The absence of such a comprehensive analysis limits our understanding of the feasibility of implementing specific LV-HIIT applications, particularly in terms of their health-enhancing effects and dose-response relationships.

Therefore, we aimed to conduct a meta-analysis on the effects of LV-HIIT on cardiometabolic health and body composition in non-athlete adults, comparing them with high-volume HIIT (HV-HIIT) and MICT, while also exploring potential dose-response relationships and the modifying effects of protocol parameters.

METHODS

This review was performed in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) (Page *et al.*, 2021) guidelines and preregistered in the PROSPERO database (ID: CRD42023422518).

Search strategy

PubMed/MEDLINE, EBSCOhost, Cochrane Library, and Web of Science (Core Collection) were searched from the database inception to 30 April 2023. A Medical Subject Heading (MeSH) search was performed to establish all related literature on LV-HIIT. Specifically, the database searches were performed using the keywords and truncations in conjunction with using the following search criteria: (high intensity interval training OR high-intensity interval training OR high intensity interval exercise OR high-intensity interval exercise OR high intensity intermittent exercise OR high-intensity intermittent exercise OR sprint interval training OR Low-volume HIIT OR Low-volume high-intensity interval training OR HIIT OR HIIE) AND (BMI OR waist circumference OR hip circumference OR waist-to-hip ratio OR resting heart rate OR percent body fat OR lean body mass OR blood pressure OR VO_{2max} OR fitness OR CRF OR VO_{2peak} OR MetS z-score) AND Humans[MeSH] AND Adult[MeSH] AND English[lang]. The reference lists of relevant meta-analyses and articles were also screened. Two reviewers (YMY and LHX) independently assessed the identified publications for eligibility, with any disagreements being resolved by a third reviewer (LYM).

Study selection

Studies were considered to be eligible for inclusion according to the following criteria: (1) the type of study was controlled between groups and consisted of a parallel randomized controlled trial or a pre-and post-randomized crossover trial; (2) Inclusion of adult participants (⩾18 years) who included any health condition; athletes or well-trained adults (participated in regular structured training programmes for at least 3 months prior to the intervention period) are excluded; (3) training needed to involve an LV-HIIT intervention, i.e., intervals of at least vigorous intensity (⩾77%HR_{max}, a rating of perceived exertion [RPE] ⩾14 [6–20 scale]) (Garber *et al.*, 2011), or 'all-out' exercise ≤5 min total for each session, and an overall session duration, including warm-up, cool-down, and recovery periods, of ≤15 min, with the intervention lasting at least 2 weeks; (4) a comparator group involving a no-training control, MICT, or HV-HIIT (i.e., any HIIT protocol not meeting the criteria for LV-HIIT); and (5) the study included a quantitative analysis of the effect of LV-HIIT on at least one of the following outcome measures (statistical comparison of intervention to baseline/pre-training values): CRF (VO_{2max}/VO_{2peak}), blood pressure, MetS z-score, fat mass (FM), fat mass% (FM%), fat free mass (FFM), or waist circumference (WC).

Data extraction and conversion

Two independent reviewers (YMY and LHX) extracted: the lead author's name, year of publication, participant characteristics, study design, training protocol, means, and standard deviations of outcome indicators at pre-and post-intervention. In addition, data on adherence, dropout rates, and adverse events were collected as available. Any disagreements were resolved by consensus. If information was missing, an attempt was made to contact the study investigators to obtain the necessary data. If the study authors were unresponsive or unreachable, the study was excluded.

We extracted the mean, SD, and sample size reported for each group pre- and post-intervention. We pooled effects using pre- and post-intervention differences ($M \pm SD$) for each outcome indicator. The first step is to calculate the difference in means (raw mean difference between post and preintervention for each intervention group) (Cumpston *et al.*, 2019):

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

where MD_{diff} is the raw mean difference, M_{post} is the reported mean post-intervention, and M_{pre} is the reported mean pre-intervention (Cumpston *et al.*, 2019).

If the study only reported confidence intervals, they were converted to SD using the following formula (Cumpston *et al.*, 2019):

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

where SD is standard deviation, N is the group sample size, CI_{high} is the upper limit of the confidence interval, CI_{low} is the lower limit of the confidence interval, and t is the t distribution with $N - 1$ degrees of freedom the respective confidence level (Cumpston *et al.*, 2019).

Then the SD of the difference in means (SD_{diff}) is calculated as follows (Cumpston *et al.*, 2019):

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

where SD_{diff} is the standard deviation of the difference in means, SD_{pre} is the standard deviation from pre-intervention, and SD_{post} is the standard deviation from post-intervention (Cumpston *et al.*, 2019). As the original studies included in the meta-analysis did not report Pearson's correlation coefficients (r) for pre- and post-intervention outcomes, we first attempted to use r = 0.95 for studies that reported a SD_{change} based on the recommendations in the Cochran (Cumpston *et al.*, 2019). Secondly, meta-analyses with similar outcome were referenced, resulting in r=0.8 (Khodadadi *et al.*, 2023), r=0.85 (Mattioni Maturana *et al.*, 2021) and r=0.89 (Bonafiglia *et al.*, 2022) respectively, with r=0.85 being the final choice after sensitivity analysis.

$$r = \frac{{SD_{pre}}^2 + {SD_{post}}^2 - {SD_{change}}^2}{2 \times SD_{pre} \times SD_{post}}$$

Methodological quality of included studies

The Physiotherapy Evidence Database (PEDro) (de Morton, 2009) scale was used to assess the risk of bias and methodological quality of included studies. The PEDro scale scores studies on a scale of 0-10; studies scoring ≥6 are considered high quality, those scoring 4-5 are considered moderate quality, and those scoring ≤3 are considered low quality. Two authors (YMY and LHX) evaluated the studies, and a third author

(LYM) double-checked the assigned scores. Evidence of effectiveness for each study was combined with quality scores for use in discussing the results.

Statistical analysis

Statistical analyses were conducted using the "meta" and "metafor" package in the statistical software R (V.4.2.0). The meta-analysis was performed using a generic inverse-variance pooling method and pooled effect sizes with a random-effects model using the DerSimonia-Laird approach (DerSimonian *et al.*, 1986) to summarize the effects of LV-HIIT on cardiometabolic health and body composition measures to compare to CONTROL, MICT, and HV-HIIT. The effects were presented as a standard mean difference (SMD) with estimated Hedges' g, and were classified as trivial (0.2), small (0.2–0.5), medium (0.5–0.8), and large (> 0.8). Statistical significance was set at $p < 0.05$.

We calculated a 95% confidence interval (CI). Also, given that the prediction interval (PI) is a measure of the effect of the treatment considering heterogeneity and can provide useful additional information for the CI, we calculated the PI based on t-distribution (Nagashima *et al.*, 2019). We identified studies as statistical outliers when the CI did not overlap with the CI of the pooled effect, and assessed the effect of individual studies with an influence analysis using the leave-one-out method. Numerous variables are currently used to assess heterogeneity (Cochrane's Q, I^2 statistic, tau^2, Tau), but most of the available textbooks and recent literature support use of I^2 statistic (I^2) as the primary source of information on the degree of heterogeneity (Nakagawa *et al.*, 2017). Therefore, the main analysis reports I^2 with the following interpretations: 0%-40%, might not be important; 30%-60%, may represent moderate heterogeneity; 50%-90%, may represent substantial heterogeneity; and 75%-100%, considerable heterogeneity.

With reference to previous studies, we selected the following variables for subgroup analyses: (1) baseline BMI; (2) baseline CRF; (3) age; (4) training frequency; (5) training intensity (6) training mode. Among these, the baseline values related to clinically relevant cutoff points were defined as follows: (1) BMI are <25 $kg{\cdot}m^{-2}$, 25~30 $kg{\cdot}m^{-2}$, and >30 $kg{\cdot}m^{-2}$; (2) CRF are 20-30 $mL{\cdot}kg^{-1}{\cdot}min^{-1}$, 30-35 $mL{\cdot}kg^{-1}{\cdot}min^{-1}$, >35 $mL{\cdot}kg^{-1}{\cdot}min^{-1}$; (3) age are 20-30 yr old and 45-57 yr old. To explore the dose-response effects of LV-HIIT on CRF, we conducted a set of meta-regression analyses based on random effects models, each including the modified variables associated with the protocol: (1) warm-up; (2) repetitions; (3) duration per repetitions; (4) recovery per repetitions: (5) high-intensity duration per sessions; (6) total duration per sessions; (7) total intervention period; (8) total intervention sessions. In addition, we used the contour-enhanced funnel plot (Peters *et al.*, 2008) combined with Egger's asymmetry test (Egger *et al.*, 1997) to check for publication bias and the $p>0.05$ was considered without any publication bias.

RESULTS

Search results

The initial database search yielded 6311 publications. Subsequent screening resulted in 21 papers (Metcalfe *et al.*, 2012; Matsuo *et al.*, 2014; Scribbans *et al.*, 2014; Foster *et al.*, 2015; Gillen *et al.*, 2016; Jabbour *et al.*, 2017; Ramos *et al.*, 2017; Ruffino *et al.*, 2017; Schubert *et al.*, 2017; Reljic, Wittmann *et al.*, 2018; Schaun *et al.*, 2018; Banitalebi *et al.*, 2019; Cuddy *et al.*, 2019; Reljic *et al.*, 2020, 2023; Reljic *et al.*, 2021;

Reljic *et al.*, 2021; Reljic, *et al.*, 2022; Reljic, *et al.*, 2022; Scoubeau *et al.*, 2023; Venegas-Carro *et al.*, 2023) eligible to be included in the meta-analysis (**Figure 1**).

******Fig. 1. Here******

Study characteristics

A total of 849 individuals (497 men and 352 women; age range: 19 to 57 years) participated in the included studies. A detailed description of the study participants is in **Table. 1.**

******Table. 1. Here******

The LV-HIIT interventions ranged from 4-24 weeks, 2-5 times/week, the mode was cycling, running/walking, and self-weight resistance exercise, with a total session duration of 4-15 min, warm-up time 0-10 min, interval training time per session 30 s-5 min, interval recovery 10 s-3 min, intensity 80% HR_{max} to “all-out”, and cool down time 3-5 min.

The MICT interventions ranged from 6-16 weeks, 2-5 times/week, the mode being cycling or walking, total session duration 30-50 min, warm-up time 0-5 min, intensity 60% HR_{max} to 75% HR_{max}, cool down time 0-5 min. The HV-HIIT interventions ranged from 4-16 weeks, 2-5 times/week, the mode was cycling or self-weight resistance exercise, with a total session duration 15-38 min, warm-up time 2-10 min, interval training time per session 6.5-9 min, interval recovery 1-3 min, intensity 85% HR_{max} to 95% HR_{max}, and a cool down time 3-5 min. A detailed description of the interventions is provided in **Table. 2**.

******Table. 2. Here******

Methodological quality of included studies

The obtained PEDro scores ranged from moderate to high quality (5 to 9) for the systematic review and meta-analysis. Table 3 provides a detailed summary of the methodological quality assessment, including individual PEDro scores for each study.

******Table. 3. Here******

Effects of LV-HIIT versus CONTROL

Thirteen studies (Metcalfe *et al.*, 2012; Gillen *et al.*, 2016; Jabbour *et al.*, 2017; Schubert *et al.*, 2017; Banitalebi *et al.*, 2019; Reljic *et al.*, 2020, 2023; Reljic *et al.*, 2021; Reljic *et al.*, 2021; Reljic, *et al.*, 2022; Reljic, *et al.*, 2022; Scoubeau *et al.*, 2023; Venegas-Carro *et al.*, 2023) assessed the effects of LV-HIIT versus CONTROL on CRF, blood pressure, MetS z-score, and body composition. Participants include normal-weight healthy, and individuals living with obesity, type 2 diabetes, and metabolic syndrome. Ten studies (Metcalfe *et al.*, 2012; Gillen *et al.*, 2016; Schubert *et al.*, 2017; Banitalebi *et al.*, 2019; Reljic *et al.*, 2020, 2023; Reljic *et al.*, 2021; Reljic *et al.*, 2021; Scoubeau *et al.*, 2023; Venegas-Carro *et al.*, 2023) reported exercise adherence for LV-HIIT ranging from 78-100%, and no studies reported adverse events for LV-HIIT.

CRF

The meta-analysis found a significant improvement effect of LV-HIIT on CRF versus CONTROL (SMD=1.19; 95% CI [0.87, 1.50]; p<0.001; I^2=58%; p=0.003; **Fig. 2**, Egger's p=0.07).

******Fig. 2. Here******

We further conducted subgroup analyses to explore modifying effects of protocol or participant characteristics (**Table 4**). We found a significant moderating effect of baseline CRF and intensity, with greater improvements in CRF with supramaximal exercise (i.e., SIT) compared to (sub-) maximal exercise (i.e., HIIT). No other significant subgroup differences were found.

Table. 4. Here

Meta-regression analyses were conducted to explore the modifying effects of warm-up, repetitions, duration per repetition, recovery per repetition, high-intensity duration per sessions, total duration per sessions, total intervention period and total training sessions (**Fig. 3**). A significant inverse dose–response relationship was found between the repetitions (β=−0.52 [-0.76, -0.28]; p<0.0001), high-intensity duration per session (β=−0.21 [-0.39, -0.02]; p=0.03), and total duration per session (β=−0.19 [-0.36, -0.02]; p=0.03) for the effects of LV-HIIT on CRF. We did not find a significant association between any other variables of exercise and the effects of LV-HIIT on CRF (p>0.05 for all). Details of the statistical results are available in **Supplementary Table 1**.

Fig. 3. Here

*** *Supplementary Table 1. Here****

Blood pressure, MetS z-score, and Body composition

The meta-analysis found a significant improvement effect of LV-HIIT on SBP (SMD= -1.44; 95% CI [-1.68, -1.20]; p<0.001; I^2=0%; p=0.89; Fig. 4-A), DBP (SMD= -1.51; 95% CI [-1.75, -1.27]; p<0.001; I^2=0%; p=0.78; Fig. 4-B), MAP (SMD= -1.55; 95% CI [-1.80, -1.30]; p<0.001; I^2=0%; p=0.70; Fig. 4-C), MetS z-score (SMD= -0.76; 95% CI [-1.02, -0.49]; p<0.001; I^2=0%; p=0.72; Fig. 4-D), FM (SMD= -0.22; 95% CI [-0.44, 0.00]; p=0.05; I^2=0%; p>0.99; Fig. 4-E), FM% (SMD= -0.22; 95% CI [-0.41, -0.02]; p=0.03; I^2=0%; p>0.99; Fig. 4-F, Egger's p=0.14), WC (SMD= -0.53; 95% CI [-0.75, -0.31]; p<0.001; I^2=0%; p=0.78; Fig. 4-H) versus CONTROL. The meta-analysis found no statistically significant differences of LV-HIIT on FFM (SMD= 0.03; 95% CI [-0.17, 0.23]; *p*=0.77; I^2=0%; *p*>0.99; Fig. 4-G, Egger's *p*=0.66) versus CONTROL.

******Fig. 4. Here******

Effects of LV-HIIT versus MICT

Nine studies (Matsuo *et al.*, 2014; Scribbans *et al.*, 2014; Foster *et al.*, 2015; Gillen *et al.*, 2016; Ramos *et al.*, 2017; Ruffino *et al.*, 2017; Reljic, Wittmann *et al.*, 2018; Schaun *et al.*, 2018; Cuddy *et al.*, 2019) assessed the effects of LV-HIIT versus MICT on CRF, blood pressure, MetS z-score, and body composition. Participants included normal-weight healthy, and individuals living with obesity, type 2 diabetes, and metabolic syndrome. The total duration of LV-HIIT sessions only required 14% to 47% than for MICT. Four studies (Matsuo *et al.*, 2014; Ramos *et al.*, 2017; Ruffino *et al.*, 2017; Reljic *et al.*, 2018) reported exercise adherence for LV-HIIT (85-99%) and MICT (79-97%); adherence to LV-HIIT was numerically higher than MICT in all studies, and no studies reported adverse events for LV-HIIT.

The meta-analysis found no significant differences between LV-HIIT and MICT on CRF (SMD= 0.18; 95% CI [-0.06, 0.42]; *p*=0.15; I^2=11%; *p*=0.35; Fig. 5-A, Egger's *p*=0.65), SBP (SMD= -0.31; 95% CI [-0.64, 0.02]; *p*=0.06; I^2=0%; *p*=0.47; Fig. 5-B), DBP (SMD= 0.09; 95% CI [-0.36, 0.54]; *p*=0.89; I^2=49%; *p*=0.10; Fig. 5-C) , MetS z-score (SMD= -0.03; 95% CI [-0.66, 0.60]; *p*=0.93; I^2=51%; *p*=0.13; Fig. 5-D), FM (SMD=0.01; 95% CI [-0.58, 0.59]; *p*=0.98; I^2=0%; *p*=0.97; Fig. 5-E), FM% (SMD=0.05; 95% CI [-0.23, 0.32]; *p*=0.75; I^2=0%; *p*>0.99; Fig. 5-F), FFM (SMD= -0.06; 95% CI [-0.52, 0.41]; *p*=0.81; I^2=0%; *p*=0.92; Fig. 5-G), and WC (SMD=0.09; 95% CI [-0.37, 0.56]; *p*=0.70; I^2=0%; *p*=0.48; Fig. 5-H).

******Fig. 5. Here******

Effects of LV-HIIT versus HV-HIIT

Five studies (Matsuo *et al.*, 2014; Foster *et al.*, 2015; Ramos *et al.*, 2017; Schubert *et al.*, 2017; Reljic *et al.*, 2018) assessed the effects of LV-HIIT versus HV-HIIT on CRF, blood pressure, MetS z-score, and body composition. Participants include normal-weight healthy, and individuals living with obesity and metabolic syndrome. The total duration of LV-HIIT sessions only required 45% to 94% than for HV-HIIT. Four studies(Matsuo *et al.*, 2014; Ramos *et al.*, 2017; Schubert *et al.*, 2017; Reljic *et al.*, 2018) reported exercise adherence for LV-HIIT (85-100%) and HV-HIIT (81-100%); except for one study, the adherence to LV-HIIT was numerically higher than HV-HIIT in all studies, and no studies reported adverse events for LV-HIIT.

The meta-analysis found no significant differences between LV-HIIT and HV-HIIT on CRF (SMD= -0.14; 95% CI [-0.45, 0.17]; p=0.39; I^2=0%; p=0.50; Fig. 6-A), SBP (SMD= -0.25; 95% CI [-0.71, 0.21]; p=0.29; I^2=33%; p=0.22; Fig. 6-B), DBP (SMD= -0.07; 95% CI [-0.45, 0.32]; p=0.74; I^2=0%; p=0.95; Fig. 6-C), MetS z-score (SMD= -0.16; 95% CI [-1.11, 0.79]; p=0.75; I^2=70%; p=0.07; Fig. 6-D), FM (SMD=0.17; 95% CI [-0.30, 0.63]; p=0.48; I^2=0%; p=0.77; Fig. 6-E), FM% (SMD=0.01; 95% CI [-0.41, 0.43]; p=0.96; I^2=0%; p=0.95; Fig. 6-F), FFM (SMD=0.07; 95% CI [-0.36, 0.49]; p=0.76; I^2=0%; p=0.91; Fig. 6-G), and WC (SMD= -0.11; 95% CI [-0.57, 0.36]; p=0.65; I^2=0%; p=0.72; Fig. 6-H).

******Fig. 6. Here******

DISCUSSION

Our main findings showed that: 1) LV-HIIT was efficacious in improving CRF, blood pressure, MetS z-score, fat mass (kg / %), and waist circumference in non-athlete adults, but there were no apparent effects on lean body mass compared to CONTROL;

2) effects of LV-HIIT on cardiometabolic health and body composition were not significantly different compared to those with MICT and HV-HIIT; 3) more repetitions, longer high-intensity exercise durations, and longer total session durations result in significantly reduced CRF gains with LV-HIIT, but higher intensity intervals significantly improve CRF gains; 4) total time commitment associated with LV-HIIT was 14-47% and 45-94% of that with MICT and HV-HIIT respectively, and adherence was high and similar (or greater) when compared to MICT and HV-HIIT.

LV-HIIT improves cardiometabolic health

CRF

The meta-analysis revealed that the effect of LV-HIIT on CRF (compared to CONTROL) can be considered large (SMD = 1.19). No previous systematic reviews have examined the effects of LV-HIIT according to the definition of <5 min high-intensity efforts/intervals and <15 min overall time, but previous meta-analyses looking at HIIT or SIT (Weston *et al.*, 2014; Sultana *et al.*, 2019) in general have found comparable effect sizes to LV-HIIT as the present study. Weston et al. (2014) reported a potentially modest improvement in CRF among active non-athletic men when comparing "LV-HIIT" (SIT) to untrained CONTROL. Sultana et al. (2019) observed a significant improvement in maximal oxygen uptake under LV-HIIT, with a pooled effect size that can be classified as moderate (SMD = 0.79). However, it is worth noting that the studies conducted by Weston et al. (2014) and Sultana et al. (2019) cannot be considered as "low volume," and the inclusion criteria for HIIT protocols were different from ours. Weston et al. (2014) examined SIT with most of the included studies involving 4-6 sprints, with the total time spent in the sessions approaching 30 min, and therefore were not necessarily time efficient. The studies analyzed in the study by

Sultana et al. (2019) exhibited significant variations in the total exercise session duration. In contrast, our meta-analysis utilized the practical definition of "≤5 min high intensity, ≤15 min total session duration" (Gibala *et al.*, 2020). Our findings further contribute to the existing evidence supporting the effectiveness of low-volume, time-efficient exercise performed as HIIT in improving CRF.

The difference between the effects of HIIT and MICT on CRF has been a topic of increasing interest among researchers and practitioners (Milanović *et al.*, 2015; Su *et al.*, 2019; Sultana *et al.*, 2019). In our meta-analysis, the effect of LV-HIIT on CRF (compared to MICT) was not significant, although the *p*-value was 0.15 and the results appeared to indicate a tendency for very small effect size (SMD= 0.18 [-0.06, 0.42]), suggesting that LV-HIIT is not inferior to MICT in improving CRF. This finding is supported by other meta-analyses. For example, Su et al. (2019) found no statistically significant difference between HIIT and MICT in improving CRF in adults with overweight and obesity, despite HIIT sessions being 9.7 min shorter. Moreover, Milanovic (2015) (likely a large beneficial effect [5.5 mL/kg/min; ±1.2 mL/kg/min]) and Sultana (2019) (SMD = 0.175), suggested that HIIT may offer a slight advantage over MICT in improving CRF. Our study builds on previous findings by only including protocols involving ≤15 min overall session time. We found that LV-HIIT appears at least equivalent to MICT in improving CRF, despite only requiring 14-47% of an exercise time commitment compared to MICT. This suggests it is worthwhile to further explore the most time-efficient HIIT protocols for improving CRF.

Blood pressure

The effect of LV-HIIT (compared to CONTROL) on SBP (SMD = -1.44), DBP (SMD = -1.51), and MAP (SMD = -1.55), as found in our meta-analysis, can be classified as large. Batacan et al. (2017) previously meta-analysed the effects of short-term (<12 weeks) HIIT (i.e., ≥85% VO_{2max}, lasting ≤4 min/set interspersed with an interval of recovery) and did not find significant improvements in SBP (SMD = -0.01) and DBP (SMD = -0.15) in normal-weight individuals. However, both short-term and long-term (>12 weeks) HIIT resulted in improvements in SBP (SMD = -0.28/-0.35) and DBP (SMD = -0.52/-0.38) among participants with overweight/obesity. Our findings of improved blood pressure with LV-HIIT appear to rely on the inclusion of clinically hypertensive subjects, as subgroup analysis demonstrated that hypertensive subjects had a significantly greater reduction in SBP compared to pre-hypertensive subjects. Considering a reduction of 4 mmHg or more in SBP is expected to lead to a decrease in cardiovascular disease (CVD) mortality by 5-20% (Taylor *et al.*, 2011), our finding of a reduction in SBP of ~10 mmHg has clinical relevance.

The effect of LV-HIIT compared to MICT on SBP was not significant in our meta-analysis, although the *p*-value was 0.06 and the results appeared to indicate a tendency for a small (SMD = -0.31) greater improvement after LV-HIIT, and while no difference was observed for DBP (SMD = 0.09). A previous meta-analysis by Cornelissen et al. (2013) reported that aerobic training reduced blood pressure by an average of 2.1 mmHg for SBP and 1.7 mmHg for DBP in pre-hypertensive individuals, and 8.3 mmHg for SBP and 5.2 mmHg for DBP in hypertensive patients. However, most of these sustained aerobic interventions required close to 200 min of exercise per week. Subsequent meta-analyses have found that both HIIT and MICT have comparable and in some cases superior, effects in youth with overweight/obesity and adults with pre-hypertension. García-Hermoso et al. (2016) found that 4-12 weeks of HIIT led to greater reductions in SBP (SMD = -0.39) in youth with overweight and obesity compared to MICT. The meta-analysis conducted by García-Hermoso et al. (2016)

incorporated fewer included trials with generally poor methodological quality. Furthermore, the study amalgamated moderate- and high-intensity continuous training within the comparison group, leading to a comparison group that was not exclusively moderate-intensity or MICT.Additionally, the study included participants aged 6-17 years (Lambrick *et al.*, 2016). Similarly, Costa et al. (2018) found no differences in the change in SBP (MD = 0.22 mmHg) and DBP (MD = -0.38 mmHg) between HIIT and MICT in adults with pre- to established hypertension.

MetS z-score

The MetS z-score enables the classification of metabolic syndrome severity and is considered a better indicator for capturing the range of cardiometabolic risk states. In our meta-analysis, the effect of LV-HIIT (compared to CONTROL) on the MetS z-score (SMD = -0.76) was categorized as moderate. However, we found that the MetS z-score reduction by an average of 1.40, and previous studies have found that a reduction of 0.15 in the MetS z-score corresponds to approximately a 10% improvement in one component of MetS (Wiley *et al.*, 2016). These findings suggest that LV-HIIT elicits beneficial changes in several cardiometabolic outcomes.

The pooled effect of LV-HIIT (compared to MICT) on MetS z-score (SMD = -0.03) as found in our meta-analysis, did not show a statistically significant difference. Specific low-intensity training protocols have been shown to induce beneficial changes in cardiometabolic outcomes, particularly the MetS z-score, in high-risk populations (Johnson *et al.*, 2007). Our findings confirm that these gains can be achieved with ≤15 min of LV-HIIT per session and that LV-HIIT may improve the MetS z-score to a similar degree as MICT by exerting similar improvements on CRF.

LV-HIIT Has a Modest Impact on Body Composition

We observed a significant effect of LV-HIIT on FM (SMD = -0.22), FM% (SMD = -0.22), and WC (SMD = -0.53) compared to CONTROL, but no significant effect in FFM (SMD = 0.03) following LV-HIIT. Our findings are similar to those of Sultana et al. (2019), who also reported no improvement in FM, FM%, and FFM with ≤ 500 MET-min/week of HIIT. However, Batacan et al. (2017) found a marginal improvement in FM% among individuals with overweight/obesity in >12-week HIIT interventions (SMD = -0.40). This discrepancy may be attributed to differences in training duration, or by the exercise mode utilized in the studies included in our meta-analysis, which primarily involved cycling. In contrast, previous studies have shown that running-based HIIT has a pronounced effect on improving body fat mass (kg), but this effect diminishes when cycling is employed (Wewege *et al.*, 2017). This could potentially be because running recruits a greater muscle mass, leading to increased energy expenditure (Millet *et al.*, 2009) and/or because running exhibits a higher maximal rate of fat oxidation compared to cycling (Knechtle *et al.*, 2004; Chenevière *et al.*, 2010), as cycling predominantly engages the lower limbs and relies more on carbohydrate oxidation. Consequently, exercise performed at the same volume may result in greater fat utilization during running than during cycling.

We observed a small but significant improvement in WC with LV-HIIT, which holds clinical implications since a 10% reduction in WC has been associated lower risk of mortality (Ross *et al.*, 2020). This finding is consistent with the results of Batacan et al. (2017) who reported improvement in WC with HIIT lasting more than 12 weeks (SMD = -0.20). However, our study included LV-HIIT interventions lasting less than 12 weeks, thereby extending the previous findings.

The low volume of high-intensity exercise during LV-HIIT means that calorie expenditure is low compared to MICT, making it less likely to achieve beneficial changes in FM, FM%, and FFM. Despite this, there were no significant differences between the effects of LV-HIIT and MICT on body composition. Our findings are consistent with those of Sultana et al. (2019), who reported non-significant differences between HIIT and MICT in terms of overall FM, FM%, and FFM. Similarly, Wewege et al. (2017) found no significant difference between HIIT and MICT in terms of FM and WC, although HIIT saved approximately 40% of the time. Additionally, Wewege et al. (2017) found that cycling-based HIIT did not lead to fat loss, which may partially explain our findings of no reduction in FM with LV-HIIT. Keating et al. (2017) also found no significant difference between HIIT and MICT in terms of FM.

Health Benefits of HIIT and Dose-response: Is More Better?

The positive dose-response effect of MICT for improving health has long been supported by expert consensus (Garber *et al.*, 2011), and the relationship reveals, as far as possible, the balance between “risk and gains” (Nassis, 2017). However, this crucial relationship has not been adequately explored for brief, high-intensity exercise (e.g., HIIT).

Interestingly, we found a significant inverse dose-response relationship between the effects of LV-HIIT on CRF with greater repetitions (β = -0.52), high-intensity duration per session (β = -0.21), and total duration per session (β = -0.19) being associated with lower gains in CRF. However, these effects appear to have been driven by the inclusion of both HIIT protocols and SIT protocols, as the SIT protocols involved higher intensities alongside fewer sprints, shorter high-intensity duration, and shorter total duration per session. This was further supported by our subgroup analysis, which found that supramaximal intensity (SIT) elicited higher CRF gains than maximal intensity (HIIT), although the volume of SIT was all less than HIIT (e.g., repetitions). It has previously been found that the effect of SIT on improving CRF does not diminish with fewer sprint repetitions; instead, a similar inverse dose-response relationship was reported (-1.2±0.8% decrease per 2 additional repetitions) (Vollaard *et al.*, 2017). In addition, it appears that only 2 times/week of SIT is required to maximize CRF gains (Thomas *et al.*, 2020). Our results above suggest that for HIIT, boosting intensity may produce higher CRF gains than increasing volume. These finding adds to our understanding of the "minimum threshold" HIIT protocol required to improve CRF by suggesting that if a minimal dose is sought, the intensity of the intervals likely needs to be supramaximal.

It remains unclear what drives the adaptations to HIIT and SIT, and indeed if the mechanisms associated with HIIT and SIT are the same (Vollaard *et al.*, 2017). It has been suggested that rapid glycogenolysis during high-intensity exercise may play a role (Metcalfe *et al.*, 2015). As such, the finding by Parolin et al. (1999) that during repeated supramaximal sprints, muscle glycogenolysis is attenuated by the third repetition may provide a reason for the lack of additional benefits of performing more than 2 supramaximal sprints within an SIT session (Vollaard *et al.*, 2017). Further research into the mechanisms responsible for adaptations to HIIT and SIT is warranted to aid in elucidating the lowest volume of exercise to achieve desired adaptations and/or the volume of HIIT and SIT needed to achieve the most pronounced adaptations.

We also found no significant differences between LV-HIIT and HV-HIIT in terms of effects on cardiometabolic health and body composition. These findings further support the notion that excessive emphasis on exercise "volume" may not be necessary when performing HIIT. Even a few min of HIIT may provide similar health benefits to those of more traditional high-volume HIIT protocols. The findings also support our above meta-regression findings wherein increasing the number or duration within LV-HIIT protocols did not result in greater adaptations (in fact, the opposite was found). However, the HV-HIIT to LV-HIIT comparison in our meta-analyses was limited to a small number of studies, and a lot of the studies compared SIT versus HIIT (i.e., not intensity matched), so more work is clearly needed in this area.

Practical Implications

We found that LV-HIIT is efficacious in improving CRF, blood pressure, MetS z-score, and waist circumference in non-athlete adults. The definition of "low-volume" in our study of "high-intensity training lasting for 5 min maximum with a total session duration less than 15 min or less" would be expected to reduce the "lack of time" perceived barrier to exercise. Several studies included whole-body exercise modes that can be easily incorporated into daily life, whether at work or at home, further increasing the practicality of LV-HIIT approaches.

The finding that performing a lower number of repetitions or lower interval durations was associated with the potential for greater benefits to CRF indicates that time-efficient, low-volume HIIT could hold promise for making the cardiometabolic benefits of exercise more accessible for the general population. In this regard, the emerging concept of "exercise snacks" (Islam *et al.*, 2022) could help to extend this evidence further into the "real-world", for example, by using intense stair climbing rather than lab-based cycling to perform a few short high-intensity efforts sporadically throughout the day (Allison *et al.*, 2017; Jenkins *et al.*, 2019). Meanwhile, the recent large-scale cohort studies of "vigorous intermittent lifestyle physical activity" (VILPA) (Stamatakis *et al.*, 2022) hold promise to further extend the application of such low-volume vigorous exercise to the forefront of public health (Gibala *et al.*, 2020). Additionally, LV-HIIT could be performed multiple times throughout the day to increase activity and break up sedentary periods, thereby countering potential negative effects on cardiometabolic health. (Dunstan *et al.*, 2021).

However, for further improvements in body composition, such as reducing body fat, it appears that longer sessions of MICT combined with dietary control are needed. Nonetheless, as exercise on its own is not a particularly effective weight loss strategy (Swift *et al.*, 2014), the lack of body fat reduction does not necessarily undermine the benefits of incorporating LV-HIIT for ≤15 min into daily routines.

Limitations and Future Research

This is the first systematic review and meta-analysis of the effects of LV-HIIT (≤5 min high-intensity exercise and <15 min session duration) on cardiometabolic health and body composition. Despite this, several limitations need to be mentioned.

First, we included 21 peer-reviewed published studies, but we could not exclude that there was some grey literature that we did not consider, which influenced the meta-analysis results. Therefore, there is a risk of publication bias and hence misleading results, but we fully searched mainstream databases to reduce this risk and used Egger's test to verify that such bias was not present.

Second, potential bias is introduced because some of our outcomes (e.g., blood pressure) for the LV-HIIT versus CONTROL comparisons were largely from the same research group (Relijc et al.). Furthermore, there were only five studies included in the LV-HIIT versus HV-HIIT meta-analysis and the small sample size limits the interpretation of our results for this comparison. More research is needed to further address these limitations.

Third, despite performing subgroup and regression analyses, interpreting the results remains challenging due to variations in interventions and study designs. The absence of key information in some studies, such as BMI, prevented further subgroup analyses across the literature. Second, some of the outcome indicators involved similar or even identical exercise protocols, limiting our ability to conduct further meta-regression analyses. Additionally, although we conducted subgroup analyses of intensity, this was hampered by inconsistencies in the quantification of intensity across study protocols (e.g., SIT protocols mostly used external loading, whereas HIIT mostly used %HRmax to record intensity during the intervention). This precludes treating intensity as a continuous variable in further meta-regression analyses. Future studies should address these limitations by enhancing methodological quality and using consistent methods to assess outcome indicators.

Fourth, the sample sizes in some of the studies were quite small, leading to the potentially limited overall efficacy of the meta-analysis. Furthermore, the duration of the LV-HIIT interventions we included was mainly focused on 2-16 weeks, with only one study lasting up to 24 weeks. Given the need for maximum impact in clinical and public health practice (e.g., organizations such as the National Institute for Health and Care Excellence (NICE) typically focus on RCTs with at least 12 months of follow-up), the health benefits of long-term HIIT deserve to be answered in the future by large-scale studies of long-term RCTs.

Fifth, our included studies are based mostly on controlled laboratory intervention studies, typically under strict conditions of supervision, research-grade exercise equipment, and systematic training arrangements. However, it remains unclear to what extent this efficacy, obtained from laboratory-based research, translates to effectiveness in "real world" LV-HIIT. Recently evidence has been emerging for LV-HIIT interventions in the workplace (Metcalfe *et al.*, 2020; Amatori *et al.*, 2023), this transition from the laboratory to the real-world warrants more research in many more scenarios. We also recommend that future LV-HIIT studies give more data related to the feasibility (e.g. satisfaction, adherence, fidelity, and retention); these details could assist the future translation of LV-HIIT into "real world" applications.

Lastly, it is difficult to comment on any of the molecular mechanisms of the physiology of LV-HIIT for health in our review, so we recommend interested readers to previous reviews highlighting how brief, vigorous, or HIIT exercise might elicit adaptations (Gibala *et al.*, 2020; Sabag *et al.*, 2022).

CONCLUSION

The present meta-analysis evidence that LV-HIIT is efficacious for improving CRF, blood pressure, MetS z-score, and waist circumference in non-athlete adults, but not overall fat or lean body mass. Higher repetitions, longer high-intensity durations, and longer total session durations do not result in additional CRF gains from applying LV-HIIT, but higher intensities may be associated with greater CRF gains. LV-HIIT offers similar health benefits only requiring 14-47% and 44-94% of the time compared to MICT and HV-HIIT.

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AUTHOR CONTRIBUTIONS

YMY designed the study and search strategy. YMY, LHX, and BMY performed abstract and full-text screening, and methodological quality, and contributed to the completion of screening and data extraction for all data within this manuscript. YMY, JL, and NV designed and calculated meta-analyses, subgroup analyses, regression analyses, sensitivity analyses, and publication bias, and created images and tables. YMY wrote the original draft preparation, performed review and editing, and prepared the final draft. JL and NV contributed to the critical evaluation of the method and findings and the drafting of the manuscript. JL, NV, CZL, LHS, DJF, DSJ, CM, and LYM contributed to editing and revising the manuscript in its final version. All authors read and approved the final version of the manuscript and agree with the order of presentation of the authors.

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Not applicable.

COMPETING INTERESTS

No conflicts and interests are relevant to the content of this review.

DATA AVAILABILITY

Most of the data from this study is available within the article and supplementary files. If there are any other data requests, we will provide them unconditionally via email.

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990 **Figure 1 PRISMA flow diagram for included and excluded study**

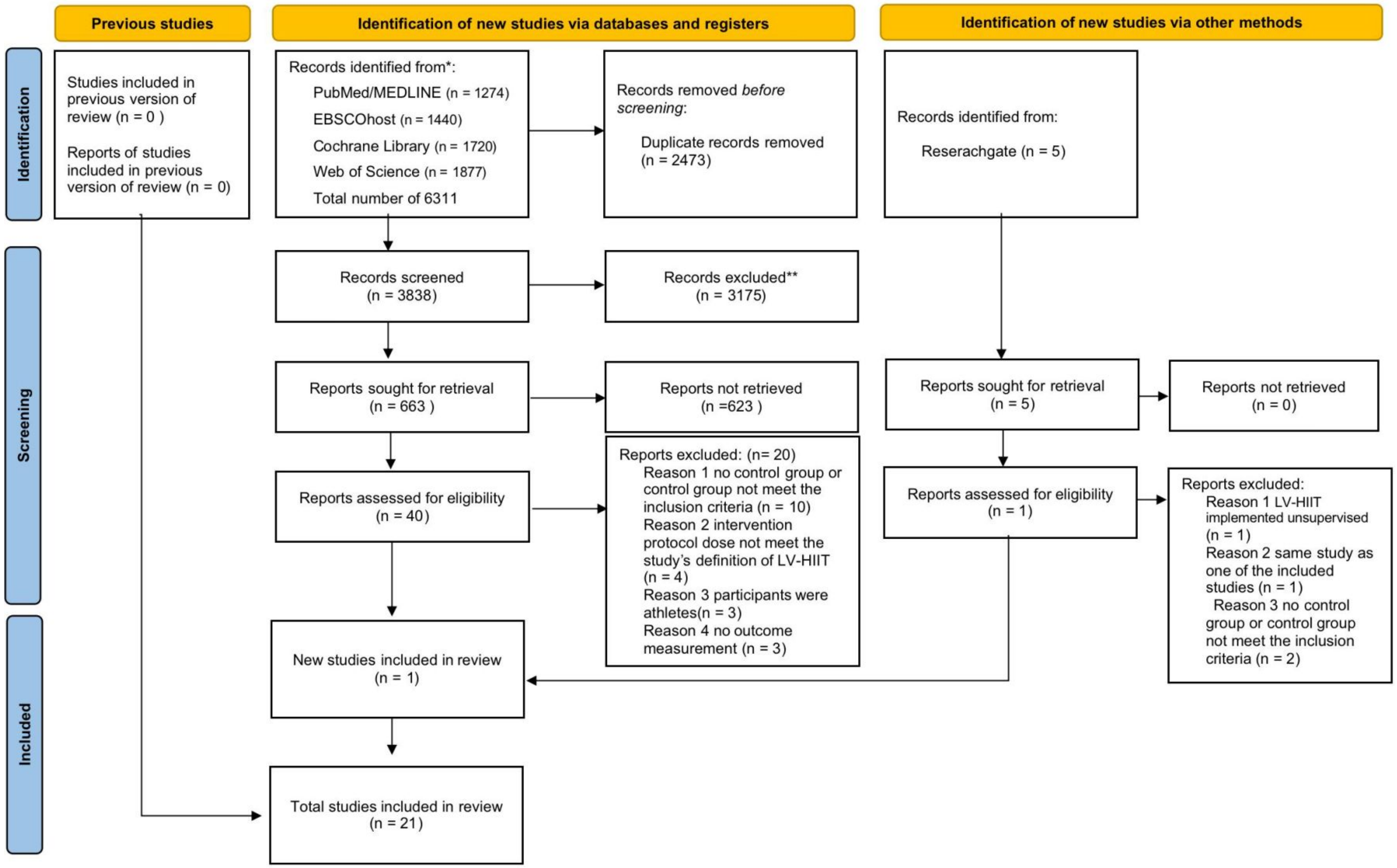

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Table 1 Participant characteristic

Study	Groups	Subjects	Men ratio	population	CRF	Age	BMI
Reljic-2023	LV-HIIT	20	n/a	metabolic syndrome	21.6	n/a	n/a
	LV-HIIT	20			22.0	n/a	n/a
	CON	18			21.6	n/a	n/a
Venegas-Carro-2023	LV-HIIT	15	0.54	healthy	42.2	23.3	22.5
	LV-HIIT	16			41.3	24.5	22.7
	CON	15			40.6	24.8	23.8
Scoubeau-2023	LV-HIIT	14	0.57	healthy	2.35	23.1	21.7
	CON	14			2.25	24.0	23.8
Reljic-2022	LV-HIIT	19	0.66	overweight	35.0	50	26.9
	CON	26			37.5	47	26.9
Reljic-2022	LV-HIIT	26	0.46	metabolic syndrome	22.6	50.6	37.8
	CON	26			20.6	49.0	38.0
Reljic-2021	LV-HIIT	29	0.43	metabolic syndrome	20.5	52.1	40.9
	CON	17			17.1	56.7	39.4
Reljic-2021	LV-HIIT	32	n/a	metabolic syndrome	21.9	49.6	38.
	CON	33			21.0	48.8	37.5
Reljic-2020	LV-HIIT	36	0.44	obese	22.5	48.5	40.4
	CON	29			23.1	49.0	38.5
Cuddy-2019	LV-HIIT（SIT）	12	0.5	obese	25.3	40.8	n/a
	MICT	15		obese	26.2	42.2	n/a
Banitalebi-2019	LV-HIIT（SIT）	14	0	type 2 diabetic	33.2	55.3	29.2
	CON	14			31.1	55.7	30.1
Schaun-2018	LV-HIIT	15	1	healthy	47.2	23.0	23.63
	LV-HIIT	12			46.0	24.2	25.63
	MICT	14			47.5	24.1	24.78
Reljic-2018	LV-HIIT	11	0.35	overweight	29.4	29.2	24.9
	HV-HIIT	9			30.3	29.9	25.8
	MICT	7			28.8	32.8	25.6
Ramos-2017	LV-HIIT	21	0.60	metabolic syndrome	27.7	57	32
	HV-HIIT	22			24.5	56	35
	MICT	22			28.1	55	32
Jabbour-2017	LV-HIIT	12	0.45	obese	22.2	23.1	33.7
	CON	12			23.4	23.3	33.3
Schubert-2017	LV-HIIT（SIT）	12	0.43	overweight	32.3	28.8	28.4
	HV-HIIT	12			31.35	n/a	26.9
	CON	6			37.5	n/a	26.6
Ruffino-2017	LV-HIIT	16	1	type 2 diabetic	2.6	55	30.6
	MICT	16			2.6	55	33.7
Gillen-2016	LV-HIIT（SIT）	9	1	overweight	20.2	27	27
	MICT	10			22.9	28	26
	CON	6			20.7	26	25
Foster-2015	LV-HIIT	21	0.30	healthy	34.0	20	n/a
	HV-HIIT	15			34.3	20	n/a
	MICT	19			33.6	20	n/a
Scribbans-2014	LV-HIIT（SIT）	10	0.84	healthy	48.3	21	n/a
	MICT	9			47.6	21	n/a
Matsuo-2014	LV-HIIT（SIT）	14	1	healthy	43.9	26.4	21.3
	HV-HIIT	14			41.9	27.2	21.4
	MICT	14			42.0	25.9	21.2
Metcalfe.-2012	LV-HIIT	15	0.44	healthy	34.27	25	n/a
	CON	14			35.08	20	n/a

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Table 2 Intervention protocol

Study	Groups	Mode	Warm-up	Duratuon	Intensity	Cool-down	High intensity /session	Total duration/session	Frequency	duration
Reljic-2023	LV-HIIT	cycling	2min	5 x 1min	85-95%HR_{max}	1min	5min	14min	2	12wk
	LV-HIIT	cycling	2min	5 x 1min	85-95%HR_{max}	1min	5min	14min	2	12wk
	CON	no-exercise	n/a	n/a	n/a	n/a	n/a	n/a	n/a	12wk
Venegas-Carro-2023	LV-HIIT	Running	6min	5-8 x 30s	18 ± 0.7 (RPE)	n/a	4min	12min	3	6wk
	LV-HIIT	Jump	6min	5-8 x 30s	17±0.8 (RPE)	n/a	4min	12min	3	6wk
	CON	no-exercise	n/a	n/a	n/a	n/a	n/a	n/a	n/a	6wk
Scoubeau-2023	LV-HIIT	Self-weight	3min	4 x 30s	74±5%HR_{max}	n/a	2min	6min	3	8wk
	CON	no-exercise	n/a	n/a	n/a	n/a	n/a	n/a	n/a	8wk
Reljic-2022	LV-HIIT	cycling	2min	5 x 1min	85-95%HR_{max}	3min	5min	10min	2	24wk
	CON	no-exercise	n/a	n/a	n/a	n/a	n/a	n/a	n/a	24wk
Reljic-2022	LV-HIIT	cycling	2min	5 x 1min	80-95%HR_{max}	3min	5min	10min	2	12wk
	CON	no-exercise	n/a	n/a	n/a	n/a	n/a	n/a	n/a	12wk
Reljic-2021	LV-HIIT	cycling	2min	5 x 1min	80-95%HR_{max}	3min	5min	10min	2	12wk
	CON	no-exercise	n/a	n/a	n/a	n/a	n/a	n/a	n/a	12wk
Reljic-2021	LV-HIIT	cycling	2min	5 x 1min	80-95%HR_{max}	3min	5min	10min	2	12wk
	CON	no-exercise	n/a	n/a	n/a	n/a	n/a	n/a	n/a	12wk
Reljic-2020	LV-HIIT	cycling	2min	5 x 1min	80-95%HR_{max}	3min	5min	10min	2	12wk
	CON	no-exercise	n/a	n/a	n/a	n/a	n/a	n/a	n/a	12wk
Cuddy-2019	LV-HIIT	cycling	3min	2 x 20s	all out	3min	40s	10min	3	8wk
	MICT	cycling	n/a	30min	50%–65% HRr	n/a	n/a	30min	4	8wk
Banitalebi-2019	LV-HIIT	cycling	5min	4 x 30s	all out	n/a	2min	6min	3	10wk
	CON	no-exercise	n/a	n/a	n/a	n/a	n/a	n/a	n/a	10wk
Schaun-2018	LV-HIIT	cycling	4min	8 x 20s	130%	n/a	3.7min	11.1min	3	16wk
	MICT	cycling	n/a	30min	90 – 95% HR_{VT2}	n/a	n/a	30min	3	16wk
Reljic-2018	LV-HIIT	cycling	2min	5 x 1min	85-95%HR_{max}	3min	5min	10min	2	8wk
	HV-HIIT	cycling	2min	2 x 4min	85-95%HR_{max}	3min	8min	16min	2	8wk
	MICT	cycling	2min	38	65-75%HR_{max}	3min	n/a	43min	2	8wk
Ramos-2017	LV-HIIT	cycling	10min	1 x 4min	85-95%HR_{max}	3min	4min	14min	3	16wk
	HV-HIIT	cycling	10min	4 x 4min	85-95%HR_{max}	3min	16min	48min	3	16wk
	MICT	cycling	n/a	30	60-70%HR_{max}	n/a	n/a	30min	5	16wk
Jabbour-2017	LV-HIIT	cycling	5min	6 x 6s	all out	n/a	36s	5.5min	3	2wk
	CON	no-exercise	n/a	n/a	n/a	n/a	n/a	n/a	n/a	2wk
Schubert-2017	LV-HIIT	cycling	2min	3-5 x 20s	all out	3min	1.5min	4.5min	3	4wk
	HV-HIIT	cycling	2min	6-8 1min	90% PPO	3min	7min	21min	3	4wk

	CON	no-exercise	n/a	n/a	n/a	n/a	n/a	n/a	n/a	4wk
Ruffino-2017	LV-HIIT	cycling	n/a	2 x 10-20s	all-out	n/a	20-40s	20-40s	3	8wk
	MICT	walking	n/a	30min	40-55%HRr	n/a	n/a	30min	5	8wk
Gillen-2016	LV-HIIT	cycling	2min	3 x 20s	all out	3min	1min	3min	3	12wk
	MICT	cycling	2min	45	70% HR_{max}	3min	n/a	n/a	3	12wk
	CON	no-exercise	n/a	n/a	n/a	n/a	n/a	n/a	n/a	12wk
Foster-2015	LV-HIIT	Self-weight	5min	8 x 20s	170%PPO	5min	2.6min	7.8min	3	8wk
	HV-HIIT	cycling	5min	13 x 30s	170%PPO	5min	6.5min	19.5min	3	8wk
	MICT	cycling	5min	20min	90%VT	5min	n/a	n/a	3	8wk
Scribbans-2014	LV-HIIT	cycling	n/a	8 x 20s	170% PPO	5min	3.7min	14.8min	4	6wk
	MICT	cycling	n/a	20min	65% VO_2peak	n/a	n/a	n/a	4	6wk
Matsuo-2014	LV-HIIT	cycling	2min	7 x30s	120% VO_2max	3min	3.5min	8.5min	5	8wk
	HV-HIIT	cycling	2min	3 x 3min	80%–85%VO_2max	3min	n/a	18min	5	8wk
	MICT	cycling	n/a	45min	65% VO_2max	n/a	n/a	45min	5	8wk
Metcalfe -2012	LV-HIIT	cycling	n/a	2 x 10-20s	all out	n/a	1min	10min	3	6wk
	CON	no-exercise	n/a	n/a	n/a	n/a	n/a	n/a	n/a	6wk

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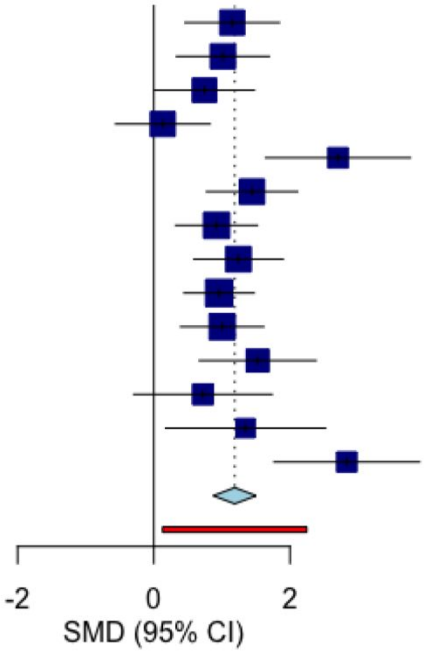
Table 3 Summary of the methodological quality assessment

Author -year	Eligibility criteria	Random allocation	Concealed allocation	Similar baseline	Participant blinding	Investigator blinding	Assessor blinding	Completeness of follow-up	Intention to treat	Between-group comparisons	Point measures and variability	Total score
Reljic -2023	YES	1	1	1	0	0	0	0	1	1	1	6
Venegas-Carro -2022	YES	1	1	1	0	0	0	1	1	1	1	7
Scoubeau -2023	YES	1	1	1	0	0	0	1	1	1	1	7
Reljic -2022	YES	1	1	1	0	0	0	1	1	1	1	7
Reljic -2022	YES	1	1	1	0	0	0	0	1	1	1	6
Reljic -2021	YES	1	1	1	0	0	0	0	1	1	1	6
Reljic -2021	YES	1	1	1	0	0	0	0	1	1	1	6
Reljic -2020	YES	1	1	1	0	0	0	0	1	1	1	6
Cuddy -2019	YES	0	1	1	0	0	0	1	1	1	1	6
Banitalebi -2019	YES	1	1	1	0	0	0	0	1	1	1	6
Schaun -2018	YES	1	1	1	0	0	0	1	1	1	1	7
Reljic -2018	YES	1	1	1	0	1	1	0	1	1	1	8
Ramos -2017	YES	1	1	1	0	0	0	0	1	1	1	6
Jabbour -2017	YES	1	1	1	0	0	0	0	1	1	1	6
Schubert -2017	YES	1	1	1	0	0	0	1	1	1	1	7
Ruffino -2016	YES	0	1	1	0	0	0	1	1	1	1	6
Gillen -2015	NO	0	1	1	0	0	0	1	1	1	1	6
Foster -2014	YES	0	1	1	0	0	0	0	1	1	1	5
Scribbans -2014	YES	0	1	1	0	0	0	1	1	1	1	6
Matsuo -2014	YES	1	1	1	0	1	1	1	1	1	1	9
Metcalfe -2012	YES	1	1	1	0	0	0	1	1	1	1	7

Fig. 2 Forest plot of the effects of LV-HIIT versus CONTROL on CRF. SMD standard mean differences, 95% CI confidence interval. A positive value indicates a larger increase in CRF as a result of LV-HIIT versus CONTROL.

Source	SMD (95% CI)
Reljic et al-2023	1.15 (0.46-1.84)
Reljic et al-2023	1.01 (0.33-1.70)
Venegas-Carro et al-2023	0.74 (0.01-1.48)
Venegas-Carro et al-2023	0.13 (-0.56-0.83)
Scoubeau et al-2023	2.71 (1.64-3.77)
Reljic et al-2022	1.44 (0.77-2.11)
Reljic et al-2022	0.92 (0.32-1.52)
Reljic et al-2021	1.24 (0.59-1.90)
Reljic et al-2021	0.96 (0.44-1.47)
Reljic et al-2020	1.00 (0.39-1.62)
Banitalebi et al-2019	1.53 (0.67-2.38)
Schubert et al-2017	0.72 (-0.29-1.74)
Gillen et al-2016	1.35 (0.17-2.52)
Metcalfe et al-2012	2.83 (1.77-3.90)
Total	1.19 (0.87-1.50)
Prediction interval	(0.13-2.25)



Heterogeneity: χ^2_{13} = 30.89 (P = .003), I^2 = 58%
Test for overall effect: z = 7.37 (P < .001)

Table. 4 Results of subgroup analysis

Subgroup		N	SMD [95%CI]	I^2	*p* (subgroup)
BMI ($kg·m^{-1}$)	20-25	3	1.15 [-0.33, 2.63]	87.4%	0.53
	25-30	4	1.32 [0.88, 1.75]	0%	
	>30	4	1.02 [0.72, 1.31]	0%	
Baseline CRF ($mL·kg^{-1}·min^{-1}$)	20-30	7	1.05 [0.80, 1.29]	0%	0.04
	30-35	2	0.43 [0.83, 2.38]	63.4%	
	>35	4	1.60 [-0.17, 1.03]	29.4%	
Age (y)	20-30	6	1.37 [0.47, 2.27]	82.1%	0.61
	>45	6	1.12 [0.87, 1.38]	0%	
Mode	cycling	11	1.18 [0.96, 1.39]	24.7%	0.97
	self-weight	3	1.15 [-0.33, 2.63]	87.4%	
Intensity	submaximal	1	n/a	n/a	
	maximal	9	0.97 [0.75, 1.18]	9.8%	<0.01
	supramaximal	4	1.60 [0.75, 2.45]	63.4%	
Frequency	2	7	1.09 [0.85, 1.32]	0%	0.46
	3	7	1.38 [0.62, 2.14]	79.1%	

Fig. 3 Dose–response effects of LV-HIIT on CRF (SMD): results of meta-regression analysis for predictors related to a training protocol. The circle sizes are proportional to the precision of the effect(s) observed in each study. A positive value indicates a larger increase in CRF as a result of LV-HIIT compared with CONTROL. The dashed line represents the 95% CI of the regression line.

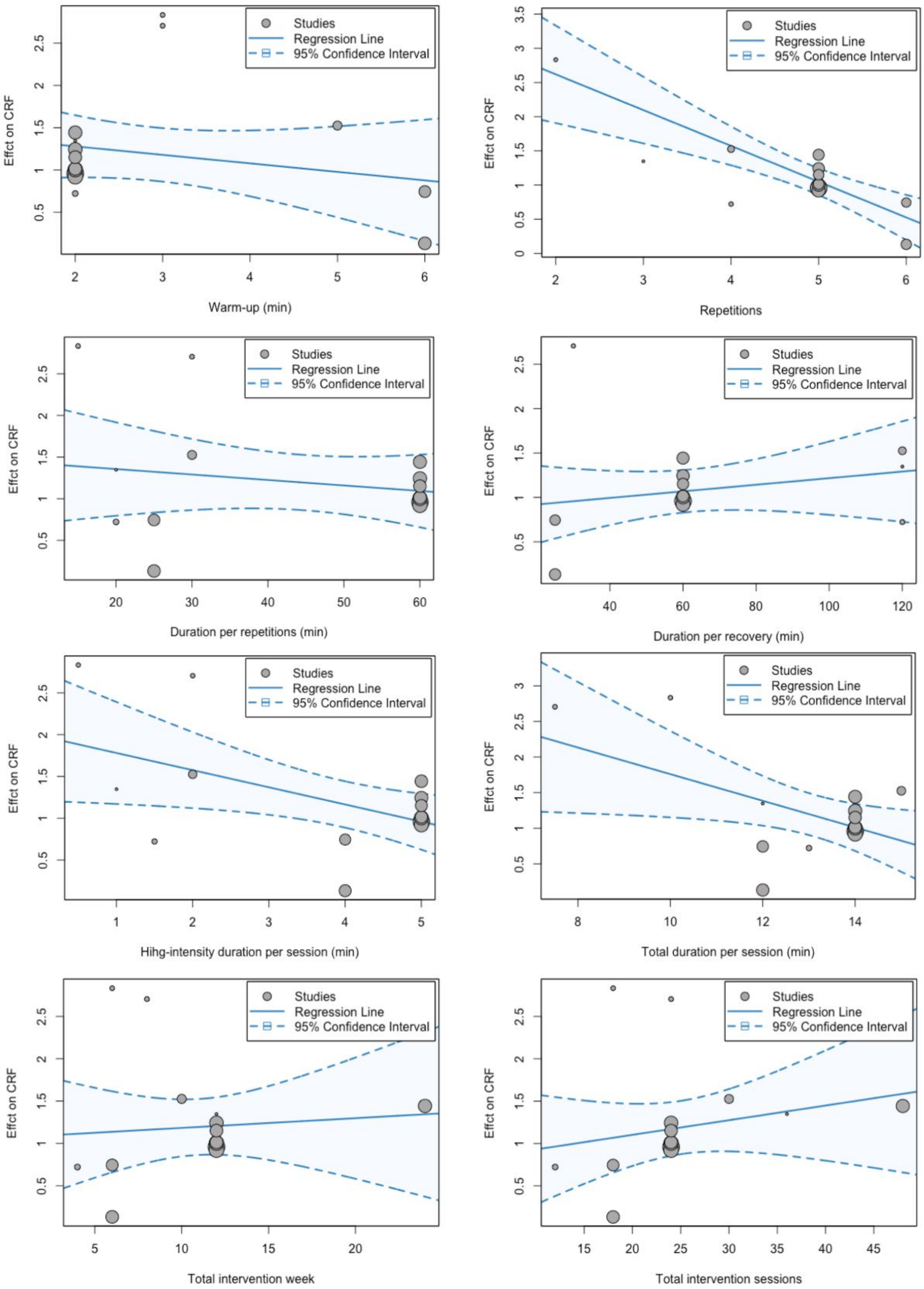


Fig. 4 Forest plot of the effects of LV-HIIT versus CONTROL on SBP (A), DBP (B), MAP (C), MetS z-s core (D), FM (E), FM (%) (F), FFM (G), WC (H). SMD standard mean differences, 95% CI confidence interval. A positive value indicates a larger increase in (A-H) as a result of LV-HIIT versus CONTROL.

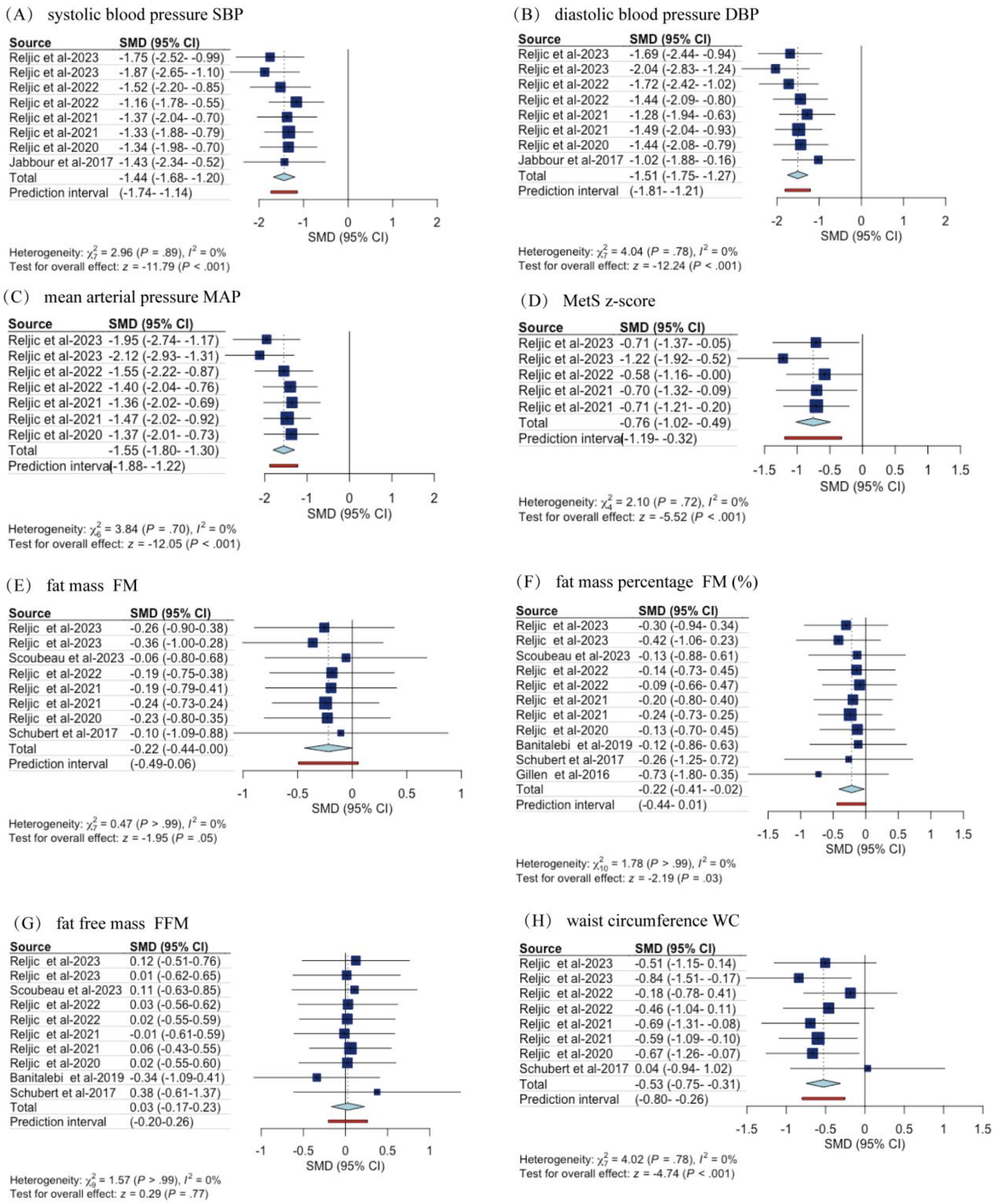


Fig. 5 Forest plot of the effects of LV-HIIT versus MICT on CRF (A), SBP (B), DBP (C), MetS z-score (D), FM (E), FM (%) (F), FFM (G), WC (H). SMD standard mean differences, 95% CI confidence interval. A positive value indicates a larger increase in (A-H) as a result of LV-HIIT versus MICT.

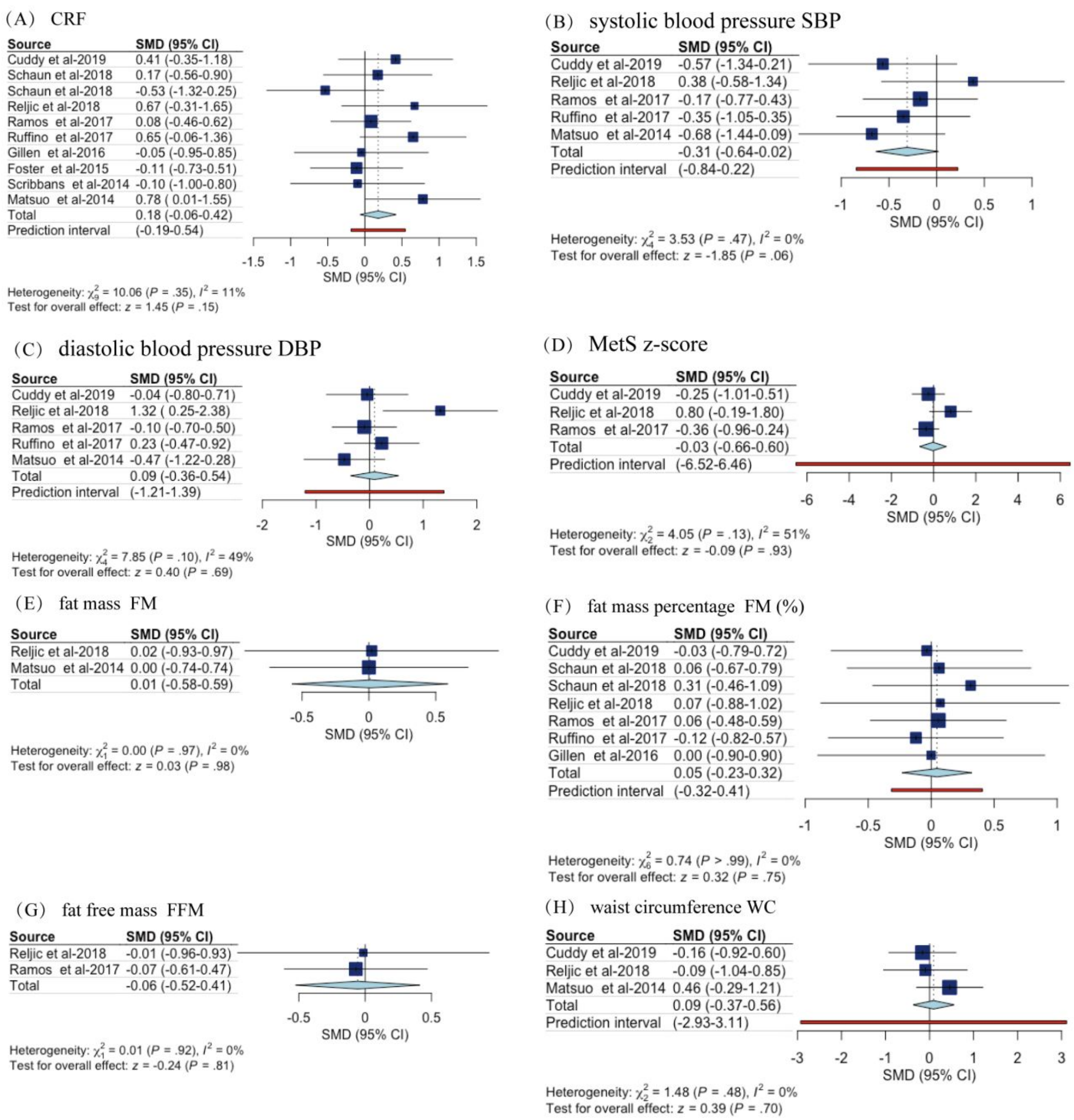


Fig. 6 Forest plot of the effects of LV-HIIT versus HV-HIIT on CRF (A), SBP (B), DBP (C), MetS z-score (D), FM (E), FM (%) (F), FFM (G), WC (H). SMD standard mean differences, 95% CI confidence interval. A positive value indicates a larger increase in (A-H) as a result of LV-HIIT versus HV-HIIT.