One Size Doesn't Fit All: A Meta-Analysis of 115 Trials Comparing High-Intensity Interval and Moderate- to Vigorous-intensity Continuous Training Across Diverse Participants, Protocols, and Outcomes

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ABSTRACT

This study compares the effects of high-intensity interval training (HIIT) and Moderate to Vigorous-intensity Continuous Training (MVICT) on physiological adaptations and physical performance across a broad population, from the general public to athletes. Additionally, it also explores how participant characteristics (e.g., sex, age, and training status) and training protocol parameters (e.g., mode, interval type, and intensity) influence the comparison. Following PRISMA guidelines, a systematic search was conducted in PubMed, Web of Science, and CNKI databases, completed on September 21, 2024. Eligible studies were randomized controlled trials comparing the chronic effects of HIIT and MVICT. A three-level meta-analysis was employed to calculate standardized mean differences (SMD, Hedge's *g*), with subgroup analyses and meta-regression used to examine potential moderators of any observed effects. A total of 115 studies involving 3,196 participants were included, with a mean age range from 8 to 68 years, spanning populations from untrained sedentary individuals to elite/world-class athletes. Compared to MVICT, HIIT demonstrated significantly superior improvements in relative maximal oxygen uptake (*SD*=1.30 $ml \cdot kg^{-1} \cdot min^{-1}$, *g*=0.39, 95% CI [0.27, 0.51]), absolute maximal oxygen uptake (*SD*=0.09 $L \cdot min^{-1}$, *g*=0.29, 95% CI [0.15, 0.43]), maximal aerobic power/speed (*g*=0.31, 95% CI [0.17, 0.47]), and mean anaerobic power (*g*=0.47, 95% CI [0.08, 0.86]). No significant differences were observed between HIIT and MVICT in peak anaerobic power (*g*=0.31, 95% CI [-0.06, 0.68]), first intensity thresholds (*g*=0.43, 95% CI [-0.38, 1.25]), second intensity threshold (*g*=0.06, 95% CI [-0.25, 0.36]), exercise economy (*g*=0.26, 95% CI [-0.03, 0.54]), and on indices of physical performance (*g*=0.04, 95% CI [-0.46, 0.54]). Subgroup analyses revealed that training status (6-tiered participant classification framework), age, sex, interval type, and exercise mode significantly moderated the effect. Specifically, compared to MVICT, HIIT demonstrated greater improvements in maximal oxygen uptake among individuals at Tier 0 (inactive; *g*=0.34), Tier 1 (recreationally active; *g*=0.57), and Tier 3 (elite/national; *g*=0.83), in males (*g*=0.43) and mixed-sex populations (*g*=0.42), using short-interval (*g*=0.55) or long-interval HIIT (*g*=0.57), and with rowing (*g*=0.71), running (*g*=0.53), or cycling (*g*=0.29) as the training modes. Compared to MVICT, HIIT offers superior benefits for improving maximal oxygen uptake and anaerobic capacity, while both modalities show comparable outcomes for intensity thresholds, exercise economy, and physical performance. The relative superiority of HIIT compared to MVICT is influenced by participant characteristics (e.g., training background, age, and sex) and by the characteristics of the HIIT protocol.

Keywords: interval training; continuous training; aerobic capacity; anaerobic capacity; athletic performance

1. INTRODUCTION

Cardiorespiratory fitness (CRF), typically measured by maximal oxygen uptake ($\dot{V}O_{2max}$), is a strong predictor of mortality, on par with other established risk factors such as smoking, hypertension, high cholesterol, and type 2 diabetes[1]. An increase of one metabolic equivalent (MET) in CRF (i.e., ~ 3.5 $ml \cdot kg^{-1} \cdot min^{-1}$) is associated with 13% lower all-cause mortality, which is comparable to the effect of lowering systolic blood pressure by 5 mmHg or a reduction of fasting blood glucose by 1 mmol/L[2, 3]. On the other hand, low CRF significantly elevates the risk of metabolic disorders, cardiovascular diseases (CVD), and cancer, with those in the lowest CRF quintile (bottom 20%) facing a fourfold higher risk of death compared to those in the highest category (top 2%)[4, 5]. Even modest CRF improvements of 1 to 2 METs can reduce cardiovascular events risk by 10% to 30%[1].

Cardiorespiratory fitness is also a key physiological determinant of endurance performance[6]. Indeed, $\dot{V}O_{2max}$, together with intensity thresholds (i.e., lactate thresholds, ventilatory thresholds, and critical power) and exercise economy, are primary metrics for evaluating endurance performance, monitoring training effects, and predicting athletic potential. These indicators are central to assessing aerobic capacity[6]. Conversely, anaerobic capacity plays a critical role in short-duration, high-intensity events[7, 8]. Nevertheless, although long-duration endurance events predominantly rely on aerobic metabolism, anaerobic capacity remains important at certain points, as it enables athletes to generate higher power outputs over short periods, which is essential for rapid starts, accelerations, or finishing sprints[9]. Enhanced anaerobic capacity also supports better energy distribution, tactical decisions, and psychological regulation, thereby enhancing overall performance[10, 11].

The World Health Organization (WHO) recommends that adults engage in at least 150 minutes of moderate-intensity or 75 minutes of vigorous-intensity exercise per week to improve CRF, cardiovascular health, and reduce the risk of chronic diseases[5, 12]. However, most adults, especially in high-income countries, fall short of these recommendations, citing barriers that include *"lack of time"* and *"low priority"*[13, 14]. To address this issue, high-intensity interval training (HIIT) has gained attention as an important training modality, characterized by alternating high-intensity and low-intensity recovery phases[15]. HIIT has been shown to improve cardiovascular risk factors and reduce all-cause mortality[1, 16]. Short-term HIIT, when integrated into high-volume training, has also been shown to enhance athletic performance in elite athletes[17, 18]. Consequently, HIIT has become a leading global fitness trend, embraced by athletes, recreational exercisers, and the public health sector[19, 20].

High-intensity interval training is often compared to Moderate to Vigorous-intensity Continuous Training (MVICT) to verify that it can achieve the same or even better physiological adaptations under lower training volume or dose[21-23]. Yet, whilst research on this comparison is extensive, no definitive conclusions have been reached. For instance, a meta-analysis by Milanović et al.[16] in untrained healthy adults aged 18-45, showed greater improvement in $\dot{V}O_{2max}$ with

HIIT compared to MVICT (Mean Difference, MD=1.2 mL·kg^{-1}·min^{-1}, 95% CI [0.3, 2.1]). Subsequently, Sultana et al.[24] found a significant advantage of low-volume HIIT (defined as ≤ 500 MET-minutes/week) over MVICT in improving $\dot{V}O_{2max}$ in normal-weight, overweight, and obese adults. HIIT has also been shown to enhance $\dot{V}O_{2max}$ across various populations, including young and middle-aged adults (29 studies included)[25], older adults over 65 years of age (15 studies included)[26], and overweight individuals (11 studies included)[27]. However, recent research results present contradictions. For example, low-volume HIIT, defined as ⩽5 min high-intensity exercise within a ⩽15 min session (21 studies included)[5], home-based HIIT, defined as high-intensity interval training performed in a home environment (15 studies included)[28], or sprint interval training (SIT), defined as involving repeated supramaximal bouts of exercise interspersed with brief periods of rest (28 studies included)[29], showed no significant difference from MVICT in improving $\dot{V}O_{2max}$. In addition, the meta-analysis by Lindner and colleagues (20 studies included) found no differences between the effects of HIIT and MVICT on $\dot{V}O_{2max}$ specifically in females[30]. Furthermore, a recent meta-analysis by Liang et al. (including 8 studies)[31] indicated that MVICT was more effective than SIT for improving $\dot{V}O_{2peak}$ (MD=-1.36 mL·kg^{-1}·min^{-1}, 95% CI [-2.31, 0.40]).

Overall, the impact of HIIT *versus* MVICT on improving $\dot{V}O_{2max}$ remains controversial. This may largely be attributed to the considerable between-study heterogeneity in intervention populations and training protocols. Existing studies often focus on specific subgroups, such as individuals with obesity or certain age ranges, without offering a comprehensive overview across the broader healthy populations. This limits the generalizability of conclusions regarding the superiority of one intervention over the other. Moreover, inconsistency or poorly defined protocols in some studies hinder direct comparison between HIIT and MVICT[16, 24, 26, 28, 32], making it difficult to interpret their findings. For example, Wang et al.[33] did not rigorously examine MVICT protocols alone, invalidating their analysis by including MVICT interventions that combined both HIIT and endurance training (ET)[34]. Most previous meta-analyses reported only the 95% confidence intervals of effect sizes, without providing prediction intervals[16, 24-26, 28-31]. However, in random-effects models, confidence intervals do not reflect the variability of true effects across different studies and are therefore insufficient to fully capture between-study heterogeneity and its implications for the uncertainty of outcomes in future research or practical applications[35].

Importantly, the vast majority of research has focused on $\dot{V}O_{2max}$. Wenger et al.[36] review systematically synthesized studies across diverse populations and training protocols, highlighting the interactive effects of exercise intensity, frequency, and duration, as well as the influence of baseline fitness and training duration on $\dot{V}O_{2max}$. Direct comparative evidence on the effects of HIIT *versus* MVICT on other indices of aerobic capacity (e.g., threshold parameters), anaerobic capacity, and endurance performance remains limited. As such, further meta-analyses are needed to synthesize the effects of HIIT and MVICT on a broader range of outcomes, and across a range of populations where training objectives will be different (i.e., health *versus*

performance). Such analyses should aim to identify key moderators of the comparison to provide stronger evidence supporting the promotion of one training model over another for either health promotion or performance enhancement. At present, the lack of comprehensive comparisons across diverse healthy individuals and athletes limits our understanding of their relative effectiveness and feasibility in public health and competitive sports contexts.

Therefore, this meta-analysis aims to compare the effects of HIIT and MVICT on nine key outcomes: (1) relative maximal/peak oxygen uptake, (2) absolute maximal/peak oxygen uptake, (3) maximal aerobic power/speed, (4) mean anaerobic power, (5) peak anaerobic power, (6) first intensity thresholds power/speed, (7) second intensity thresholds power/speed, (8) exercise economy, and (9) exercise performance. In addition, subgroup analyses were conducted to explore whether the effect of HIIT *versus* MVICT on each outcome was different based on (1) sex, (2) age, (3) training status, (4) training modality, (5) interval type, and (6) interval intensity. The primary hypothesis of this study is that HIIT is significantly superior to MVICT in improving maximal/peak oxygen uptake, maximal aerobic power/speed, and mean anaerobic power. There are no significant differences between the two training methods in improving intensity threshold parameters, exercise economy, and athletic performance. The secondary hypothesis is that these differences in effects may be moderated by participant and training characteristics.

2. METHODS

This meta-analysis followed the 2020 PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines[37], and study quality was assessed using the AMSTAR 2 (Assessing the Methodological Quality of Systematic Reviews 2) checklist. In line with open science principles, the review was pre-registered on the PROSPERO platform (CRD420251019855) to enhance transparency and reproducibility. All data extraction files, statistical and graphical codes, and results (i.e., including figures) are publicly available on the PROSPERO platform.

2.1. Data Sources

Literature searches were conducted in PubMed, Web of Science (Core Collection), and CNKI databases. Included articles had to be full-text available and peer-reviewed. There were no restrictions on date, sample size, or language. Both Chinese and English articles were included. Additional studies were identified through: 1) checking the reference lists of included articles; 2) reviewing citations; and 3) searching for "similar articles" in MEDLINE and Embase. The initial search was conducted on September 21, 2024, and an updated search was performed in April 2025.

2.2. Search Strategy

The search terms were categorized into four groups based on the PICOS framework (Population, Intervention, Comparison, Outcome): Population (no

restrictions), Intervention ("interval training"), Comparison ("continuous training"), and Outcome (no restrictions). No restrictions were placed on publication dates. A search of the PROSPERO and Cochrane systematic review databases was also conducted to determine whether relevant systematic review protocols had already been published. The search strategy was developed based on previous similar systematic reviews (Supplementary Table 1), using the following syntax: ("Interval Training" OR "High-Intensity Interval Training" OR "High Intensity Interval Training" OR "High-Intensity Interval Trainings" OR "Interval Training, High-Intensity" OR "Interval Trainings, High-Intensity" OR "Trainings, High-Intensity Interval" OR "High-Intensity Intermittent Exercise" OR "Exercise, High-Intensity Intermittent" OR "Exercises, High-Intensity Intermittent" OR "High-Intensity Intermittent Exercises" OR "Sprint Interval Training" OR "Sprint Interval Trainings" OR "Moderate-Intensity Interval Training" OR "Aerobic Interval Training" OR "High-Volume Interval Training" OR "Repeated Sprint Training" OR "Intermittent Exercise Training" OR "HIIT" OR "SIT" OR "HIT" OR "MIIT" OR "HIIE" OR "AIT" OR "RST" OR "IET") AND ("Continuous Training" OR "Low-Intensity Continuous Training" OR "Continuous Low-Intensity Exercise" OR "Low-Intensity Endurance Training" OR "Steady-State Low-Intensity Training" OR "Low-Intensity Aerobic Training" OR "Low-Intensity Exercise" OR "Moderate-Intensity Continuous Training" OR "Moderate to Low-Intensity Continuous Training" OR "Submaximal Continuous Training" OR "High-Volume Training" OR "Steady-State Continuous Training" OR "Aerobic Continuous Training" OR "Steady-State Training" OR "Volume Training" OR "Endurance Training" OR "Aerobic Endurance" OR "Aerobic Exercise" OR "Aerobic Training" OR "ET" OR "CT" OR "LCT" OR "HVT" OR "SCT" OR "ACT" OR "SST" OR "VT" OR "CET"). Additionally, searches were conducted in the PROSPERO and Cochrane systematic review databases to determine whether any relevant systematic review protocols had been published.

2.3. Literature Handling and Screening

Search record deduplication was manually performed by an independent reviewer (BZY) using EndNote X9 [Clarivate Analytics, 2018]. Subsequently, the deduplicated records were exported and reviewed by two independent researchers (BZY and YMY). They screened the titles and abstracts of all articles based on the inclusion and exclusion criteria. Disagreements were resolved through discussion. If consensus could not be reached, a third independent researcher (ZYM) was consulted to determine the inclusion of studies. A similar process was followed for the full-text review. Additional literature was sourced from prior systematic reviews and the research team's individual expertise in identifying relevant studies that may not have been captured in the initial search.

2.4. Inclusion and Exclusion Criteria

2.4.1. Inclusion Criteria

The inclusion and exclusion criteria were based on the PICOS framework:

1) Population: Studies must have involved human subjects, with no restrictions on sex, age, or training status (as defined by McKay et al.[38]), but excluding studies in individuals with chronic diseases or in animals. They were excluded during the title/abstract screening phase.

2) Intervention: The intervention group must have engaged in HIIT, defined as repeated bouts of relatively high-intensity exercise bouts interspersed with lower-intensity recovery periods or rest. For exercise performance, this typically involves intensities above the moderate-intensity zone, as determined by the second metabolic threshold or by indicators such as a $\dot{V}O_2 \geq 80\%\ \dot{V}O_{2max}$, a heart rate (HR) $\geq 90\%\ HR_{max}$, heart rate reserve (HRR) $\geq$ 80% HRR, or a rating of perceived exertion (RPE) $\geq$ 16/20[15, 39]. The training program must have been clearly defined (i.e., mode, intensity, volume, frequency) and performed for at least two weeks. The comparison group must have undergone continuous training of moderate to vigorous intensity without significant rest or interruptions, maintaining a relatively stable intensity throughout. This intensity was defined by $\dot{V}O_2$ (46-80% $\dot{V}O_{2max}$), HR (55-85% HR_{max}), HRR (40-80% HRR), or RPE (11-16/20 RPE)[39], and with a clearly defined training program lasting at least two weeks. The training intensity of HIIT had to be significantly higher than that of MVICT.

3) Outcome measures: Studies must have included at least one indicator of physiological adaptation or exercise performance related to either aerobic or anaerobic capacity. Relevant indices of aerobic capacity include maximal/peak oxygen uptake, maximal aerobic power/speed, submaximal thresholds, and exercise economy. Maximal oxygen uptake is defined as the highest rate of oxygen uptake attained during an incremental exercise test when oxygen consumption reaches a plateau despite a continued increase in external workload. In contrast, peak oxygen uptake refers to the highest oxygen uptake value recorded in the absence of a clearly identifiable plateau. Maximal aerobic power or velocity is defined as the external power output or running speed corresponding to the attainment of $\dot{V}O_{2max}$ or $\dot{V}O_{2peak}$ during an incremental exercise test. Submaximal thresholds include the first intensity threshold power/speed (lactate threshold 1, ventilatory threshold 1) and the second intensity threshold power/speed (lactate threshold 2, ventilatory threshold 2, maximal metabolic steady state, and critical power). Exercise economy refers to the amount of oxygen consumed per unit time at a given speed or power. Relevant indices of anaerobic work capacity include peak and mean power during a 30-s Wingate test. Relevant tests of exercise performance included time trial durations primarily supported by aerobic energy systems (i.e., lasting ≥75 seconds), and time to exhaustion during exercise[40-42].

4) Included studies: they must be original research with a between-group experimental design, including both parallel and crossover group designs.

2.4.2. Exclusion Criteria

Studies were excluded based on the following criteria:

1) Non-experimental studies, acute studies, or studies with unclear training protocols.

2) Qualitative studies, systematic reviews/meta-analyses, and review/opinion

articles.

3) Studies where the interventions involved combined intermittent or continuous training, or a combination of HIIT or MVICT with other training methods (e.g. resistance training).

4) Studies that combined intermittent or continuous training with other nutritional interventions.

5) Books, conference proceedings, and non-peer-reviewed articles.

2.5. Data Extraction and Conversion

Data extraction was carried out by two independent reviewers (BZY and YMY) using a customized extraction worksheet in Excel created before full-text screening. The two reviewers independently extracted the following information: author and study details, participant characteristics, intermittent and continuous training protocols, and measures of aerobic / anaerobic capacity and exercise performance. A third reviewer (ZYM) conducted a verification round. In the case of discrepancies, a fourth independent reviewer (GZQ) was consulted to reach a consensus. If data were missing or presented only in graphical form, the authors were contacted to request the necessary information. If contact attempts failed and data were only available in graphical form, the GetData software (https://getdata-graph-digitizer.software.informer.com/) was used to extract the relevant data[43]. Outcome measures extracted included mean values, standard deviations (SD), and sample sizes before and after interventions. When only standard errors (SE) were reported, they were converted to SD using the formula:

$$SD = \sqrt{N} \times SE \qquad (1)$$

2.6. Risk of Bias and Methodological Quality

The risk of bias was independently assessed by two reviewers (BZY and YMY). Any discrepancies were resolved through discussion, and if consensus could not be reached, a third reviewer (ZYM) provided arbitration. The risk of bias was evaluated using the Risk of Bias 2 tool from the Cochrane Collaboration[44], which includes assessment of random sequence generation, allocation concealment, blinding of participants and personnel, blinding of outcome assessment, incomplete outcome data, selective reporting, and other potential biases. In addition, the Physiotherapy Evidence Database (PEDro) scale was used to assess both bias risk and methodological quality[45]. The PEDro score ranges from 0 to 10, with scores ≥6 for *high* quality, 4–5 for *moderate* quality, and ≤3 for *low* quality.

2.7. Assessment of Evidence Certainty

The certainty of the evidence was evaluated using the Grading of Recommendations Assessment, Development, and Evaluation (GRADE) approach[46], categorized as "high," "moderate," "low," or "very low." The GRADE assessment was be conducted by one reviewer (BZY) and reviewed by a second (YMY).

2.8. Statistical Methods

2.8.1. Multi-level Meta-analysis

This meta-analysis employed a three-level model to extract the mean difference, standard deviation (SD), 95% confidence intervals (95% CI), and prediction intervals from each study to calculate the combined main effect. A variance-covariance matrix-based clustering-robust variance estimation was applied, with small-sample adjustments to account for correlations between effect sizes within studies[47, 48]. Since the outcome measures often involved multiple testing units, effect sizes (Standardized Mean Difference, SMD) were prioritized. Hedge's g, adjusted for bias using precise formulas, was the primary effect size indicator, given the relatively small sample sizes in most studies. Hedge's g was categorized as follows: 0.2 (*small* effect), 0.5 (*moderate* effect), and 0.8 (*large* effect). In line with recent methodological reviews' recommendations, I^2 was used as the primary source of information regarding heterogeneity and was interpreted as follows: 0%-25% (*low* heterogeneity); 25%-50% (*moderate* heterogeneity); 50%-75% (*substantial* heterogeneity); and 75%-100% (*very high* heterogeneity). Prediction intervals (PI) were used to assess the expected range of true effect, providing a practical interpretation of between-study heterogeneity. Additionally, the statistical power of the primary pooled effect was calculated, and the possibility of false negatives due to insufficient statistical power was considered. Statistical power calculations were performed using the *metameta* package.

2.8.2. Subgroup and Regression Analysis

To explore the sources of heterogeneity between studies and potential moderators, this study employed subgroup analysis and meta-regression analysis for both binary and continuous variables. To avoid the risk of false negatives due to insufficient statistical power, power calculations for each subgroup were performed. Subgroup analysis was primarily based on the following variables: 1) Sex; 2) Age; 3) Training status; 4) Training method; 5) Interval type; 6) Intensity of interval training.

Training levels were categorized according to McKay et al.[38] into six tiers: Tier 0 (sedentary population without training); Tier 1 (recreationally active individuals); Tier 2 (training/development level); Tier 3 (elite/national level); Tier 4 (elite/international level); Tier 5 (world-class). Participants were grouped by age according to the World Health Organization (WHO) classification[49]: adolescents (<18 years); young adults (18-44 years); middle-aged adults (45-59 years); older adults (≥60 years). Based on Buchheit and Laursen's classification[50], the types of interval training (IT) were categorized as: long intervals (repetition time ≥ 60 seconds， intensity at 80-105% of maximal aerobic power/speed (MAP/MAV), with 1-3 minutes of recovery), short intervals (repetition time < 60 seconds, intensity at 100-120% MAP/MAV, with recovery duration similar to the exercise bout), repeated sprints (4-10 seconds of all-out efforts with 15-60 seconds of recovery), Sprint Intervals (20-30 seconds of all-out efforts with 1-4 minutes of recovery), and small-sided games (Game-based long-interval training). For interval training intensity, based on Bishop et al.'s framework[39], two categories were used: High intensity and Very High intensity. For high intensity, the intensity was 80-100% of the power or

running speed at $\dot{V}O_{2max}$, and for very high intensity, it was >100% of the power or speed at $\dot{V}O_{2max}$.

2.8.3. Risk of Publication Bias and Sensitivity Analysis

Funnel plots combined with Egger's test were used to investigate the risk of publication bias, with $p > 0.05$ indicating no publication bias. Statistical analysis and graphical representation were performed using the "*meta*" and "*metafor*" packages in R (version 4.2.0). Statistical significance was set at $p < 0.05$, and results with $p > 0.05$ were considered not statistically significant. Sensitivity analysis was conducted using a leave-one-out method to verify the robustness of the combined results.

3. RESULTS

3.1. Literature Search Results

A preliminary search across various databases yielded 9,497 articles, with 21 more from other sources. After screening, 115 studies met the inclusion criteria for the meta-analysis[21, 23, 51-163] (**Figure 1**).

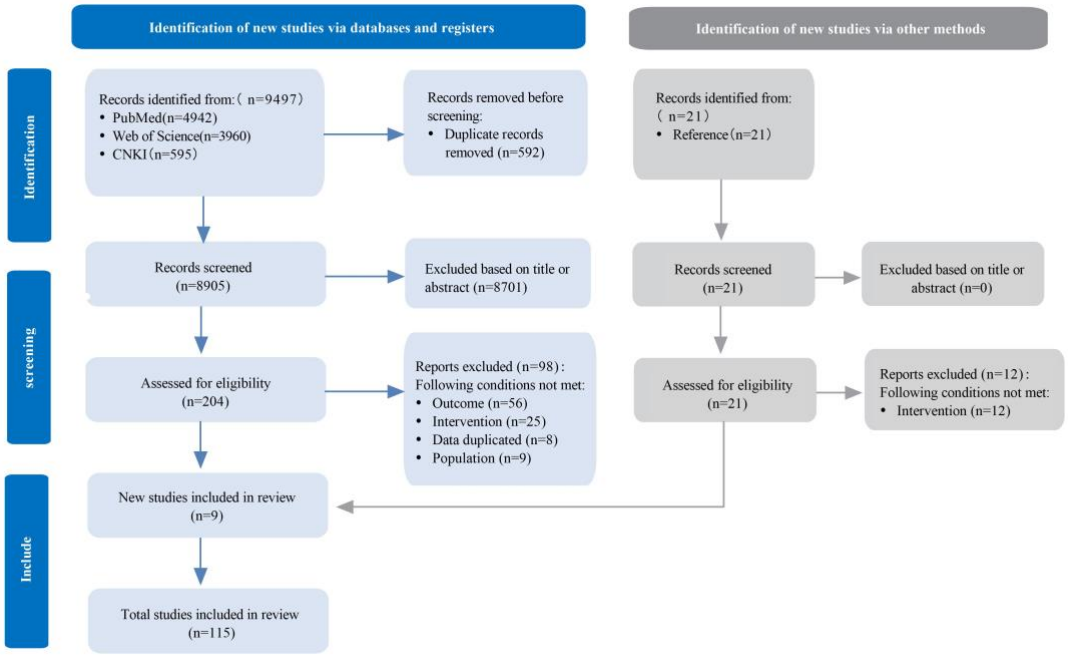

Figure 1. PRISMA Flow Diagram for Inclusion and Exclusion of Studies.

3.2. Characteristics of Included Studies

A total of 115 studies were included, comprising four longitudinal (cross-over) randomized controlled trials[57, 59, 61, 65], and 111 parallel group randomized controlled trials[21, 23, 51-56, 58, 60, 62-64, 66-163]. The total number of participants was 3,196, including 1,945 males, 1,164 females, and 87 participants with unspecified sex (61% male, 36% female, 3% unspecified). Sample sizes ranged from 10 to 85 participants per study, with mean ages ranging from 8 to 68 years. Among the participants, 75% were classified as sedentary, 5% were recreationally active, 10% were athletes in the training/development phase, 7% were high-level/national-level athletes, and 3% were elite/international-level athletes. Regarding interval training

programs, 47% were classified as High intensity and 53% were Very High intensity. Protocol types included long intervals (55%), short intervals (10%), repeated sprints (10%), Sprint Intervals (23%), and small-sided games (2%). Intervention durations ranged from 2 to 26 weeks, with training frequencies of 1 to 10 sessions per week. Outcome measures included relative $\dot{V}O_{2max}$/$\dot{V}O_{2peak}$ (96%), absolute $\dot{V}O_{2max}$/$\dot{V}O_{2peak}$ (42%), MAP/MAV (40%), exercise economy (10%), first intensity thresholds (10%), second intensity threshold (12%), and exercise performance (11%).

3.3. Main Effect Analysis

For all studies combined, HIIT significantly outperformed MVICT in improving relative $\dot{V}O_{2max}$ (k=131, SD=1.30 ml·kg^{-1}·min^{-1}, g=0.39, 95% CI [0.27, 0.51], I^2=56%, PI [-0.57, 1.35], p<0.01), absolute $\dot{V}O_{2max}$ (k=62, SD=0.09 L·min^{-1}, g=0.29, 95% CI [0.15, 0.43], I^2=29%, PI [-0.27, 0.86], p<0.01), maximal aerobic power/speed (k=58, g=0.31, 95% CI [0.17, 0.47], I^2=37%, PI [-0.36, 1.00], p<0.01), and mean anaerobic power (k=10, g=0.47, 95% CI [0.08, 0.86], I^2=22%, PI [-0.19, 1.12], p=0.02) (**Figure 2**). However, there were no significant differences between the two training methods for improving peak anaerobic power (k=11, g=0.31, 95% CI [-0.06, 0.68], I^2=28%, PI [-0.41, 1.03], p=0.09), first intensity thresholds indicators (k=19, g=0.43, 95% CI [-0.38, 1.25], I^2=90%, PI [-2.36, 3.23], p=0.28), second intensity thresholds indicators (k=23, g=0.06, 95% CI [-0.25, 0.36], I^2=57%, PI [-0.99, 1.10], p=0.71), exercise economy (k=25, g=0.26, 95% CI [-0.03, 0.54], I^2=31%, PI [-0.45, 0.96], p=0.07), or exercise performance (k=21，g=0.04，95% CI [-0.46, 0.54], I^2= 71%, PI [-1.64,1.72], P=0.87) (**Figure 2**).

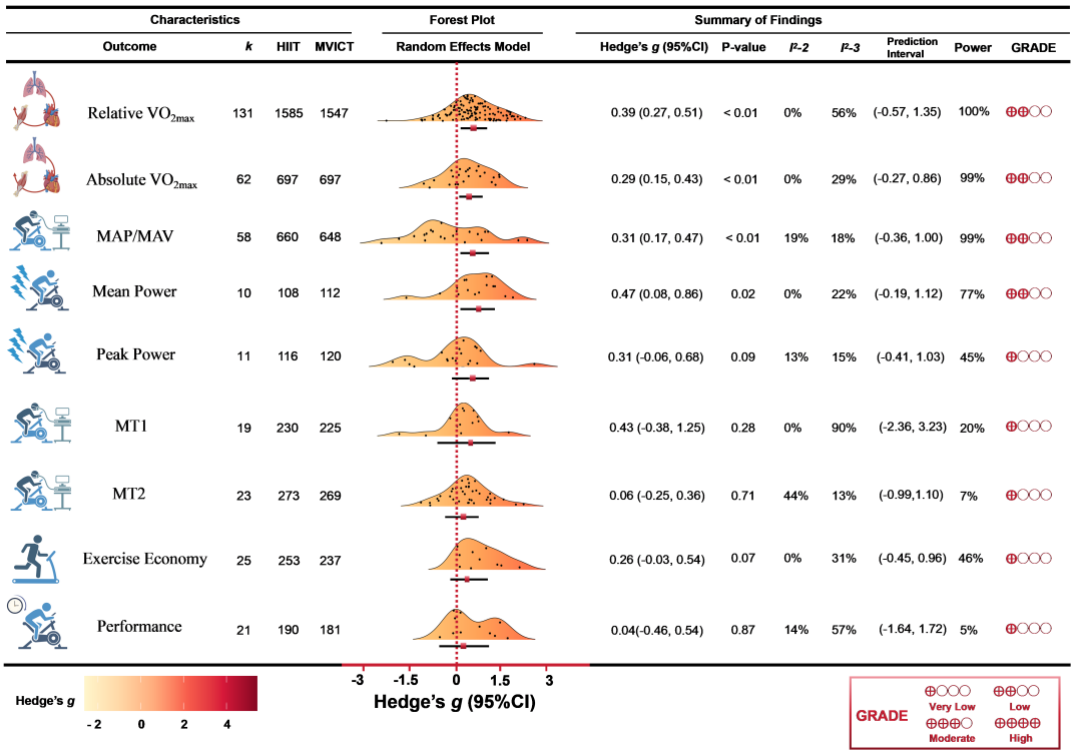

Fig. 2. Primary pooled effect sizes for the outcomes.

g, the effect size indicators used in the pooled; I^2, quantitative indicators of

heterogeneity; HIIT, high-intensity interval training; MVICT, moderate to vigorous-intensity continuous training; MAP/MAV, maximal aerobic power/speed; MT1, lactate threshold 1, ventilatory threshold 1; MT2, lactate threshold 2, ventilatory threshold 2, maximal lactate steady stateand, and critical power; k, the total number of effects included in the pooled effect size; p value, statistically significant p values for pooled results; GRADE, Grading of Recommendations Assessment, Development, and Evaluation (a system for evaluating the quality of evidence and strength of recommendations); the height of the dots represents weight, which reflects the degree of contribution of a single study to the pooled effect size. The higher the dot, the greater the weight of the study and the stronger its influence on the final pooled effect estimate.

3.4. Moderator Analysis

We conducted a moderator analysis to examine whether the effects HIIT compared to MVICT on all outcomes were consistent based on training status, age, sex, interval type, interval training intensity, and exercise modality.

3.4.1. Potential Moderators of relative $\dot{V}O_{2max}$/$\dot{V}O_{2peak}$

Age, interval type, and interval training intensity significantly moderated the effects of HIIT compared to MVICT on relative $\dot{V}O_{2max}$/$\dot{V}O_{2peak}$ (p<0.05 between subgroups; Figure 3). HIIT led to greater improvements than MICT among individuals at Tier 0 (g=0.34), Tier 1 (g=0.57), and Tier 3 training status (g=0.83). Across age groups, HIIT was significantly more effective than MVICT for adolescents (g=0.75), young adults (g=0.28), middle-aged adults (g=0.40), and older adults (g=0.82). For sex, HIIT demonstrated significantly greater effects than MVICT in males (g=0.43) and mixed-sex populations (g=0.42), but not in females (g=0.14). Regarding interval type, both short intervals (g=0.55) and long intervals (g=0.57) of HIIT resulted in superior changes in relative $\dot{V}O_{2max}$/$\dot{V}O_{2peak}$ compared with MVICT. For interval intensity, both high intensity and very high intensity led to significant enhancements in $\dot{V}O_{2max}$/$\dot{V}O_{2peak}$ compared with MVICT. Regarding exercise modality, HIIT was significantly more effective than MVICT in comparisons of upper body handgrip (g=1.15), rowing (g=0.71), running (g=0.53), and cycling (g=0.29), but effects of HIIT and MVICT were not different for boxing (g=1.18), swimming (g=0.39), stair climbing (g=0.44), football (g=-0.25), or for mixed exercise modalities (g=0.16) (**Figure 3,** Supplementary Table 2-3).

3.4.2. Potential Moderators of Maximal Aerobic Power/Speed

Interval training intensity and exercise modality significantly moderated the effects on maximal aerobic power/speed (p<0.05 between subgroups). Regarding training status, individuals at Tier 0 (g=0.21), Tier 2 (g=0.71), and Tier 3 training status (g=0.65) experienced significantly greater improvements with HIIT compared to MVICT. In terms of age, HIIT was significantly more effective than MVICT among adolescents (g=0.80) and young adults (g=0.25), but not in middle-aged adults (g=0.45). There were no effect sizes available for older adults. For sex, HIIT was

more effective compared with MVICT in males (g=0.44), and mixed-sex populations (g=0.23), but not in females. In terms of interval type, both long HIIT intervals (g=0.44) and short intervals (g=0.52) led to greater improvements compared with MVICT. However, comparisons of other interval types with MVICT were not significant. When grouped by interval intensity, both high intensity (g=0.56) and very high intensity (g=0.19) yielded significant enhancements in this parameter compared with MVICT. As for exercise modality, HIIT demonstrated significantly greater effects than MVICT in running-based (g=0.62) and cycling-based interventions (g=0.22) (Supplementary Table 4).

3.4.3. Potential Moderators of Mean Anaerobic Power

While subgroup differences in mean anaerobic power improvements did not reach statistical significance overall (p>0.05), HIIT demonstrated clear advantages over MICT under specific conditions. Notably, HIIT was significantly more effective than MVICT in individuals at Tier 4 training status (g=1.01), with long-interval protocols (g=0.82), and in rowing-based interventions (g=1.01) (Supplementary Table 5-6).

3.4.4. Potential Moderators of Intensity Threshold Indicators, Exercise Economy, and Exercise Performance

Exercise intensity significantly moderated exercise economy outcomes (p<0.05 between subgroups), sex significantly moderated second intensity threshold Indicators (p<0.05 between subgroups), and training status significantly influenced exercise performance (p<0.05 between subgroups). However, no significant differences were observed for first and second intensity threshold indicators, exercise economy, and exercise performance in other subgroup comparisons (p>0.05). Nonetheless, under specific conditions, HIIT demonstrated notable advantages over MVICT in improving intensity threshold indicators, exercise economy, and exercise performance (Supplementary Table 5-7). Regarding exercise economy, a significant advantage was noted under very high intensity conditions (g=0.61). Regarding exercise performance, HIIT outperformed MVICT exclusively in individuals with a Tier 0 training background (g=1.20) (Supplementary Table 7-10).

3.5. Risk of bias and quality of methods

Risk of bias for each study is depicted in Supplementary Figure 1. Most studies, except for Cheema et al.[85] and O'Leary et al.,[108] did not disclose details on randomization or allocation concealment. Additionally, studies by Macpherson et al.[67] and Nummela et al.[98] lacked randomization, leading to a “high risk” rating for the randomization domain. Due to participant dropout and failure to employ intention-to-treat analyses, 43% of studies were rated as having "some concerns". Arboleda-Serna et al.[143] received a “some concerns” rating for missing outcome data due to a high dropout rate, despite the use of an intention-to-treat analysis. Only a few studies, including Reljic et al.[119], disclosed blinding of outcome assessors. Apart from Yin et al.[162], most studies did not pre-register their protocol on a

publicly available database, casting doubts on selective outcome reporting. Overall, 84% of studies were rated as having "some concerns" regarding risk of bias.

The average PEDro score across all studies was 5.7, indicating generally moderate to high methodological quality (Supplementary Table 11).

Details of the Evidence Certainty of GRADE can be found in Supplementary Figure 2.

4. DISCUSSION

This is the largest and most comprehensive meta-analysis performed to date comparing the training effects of HIIT compared with MVICT. Our analysis provides convincing data showing that HIIT significantly outperforms MVICT in improving $\dot{V}O_{2max}$, maximal aerobic power/speed, and anaerobic power. Interestingly, however, there were no significant differences between HIIT and MVICT for eliciting changes in first and second intensity threshold indicators, exercise economy, and exercise performance. We also performed an extensive moderator analysis and found that several factors influence the relative superiority of HIIT compared with MVICT for specific outcomes, including participant sex, age, training status, exercise modality, and interval type and intensity. Notably, though, we found no evidence that MVICT outperforms HIIT for any parameter in general or within any participant subgroup.

4.1. Physiological Adaptations

4.1.1. Aerobic Adaptations

This meta-analysis revealed that HIIT significantly improves relative maximal oxygen uptake (*SD*=1.30 $ml \cdot kg^{-1} \cdot min^{-1}$, *g*=0.39, 95% CI [0.27, 0.51]), absolute maximal oxygen uptake (*SD*=0.09 $L \cdot min^{-1}$, *g*=0.29, 95% CI [0.15, 0.43]), and maximal aerobic power/speed (*g*=0.31, 95% CI [0.17, 0.47]) compared to MVICT, demonstrating the superiority of HIIT in enhancing aerobic adaptations. Our analysis provides clarity on a series of previous studies comparing the effects of HIIT with MVICT on $\dot{V}O_{2max}$ that have yielded inconsistent results (Supplementary Table 12). For example, meta-analyses targeting healthy adults aged 18-45 (MD=1.2, 95% CI [0.3, 2.1])[16], older adults aged≥65 years (MD=3.76, 95% CI [2.96, 4.56])[26], and overweight individuals (SMD=0.30, 95% CI [0.09, 0.52])[27] showed that HIIT produced greater improvements in $\dot{V}O_{2max}$ compared to MVICT. In contrast, no significant differences were observed between HIIT and MVICT in studies focusing on female (MD=-0.42, 95% CI [-1.43, 0.60])[30] or home-based HIIT interventions (MD=1.4, 95% CI [0.5, 2.3])[28]. Additionally, a meta-analysis reported MVICT to be more effective than SIT among normotensive and hypertensive participants (MD=-1.36, 95% CI [-2.31, -0.40], *p*=0.56)[31]. These inconsistencies may be attributed to variations in participant characteristics, such as the inclusion of only partially healthy individuals[16] or a mix of healthy and clinical populations[31]), and methodological limitations, including high risk of bias from small comparison sets (e.g., only three trials analyzed[28]). By synthesizing data from 131 comparisons across a broad range of healthy individuals and athletic populations, this

meta-analysis provides a more comprehensive and generalizable evaluation of the relative efficacy of HIIT and MVICT for improving $\dot{V}O_{2max}$. Additionally, this study mainly found that HIIT is superior to MVICT by approximately 1.30 $ml \cdot kg^{-1} \cdot min^{-1}$ in improving relative $\dot{V}O_{2max}$, which might have clinical significance. In a large cohort review[164], each 1 MET (~3.5 $ml \cdot kg^{-1} \cdot min^{-1}$) higher level of cardiorespiratory fitness is associated with an 11% – 17% lower risk of all-cause mortality and an 18% lower risk of incident heart failure, as well as substantially lower cardiovascular mortality in clinical populations. Extrapolating from these dose-response gradients, a between-protocol difference of ~1.3 $ml \cdot kg^{-1} \cdot min^{-1}$ (i.e., ~0.4 MET, in some people enough associated with higher health[165, 166]) in favor of HIIT is likely to translate into a reduction in mortality risk, underscoring the potential clinical and public-health relevance of the superior fitness gains observed with HIIT over MVICT.

HIIT appears superior to MVICT in improving aerobic capacity; however, the underlying biological mechanisms remain incompletely defined, and a comprehensive mechanistic comparison is beyond the scope of the present meta-analysis. Both modalities can promote adaptations such as mitochondrial biogenesis and angiogenesis[22, 23, 167], but likely through partially distinct signaling pathways and intensity – duration profiles. The intermittent, high-intensity bouts of HIIT impose pronounced energetic and hemodynamic stress, increasing the time spent at or near intensities that may elicit high cardiac output and stroke volume, and lowering the cellular ATP/AMP ratio, thereby activating AMP-activated protein kinase (AMPK) and downstream PGC-1α – mediated transcription of mitochondrial genes[168]. In contrast, prolonged low-to-moderate intensity exercise more prominently elevates intracellular Ca^{2+} and engages CaMKII-dependent signaling that also converges on PGC-1α[168]. Thus, HIIT may provide stronger metabolic perturbations and signal intensity within shorter timeframes. Evidence supporting this view comes from a large meta-analysis by Mølmen et al., who also included 5,650 participants with different training levels (from untrained to well-trained). They found that in the early stages (2 weeks) and Shorter required time, SIT progressed faster than MVICT in improving mitochondrial markers (mainly from related enzyme activity measurements), providing some support from the cellular level[169]. Moreover, recent work indicates that prolonged SIT can induce cardiac adaptations[170, 171], although only a limited number of studies have assessed central hemodynamics and cardiac structure using gold-standard methods (e.g., direct cardiac output measurement and advanced imaging), underscoring the need for future mechanistic trials to clarify potential differences between HIIT and MVICT at the level of cardiac function and remodeling.

Training volume (intensity × duration/frequency) also strongly correlates with mitochondrial enzyme activity (e.g., citrate synthase, CS), particularly when exercise intensity is below ~100% Wmax. Bishop et al.[172] proposed that total training volume is the primary determinant of CS activity, although intensity thresholds exist: very low intensities elicit limited adaptations, while higher intensities may partially compensate for reduced volume, offering greater time efficiency. Importantly, HIIT and MVICT differ not only in intensity but also in training volume, complicating attempts to disentangle their independent effects. Using a one-legged cycling model

with matched work, MacInnis et al.[173] demonstrated that HIIT induced greater mitochondrial adaptations than MVICT, indicating that HIIT's advantage cannot be ascribed solely to training volume but also to its intensity-driven signaling. Nonetheless, given that most studies fail to rigorously match training volume, a definitive mechanistic explanation remains elusive.

Current evidence suggests that HIIT's superiority may lie in its capacity to concurrently stimulate central[174, 175] and peripheral skeletal muscle adaptations[167] with greater time efficiency. For example, a recent meta-analysis including 45 studies and 946 men and women of varying health status reported that increases in $\dot{V}O_{2max}$ induced by HIIT were largely attributable to enhanced central O_2 delivery, with little contribution from changes in hematocrit, blood volume, or plasma volume[174].

In summary, while evidence excluding confounding effects of training volume is limited, converging findings suggest that HIIT more efficiently elicits dual central and peripheral adaptations via AMPK-mediated mitochondrial biogenesis and augmented cardiac function, thereby producing modest but meaningful superiority over MVICT in improving $\dot{V}O_{2max}$, particularly when normalized for time or training volume.

4.1.2. Anaerobic Work Capacity

Previous meta-analyses have not directly compared the effects of HIIT and MVICT for improving anaerobic work capacity. For instance, Boullosa et al.[32] indicated that HIIT did not significantly improve anaerobic performance compared to a control group that included high-intensity intermittent, non-sprint interval, and continuous training. In contrast, the present analysis uniquely focuses on the direct comparison between HIIT and MVICT and shows that HIIT significantly outperforms MVICT in enhancing anaerobic work capacity (g=0.47, 95% CI [0.08, 0.86]). Notably, Boullosa et al.[32] included a variety of anaerobic performance measures, such as 30-second Wingate test power, sprint, and repeated-sprint time. In contrast, our study quantified anaerobic power specifically using mean power from the 30-second Wingate test, providing more direct and comparable evidence on the effects of HIIT versus MVICT on anaerobic power improvements.

Exercise intensity is thought to be a key factor in improving mean anaerobic power, but previous studies have yielded inconsistent findings. For example, Nalcakan's study[82] showed that SIT, despite having significantly lower total exercise volume than MVICT, led to greater improvements in anaerobic capacity in healthy male university students. The SIT regimen (4-6 sets of 30 s Wingate sprints, 3 times per week for 7 weeks) resulted in significantly higher peak and average power compared to MVICT (30-50 min of cycling at 60% $\dot{V}O_{2max}$). Conversely, Zelt et al.[84] found no difference in anaerobic power improvements between a four-week SIT program (4-6 sets of 30-second all-out sprints, three times per week) and continuous training at 65% $\dot{V}O_{2peak}$ intensity for 60-75 minutes per session. As a result, our synthesis of 10 effect sizes and over 100 participants per arm provides clarity and shows that HIIT in general is superior to MVICT for enhancing mean anaerobic power.

The superior effects of HIIT over MVICT in enhancing anaerobic work capacity

likely stem from several physiological mechanisms, including increased glycolytic enzymes, improved lactate metabolism, optimized homeostatic regulation, and enhanced tolerance to acidic environments[176]. First, HIIT increases the activity of key glycolytic enzymes, such as phosphofructokinase (PFK) and hexokinase (Hex), accelerating glycolytic flux and improving glucose utilization efficiency during both exercise and recovery. Second, HIIT significantly influences lactate metabolism by enhancing lactate production, transport, and clearance[177]. Increased lactate dehydrogenase (LDH) activity promotes the conversion of pyruvate to lactate, enabling rapid ATP production during high-intensity exercise while reducing dependence on mitochondrial oxidative pathways[176]. Additionally, HIIT accelerates the transmembrane transport and clearance of intramuscular lactate, minimizing its accumulation within muscle cells[177]. It can also strengthen Na^+-K^+ pump function and increase H^+ tolerance, which helps sustain higher output power[178]. Together, these adaptations may help to explain the greater efficacy of HIIT in improving anaerobic performance.

4.2. Effects on Intensity Thresholds, Exercise Economy, and Performance

Threshold markers of exercise intensity, including the lactate threshold, ventilatory threshold, and critical power, are strong predictors of endurance performance[6]. Exercising above these thresholds causes nonlinear increases in metabolic, respiratory, and perceptual stress, accelerating fatigue onset[179, 180]. Improvements in these intensity landmarks are clear indicators of enhanced endurance capacity[6, 181]. Interestingly, this meta-analysis found no significant differences in the efficacy of HIIT and MVICT for improving first and second-intensity threshold indicators. This contrasts with a recent meta-analysis by Pereira et al.[182] that found that HIIT was more effective than MVICT in improving anaerobic threshold in high-level athletes (*ES*=0.73; 95% CI [0.25-1.21]). The reason(s) for these differing findings is unclear, but the study by Pereira et al.[182] only included three studies with high heterogeneity. In contrast, the present study included 19 and 23 effect sizes for the first and second intensity threshold indicators, respectively, with more than 100 participants per group. Nevertheless, the first intensity threshold indicator still exhibited substantial heterogeneity and wide prediction intervals, whereas the pooled effect size for the second intensity threshold indicator was close to zero. Further post hoc power analyses indicated that the statistical power for these two indicators was only 19% and 5%, respectively, suggesting that the current evidence may be insufficient to detect small-to-moderate effects; therefore, these findings should be interpreted with caution. In addition, most studies included in the present meta-analysis did not match the duration of individual training sessions between interventions. Although HIIT is characterized by a higher overall exercise intensity than MVICT, intensity alone may be insufficient to determine the ultimate training outcome; rather, the combination of high intensity with a longer stimulus exposure appears to be equally important for improving submaximal threshold parameters. This may partly explain why no significant between-group differences were observed.

Exercise economy refers to the amount of oxygen required at a given absolute

exercise intensity[6]. Improvements in exercise economy enable athletes to maintain higher exercise intensities while consuming less oxygen or reduce oxygen consumption at the same intensity, thereby enhancing endurance performance[6]. A meta-analysis by Wang et al.[183], which included seven comparisons, found no significant differences between HIIT and MVICT in improving exercise economy. However, González-Mohíno et al.[184], in their meta-analysis incorporating six studies, demonstrated that MVICT was more effective than HIIT to improve running economy in recreational endurance runners (SMD=0.28 [95% CI 0.01, 0.54], p=0.04). Our meta-analysis, including 11 studies and 25 comparisons with participants ranging from recreationally active individuals（Tier 0）to high-level/national athletes（Tier 3）, found no significant differences between the effects of HIIT and MVICT on changes in exercise economy. These inconsistent findings may be due to the numerous factors influencing exercise economy, such as training intensity[185], duration[184], overall training volume[6, 184], and prior training experience[6]. Additionally, improvements in exercise economy often require prolonged training periods, whereas most included studies had relatively short interventions（≤ 8 weeks）. Moreover, 84% of the participants included in our meta-analysis were trained athletes (with a baseline $\dot{V}O_{2max}$ of 51 $mL \cdot kg^{-1} \cdot min^{-1}$), and the training volume in the MVICT interventions was higher than that in the HIIT interventions. These factors were possibly insufficient to detect meaningful differences between HIIT and MVICT.

Jones et al.[6] suggested that exercise economy is closely related to total endurance training volume, with superior values generally observed in older, more experienced athletes or those completing larger weekly training volumes. However, the current study lacks comparative data involving Tier 4 (elite/world-class) and Tier 5 (world-class) athletes. Therefore, caution is warranted when applying these findings to such populations. Our study reveals a clear need for further comparative studies on HIIT versus MVICT on exercise economy in higher level athletes.

This meta-analysis found no significant differences between HIIT and MVICT in improving exercise performance (g=0.04, 95% CI [-0.46, 0.54], p=0.87). Few meta-analyses have specifically evaluated the effects of HIIT versus MVICT on measures of exercise performance. Rosenblat et al.[186] reported a dose-response relationship between HIIT frequency, duration, and total volume and time-trial performance improvements, but the absence of a MICT control group limits any direct comparison.

It is curious that HIIT appears to be superior to MVICT in improving both aerobic and anaerobic work capacities, yet these gains do not translate into superior exercise performance outcomes compared to MVICT. This may reflect the multifactorial nature of exercise performance[6]. which not only depends on physiological markers like $\dot{V}O_{2max}$ and lactate threshold, but also on exercise economy, technical skills, and psychological attributes. Therefore, enhancements in isolated physiological parameters may not directly result in better exercise performance.

4.3. Impact of Participant and Intervention Characteristics

4.3.1. Aerobic Capacity

In terms of training levels, individuals at Tier 1 (g=0.57) and Tier 3 (g=0.83) training levels exhibited more substantial differences in the increase in $\dot{V}O_{2max}$ following HIIT compared to MVICT, while those at Tier 0 (g=0.34) showed relatively smaller (but still significant) differences between HIIT and MVICT. It should be noted, however, that no significant differences were observed between subgroups (p > 0.05), indicating that HIIT was generally more effective than MVICT in improving $\dot{V}O_{2max}$/$\dot{V}O_{2peak}$ across these three training-status categories. For trained or elite athletes, who typically exhibit greater metabolic adaptability and exercise tolerance, exercise intensity appears to play a critical role in eliciting further improvements in $\dot{V}O_{2max}$[178]. MVICT, with its lower intensity, may often fail to provide a sufficient physiological stimulus for higher-level athletes, and the higher intensity of HIIT may be required in these athletes to generate sufficient metabolic stress and demand to elicit adaptations. On the other hand, sedentary individuals, starting from a lower baseline, can improve cardiorespiratory fitness with exercise of almost any intensity[187-189]. Nevertheless, HIIT still appears to confer relative advantages over MVICT in this group. Laursen et al.[17] reported that sedentary populations showed significant improvements in endurance-related physiological markers following moderate-intensity endurance training. However, for high-level athletes already performing substantial volumes of low- to moderate-intensity endurance training, additional MVICT provides little further benefit in terms of $\dot{V}O_{2max}$. In these cohorts, endurance performance improvements seem to be achieved primarily through HIIT. This may partially explain the differences in effect sizes observed between individuals of varying training levels. However, given the substantial differences in the number of included studies, these effect size comparisons should be interpreted with caution.

It should also be noted that participants at Tier 2 (g=0.39) and Tier 4 (g=0.62) training levels did not show statistically significant gains in $\dot{V}O_{2max}$. This might be possibly due to smaller sample sizes or greater individual variability. Indeed, although non-significant, the effect sizes favoring HIIT were small to moderate. Further research is needed in these populations. Similarly, our analysis lacks data from a Tier 5 (world-class) group, likely due to the difficulty in recruiting elite athletes to alter their training schedules for intervention studies[17]. As such, our conclusions should be applied with caution to this population.

Regarding sex, both males (g=0.43) and mixed-sex populations (g=0.42) showed superior improvements in $\dot{V}O_{2max}$ with HIIT compared to MVICT, whereas the effect size in females was smaller (g=0.14) and not statistically significant. Previous research has indicated that endurance training has a greater effect on $\dot{V}O_{2max}$ improvement in men compared to women[190]. likely due to anatomical and physiological differences such as body composition, cardiovascular and pulmonary capacity, red blood cell mass, and hemoglobin levels[30]. Lindner et al.[30] found that while the two modalities improved $\dot{V}O_{2max}$ in females, HIIT did not show a significant advantage over MVICT. Although our study found that HIIT did not show a significant advantage compared to MVICT in the female subgroup, it is important to note that this is based on a much smaller number of effect sizes and therefore our statistical power is lower for female-only cohorts. Given the limited statistical power

of the analysis, the current findings should be interpreted with caution. Furthermore, current studies typically prescribe exercise based on %HR or %$\dot{V}O_{2max}$, but this does not guarantee a match in metabolic stress between men and women. Most studies do not match participants' fitness levels and have small sample sizes, limiting their ability to assess gender differences. Further, the large-scale use of individual thresholds to define intensity may help capture subtle underlying gender differences[191].

Our meta-analysis shows that HIIT is superior to MVICT across the spectrum of age, from young adolescents to older adults. Interestingly, both adolescents (g=0.75) and older individuals (g=0.82) exhibited larger effect sizes in $\dot{V}O_{2max}$ benefits with HIIT compared to MICT, while the pooled effect size was relatively smaller in young (g=0.28) and middle-aged (g=0.40) adults. Adolescents and older individuals showed significantly greater effects compared to young adults (p<0.05), and adolescents also differed significantly from middle-aged individuals (p<0.05). These findings should be interpreted with some caution, though, as there were a smaller number of effect sizes for both adolescents and older individuals.

Regarding interval type, both short and long intervals of training significantly improved $\dot{V}O_{2max}$, aligning with the conclusions from Laursen et al.[50]. They argued that both formats exert a strong stimulus upon aerobic metabolism. Therefore, both short and long interval training may be equally effective for improving $\dot{V}O_{2max}$ relative to MVICT. The superiority of HIIT was clearest for running, cycling, and rowing-based interventions. This is likely to partly reflect the fact that these are the most utilized exercise modalities (with a greater number of effect sizes), but also the greater precision with which differences in exercise intensities in HIIR and MVICT can be manipulated and controlled.

Exercise intensity significantly moderated the effects of HIIT. Both the high-intensity and the very high-intensity subgroups showed greater improvements in $\dot{V}O_{2max}$/$\dot{V}O_{2peak}$ compared to MVICT, suggesting that HIIT is a more effective training modality across different intensity levels. Furthermore, our findings indicate that the high-intensity subgroup exhibited significantly greater improvements than the very high-intensity subgroup. This difference likely reflects the role of total training volume, which might tend to be lower when exercise is prescribed at all-out high intensities. In support of our findings, a large meta-analysis reported mean increases in $\dot{V}O_{2max}$ of 12.5 ± 1.0%, 12.1 ± 1.3%, and 6.6 2.3% for ET, HIT, and SIT, respectively[169]. The suggestion that super high-intensity protocols (e.g., SIT) may constrain the total achievable workload and thereby attenuate the overall adaptive response, whereas high-intensity protocols permit a more favorable balance between intensity and accumulated work. This interpretation is consistent with current evidence indicating that total training volume is a key determinant of exercise-induced changes in mitochondrial content and related aerobic adaptations[172].

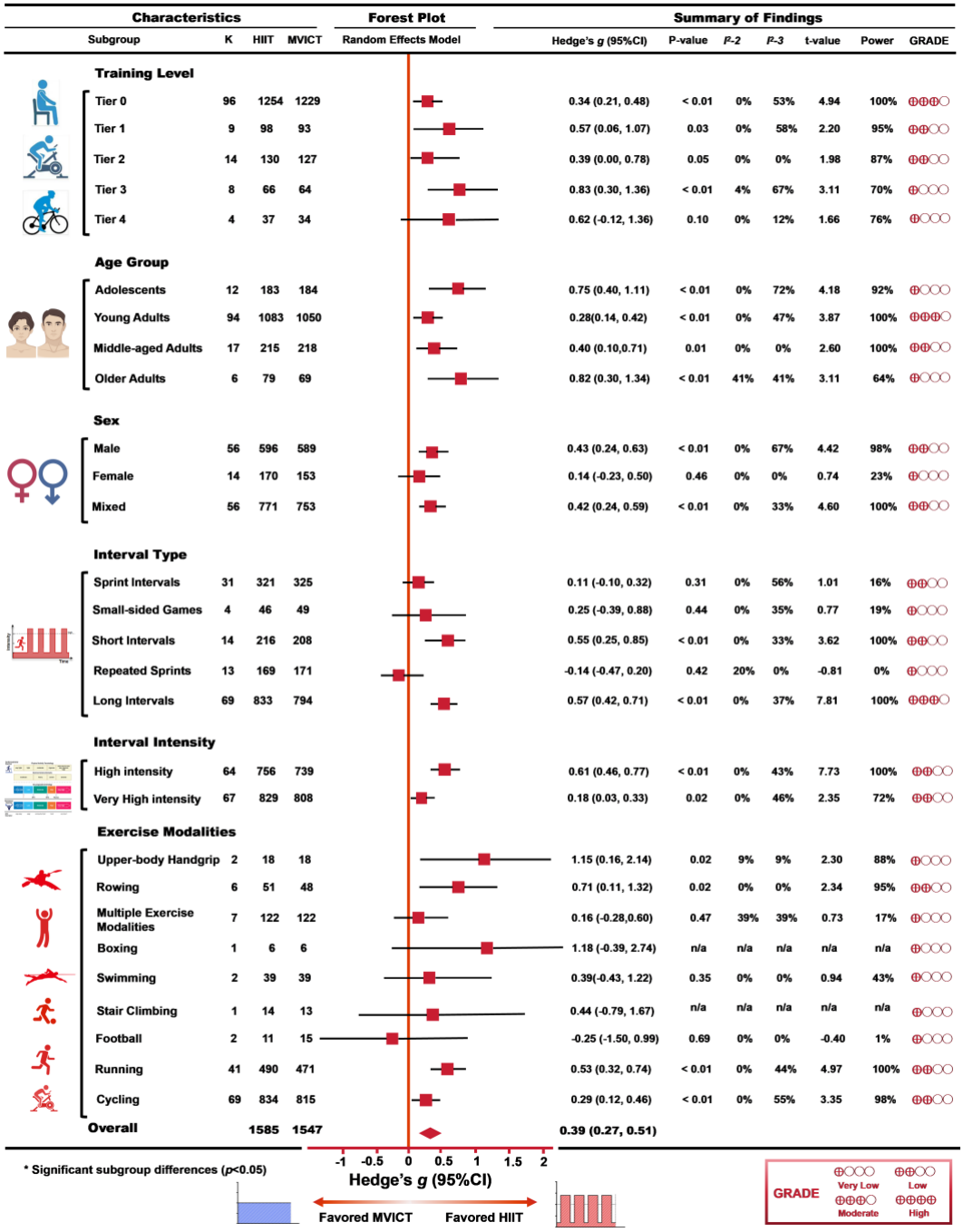

Fig. 3. Subgroup analyses based on relative $\dot{V}O_{2max}$.

95%CI, 95% confidence interval; GRADE, Grading of Recommendations Assessment, Development, and Evaluation (a system for evaluating the quality of evidence and strength of recommendations); Hedge's G, the effect size indicators used in the pooled; I^2, quantitative indicators of heterogeneity; HIIT, high-intensity interval training; MVICT, moderate to vigorous-intensity continuous training; K, the total number of effects included in the pooled effect size; p value, statistically significant p values for pooled results; Power, statistical power for pooled effect size.

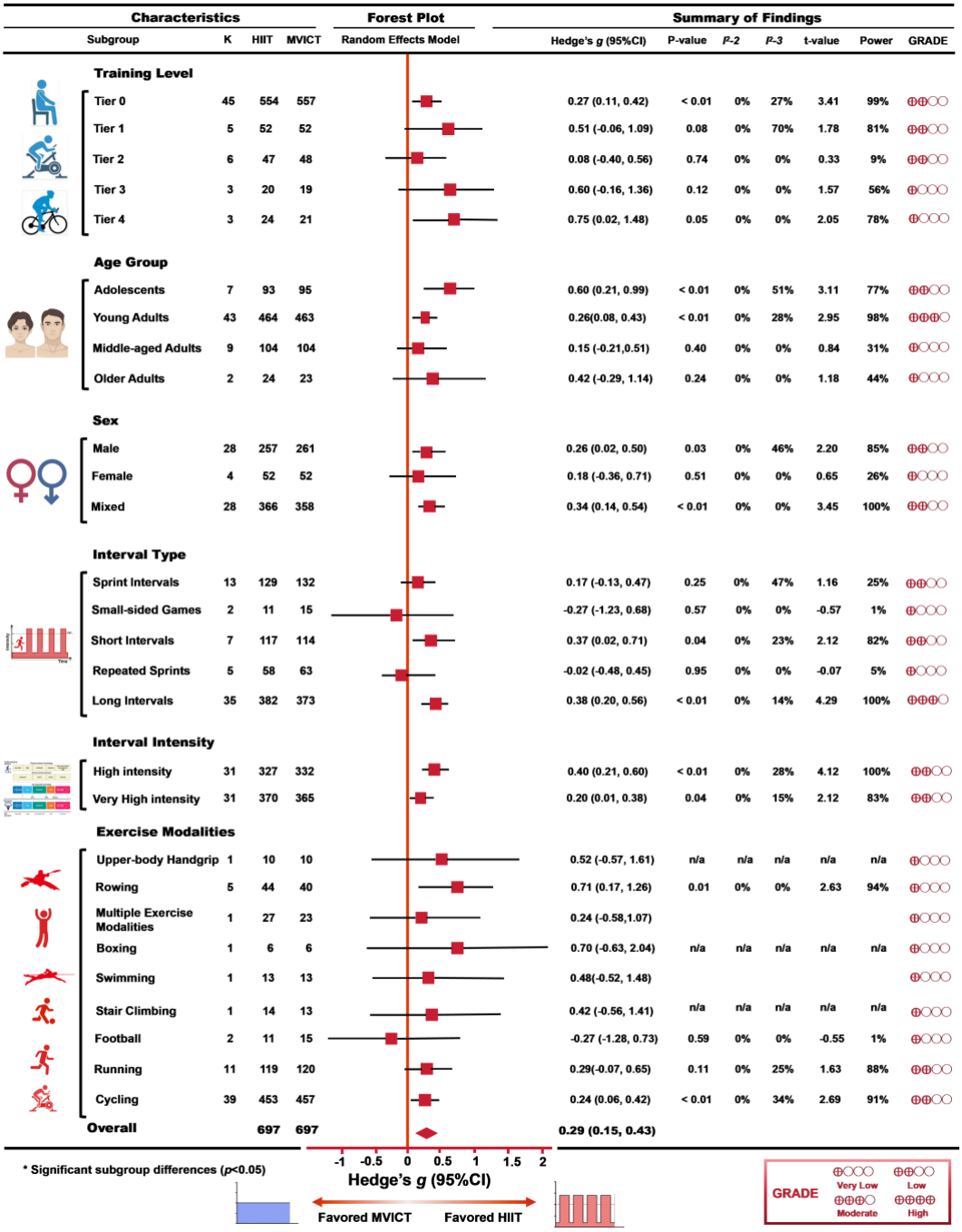

Fig. 4. Subgroup analyses based on absolute $\dot{V}O_{2max}$.

95%CI, 95% confidence interval; GRADE, Grading of Recommendations Assessment, Development, and Evaluation (a system for evaluating the quality of evidence and strength of recommendations); Hedge's G, the effect size indicators used in the pooled; I^2, quantitative indicators of heterogeneity; HIIT, high-intensity interval training; MVICT, moderate to vigorous-intensity continuous training; K, the total number of effects included in the pooled effect size; p value, statistically significant p values for pooled results; Power, statistical power for pooled effect size.

4.3.2. Maximal Aerobic Power/Speed

Participants at Tier 2 (training/development stage) and Tier 3 (elite/national level) showed more substantial increases in MAP/MAV following HIIT compared to MVICT (g=0.71, 95% CI [0.31, 1.10], p<0.01) and g=0.65 (95% CI [0.21, 1.10], p<0.01), respectively. In contrast, Tier 0 (sedentary, untrained individuals) participants showed smaller gains (g=0.21, 95% CI [0.05, 0.37], p=0.01). Considering the differences in effect size and sample numbers across subgroups, our analysis suggests that HIIT tends to be more effective than MVICT in improving MAP/MAV across individuals with varying training statuses. Nevertheless, research indicates that endurance-trained athletes already possess elevated oxidative enzyme activity, capillary density, and slow-twitch muscle fiber proportions. Consequently, moderate-intensity training has limited effects on their aerobic performance, requiring higher-intensity training stimuli for further improvements[17].

Regarding age, adolescents (g=0.80, 95% CI [0.31, 1.30], p<0.01) and young adults (g=0.25, 95% CI [0.08, 0.41], p<0.01) demonstrated significant improvements in MAP/MAV. In contrast, middle-aged individuals showed no significant improvement (g=0.45, 95% CI [-0.03, 0.94], p=0.07), although the effect size was moderate in favour of HIIT. There were comparatively fewer studies available in both adolescents and middle-aged individuals, so findings from these populations should be interpreted with more caution.

Regarding sex, males showed significant improvements in MAP/MAV following HIIT (g=0.44, 95% CI [0.22, 0.66], p<0.01). Contrastingly, females did not show significant improvement, with an effect size of g=-0.83 (95% CI [-1.99, 0.34], p=0.16). This is not surprising given we found a similar trend for $\dot{V}O_{2max}$/$\dot{V}O_{2peak}$. A comparable finding was reported by Diaz-Canestro and Montero[190], who found significantly greater improvements in aerobic capacity in males than females at equivalent training dosage[30]. However, given the limited number of studies involving female-only cohorts, future research should focus on this population across different training statuses, age groups, and other relevant characteristics to better understand sex-specific responses to HIIT compared with MICT.

Regarding interval type, compared with sprint intervals and repeated sprints, both long intervals (g=0.44, 95% CI [0.24, 0.65], p<0.01) and short intervals (g=0.52, 95% CI [0.05, 1.00], p=0.03) produced significantly greater improvements in MAP/MAV. This pattern may reflect the distinct physiological targets of these protocols: all-out, sprint intervals, and RST tend to evoke predominantly anaerobic and neuromuscular adaptations and are associated with rapid fatigue accumulation, which might limit the duration of effective aerobic stress within a session[20, 192]. In contrast, longer and high-intensity intervals allow a larger proportion of the session to be spent near the heavy-severe-intensity transition, thereby providing a stronger and more continuous aerobic stimulus, which is ultimately expressed as superior gains in MAP/MAV.

Regarding interval intensity, high intensity improved MAP/MAV (g=0.56, 95% CI [0.32, 0.80], p<0.01), whereas very high intensity protocols had relatively weaker effects (g=0.19, 95% CI [0.01, 0.37], p=0.04). High intensity protocls involves longer training sessions with greater volume, allowing participants to spend more time at

high intensity, likely providing a stronger stimulus for cardiovascular adaptations and muscle oxygen utilization, potentially thereby enhancing MAP/MAV more effectively than protocols involving very high intensity intervals.

In terms of exercise modality, running (g=0.62, 95% CI [0.34, 0.91], p<0.01) and cycling (g=0.22, 95% CI [0.06, 0.39], p=0.01) significantly improved MAP/MAV, while other exercise modalities (such as upper-body handgrip exercises, and rowing) did not. Running and cycling, as a full-body exercise, recruit more muscle mass, creating a larger disturbance of muscular and central system homeostasis[193]. This induces greater adaptations in cardiovascular function and the ability to tolerate high-intensity stimuli, thus more effectively improving MAP/MAV.

4.3.3. Anaerobic Work Capacity

Regarding training level, participants at Tier 4 exhibited the largest comparative effect size in anaerobic capacity (g=1.01, 95% CI [0.37, 1.64], p<0.01), suggesting that compared to MVICT, HIIT is particularly effective in elite/international level athletes. Long interval training and very high intensity also demonstrated larger effect sizes, with effect sizes of g=0.82 (95% CI [0.27, 1.37], p<0.01) and g=0.49 (95% CI [0.01, 0.97], p=0.05), respectively. These results align with Laursen et al.[50], who noted that long interval training and repeated sprints provide a stronger physiological stimulus to the anaerobic glycolysis system and neuromuscular function, promoting better anaerobic capacity development. Regarding exercise modalities, rowing was found to be more effective in developing anaerobic capacity (g=1.01, 95% CI [0.37, 1.64], p<0.01).

4.3.4. Intensity Threshold, Exercise Economy, and Performance

Sex, age, training level, training modality, interval type, and interval intensity did not moderate the effects of HIIT *versus* MICT on first and second intensity threshold, exercise economy, and performance. However, in long-interval training, HIIT showed a near-significant advantage over MVICT in improving the second intensity threshold (g=0.32, 95% CI [-0.01, 0.65], p=0.06). Long-interval training can elicit substantial physiological stimuli across aerobic and anaerobic glycolytic systems, as well as neuromuscular function. creating greater disturbances to whole-body homeostasis, and thereby potentially conferring greater capacity for enhancing intensity threshold parameters. In comparison, very high intensity interval training was more effective than MVICT for improving exercise economy (g=0.61, 95% CI [0.29, 0.93], p<0.01). Although exercise economy is typically assessed at submaximal intensities, the increase in upper-limit capacity induced by very high intensity interval training may reduce the relative physiological load at a given submaximal workload, thereby indirectly enhancing energy utilization efficiency and more effectively improving exercise economy.

Regarding exercise performance, HIIT led to a greater comparative effect than MVICT in performance for individuals at Tier 0 (g=1.20, 95% CI [0.48, 1.92], p=0.01). As discussed above, this may be attributed to the lower baseline fitness levels of sedentary individuals, which makes them more responsive to training stimuli The high-intensity, intermittent nature of HIIT more effectively activates the neuromuscular system, enhancing motor unit recruitment, neuromuscular

coordination, as well as improving psychological factors (such as motivation levels and tolerance to high-intensity exercise), all of which contribute to improved exercise performance[22, 167]. For highly trained athletes (Tier 2 and above), improvements in exercise performance are more complex and require a balanced training intensity to optimize the training load structure, thereby enhancing physiological adaptation stimuli[18]. Performance improvements in elite populations tend to be more gradual and may require prolonged periodized training cycles before significant progress is observed[194, 195].

5. POTENTIAL LIMITATIONS

Although the present study is based on one of the largest datasets currently available and provides a systematic comparison of HIIT and MVICT across different populations and training protocols, several limitations should be acknowledged.

First, across the included studies, maximal oxygen uptake was reported as either $\dot{V}O_{2max}$ or $\dot{V}O_{2peak}$, depending on the testing protocols and diagnostic criteria adopted by the original authors. Although both indices are widely used to assess maximal aerobic capacity and were therefore combined and analyzed as a single outcome in this meta-analysis, differences in their physiological determination, particularly across testing modalities, may have introduced additional variability. Meanwhile, the wide heterogeneity of testing protocols among different studies (e.g., relative value units, specific incremental loading protocols, etc.) needs to be acknowledged. Moreover, adaptations to endurance training are, to some extent, exercise-mode specific, and consistency between training modality and testing modality was not uniformly controlled across studies. As a result, residual confounding related to training–testing specificity cannot be fully excluded and should be carefully considered when interpreting the apparent superiority of HIIT over MVICT.

Despite several outcomes demonstrating statistically significant pooled effects favoring HIIT over MVICT, the corresponding prediction intervals consistently encompassed the null effect. This indicates substantial uncertainty in the expected intervention effect in future studies or real-world applications, with the true effect potentially ranging from meaningful benefit to trivial or even adverse outcomes. These findings underscore the importance of explicitly considering between-study heterogeneity when interpreting results derived from random-effects meta-analyses, particularly when conclusions are intended to inform practical applications.

Second, the number of studies contributing to different outcome measures varied markedly, resulting in imbalanced statistical power across outcomes (e.g., substantially greater power for $\dot{V}O_{2max}$ than for intensity-threshold or exercise performance outcomes). Consequently, some nonsignificant findings may be driven by limited sample size rather than the absence of a true effect.

Third, prescribing exercise intensity based on fixed percentages of $\dot{V}O_{2max}$ or HR_{max} has been shown to place individuals into different intensity domains, and exercise intensity is likely a key determinant of interindividual variability in training responses. Accordingly, implementing exercise prescriptions within an intensity-domain framework may help mitigate the confounding effect of

non-equivalent intensity prescriptions and thereby reduce heterogeneity in individual training responses. However, most existing studies continue to prescribe intensity using percentages of $\dot{V}O_{2max}$ or HR_{max}. In addition, substantial between-study differences in training intensity, session duration, frequency, and overall intervention length may represent major contributors to the observed heterogeneity.

It should be noted that the limitations outlined above largely reflect methodological challenges that are common and not yet fully resolved in endurance training intervention research, particularly within the HIIT literature. Within this context, the present study remains of considerable value by systematically synthesizing the available evidence and quantitatively evaluating the overall effects of HIIT versus MVICT across diverse study designs and population characteristics.

6. CONCLUSION

In the most comprehensive meta-analysis performed to date, we report that HIIT is superior to MVICT for improving $\dot{V}O_{2max}$/$\dot{V}O_{2peak}$, maximal aerobic power, and anaerobic capacity, whereas no significant differences were observed between HIIT and MVICT for threshold markers of exercise intensity, exercise economy, and overall exercise performance. We report evidence that the relative superiority of HIIT over MICT is influenced by participant characteristics (e.g., individual training status, age, and sex) and protocol-specific features (e.g., interval type and exercise modality). Notably, we also find no evidence that MVICT is superior to HIIT for any of the parameters studied. Our findings can inform the practical application of HIIT and MVICT to maximize health and performance outcomes alike.

7. PERSPECTIVE

Both high-intensity interval training (HIIT) and moderate- to vigorous-intensity continuous training (MVICT) are widely recommended for improving cardiorespiratory fitness, metabolic health, and exercise performance, but their relative effects are highly context-dependent. Based on 115 randomized controlled trials, this study employed a multilevel meta-analysis and found that HIIT tends to elicit greater improvements in cardiorespiratory fitness and exercise performance among adolescents, older adults, and sedentary or low-fitness individuals. In well-trained or high-level athletes, its benefits are primarily observed in $\dot{V}O_{2max}$/$\dot{V}O_{2peak}$, MAP/MAV, and anaerobic capacity, whereas its effects on intensity threshold indicators and exercise economy are relatively limited. Furthermore, current evidence suggests that HIIT produces more consistent outcomes in males, while results in female subgroups are less stable. Future studies should systematically consider moderating variables such as sex, age, training status, interval type, and interval intensity, and adopt refined designs to optimize individualized exercise prescriptions and enhance intervention efficacy. Overall, this study supports the implementation of individualized and context-specific training strategies across different populations and target outcomes, rather than simply promoting the “superiority” of a single training modality, to facilitate the translation of precision exercise interventions into practice. From a physiological perspective, different

training intensities and modalities may influence cardiorespiratory fitness through multiple pathways. In addition to heart rate and stroke volume regulation, changes in preload (e.g., training-induced increases in blood volume and improved ventricular filling) and afterload (e.g., modulation of mean arterial pressure during exercise) may exhibit differential adaptations across training modes, thereby affecting central hemodynamic responses. These mechanisms have not been systematically investigated in comparative studies of HIIT and MVICT and warrant further mechanism-focused research. In particular, few HIIT-MVICT studies have employed gold-standard methods to quantify cardiac output and stroke volume, and evidence comparing structural cardiac adaptations between the two modalities is currently scarce and inconclusive, representing an important avenue for future research.

Moreover, future studies should prioritize methodological standardization and transparency, including clear differentiation between $\dot{V}O_{2max}$ and $\dot{V}O_{2peak}$, controlling or reporting consistency in training and testing protocols, and preferably applying individualized exercise prescriptions based on intensity zones or metabolic thresholds. Well-designed, multicenter randomized controlled trials are also needed to verify the stability and generalizability of HIIT intervention effects, reduce inter-study heterogeneity, and enhance the practical relevance of findings. From an applied perspective, individual characteristics, training program design, and outcome measures collectively determine training responses. HIIT offers advantages in terms of time efficiency and specific adaptation goals, while MVICT is also effective in certain populations and may be more sustainable. Therefore, rather than simply comparing the superiority of training modalities, future research and practice should focus on identifying the populations, conditions, and objectives under which different training strategies can achieve maximal benefits, thereby advancing the development of precision exercise prescriptions.

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Supplementary Table 1 First Search

Data	Query	Results
PUBMED	((((((((((((((((((((((((Interval Training[Title/Abstract]) OR (High-Intensity Interval Training[Title/Abstract])) OR (High Intensity Interval Training[Title/Abstract])) OR (High-Intensity Interval Trainings[Title/Abstract])) OR (Interval Training, High-Intensity[Title/Abstract])) OR (Interval Trainings, High-Intensity[Title/Abstract])) OR (Trainings, High-Intensity Interval[Title/Abstract])) OR (High-Intensity Intermittent Exercise[Title/Abstract])) OR (Exercise, High-Intensity Intermittent[Title/Abstract])) OR (Exercises, High-Intensity Intermittent[Title/Abstract])) OR (High-Intensity Intermittent Exercises[Title/Abstract])) OR (Sprint Interval Training[Title/Abstract])) OR (Sprint Interval Trainings[Title/Abstract])) OR (Aerobic Interval Training[Title/Abstract])) OR (High-Volume Interval Training[Title/Abstract])) OR (Repeated Sprint Training[Title/Abstract])) OR (Intermittent Exercise Training[Title/Abstract])) OR (HIIT[Title/Abstract])) OR (SIT[Title/Abstract])) OR (HIT[Title/Abstract])) OR (HIIE[Title/Abstract])) OR (AIT[Title/Abstract])) OR (RST[Title/Abstract])) OR (IET[Title/Abstract])) AND ((((((((((((((((((((((((Continuous Training[Title/Abstract]) OR (Low-Intensity Continuous Training[Title/Abstract])) OR (Continuous Low-Intensity Exercise[Title/Abstract])) OR (Low-Intensity Endurance Training[Title/Abstract])) OR (Steady-State Low-Intensity Training[Title/Abstract])) OR (Low-Intensity Aerobic Training[Title/Abstract])) OR (Low-Intensity Exercise[Title/Abstract])) OR (Moderate-Intensity Continuous Training[Title/Abstract])) OR (Moderate to Low-Intensity Continuous Training[Title/Abstract])) OR (Submaximal Continuous Training[Title/Abstract])) OR (High-Volume Training[Title/Abstract])) OR (Steady-State Continuous Training[Title/Abstract])) OR (Aerobic Continuous Training[Title/Abstract])) OR (Steady-State Training[Title/Abstract])) OR (Volume Training[Title/Abstract])) OR (endurance training[Title/Abstract])) OR (aerobic endurance[Title/Abstract])) OR (aerobic exercise[Title/Abstract])) OR (aerobic training[Title/Abstract])) OR (ET[Title/Abstract])) OR (CT[Title/Abstract])) OR (LCT[Title/Abstract])) OR (HVT[Title/Abstract])) OR (SCT[Title/Abstract])) OR (ACT[Title/Abstract])) OR (SST[Title/Abstract])) OR (VT[Title/Abstract])) OR (CET[Title/Abstract]))	4942
Web of Science	((TS=(Continuous Training)) OR TS=(Low-Intensity Continuous Training)) OR TS=(Continuous Low-Intensity Exercise)) OR TS=(Low-Intensity Endurance Training)) OR TS=(Steady-State Low-Intensity Training)) OR TS=(Low-Intensity Aerobic Training)) OR TS=(Low-Intensity Exercise)) OR TS=(Moderate-Intensity Continuous Training)) OR TS=(Moderate to Low-Intensity Continuous Training)) OR TS=(Submaximal Continuous Training)) OR TS=(High-Volume Training)) OR TS=(Steady-State Continuous Training)) OR TS=(Aerobic Continuous Training)) OR TS=(Steady-State Training)) OR TS=(Volume Training)) OR TS=(endurance training)) OR TS=(aerobic endurance)) OR TS=(aerobic exercise)) OR TS=(aerobic training)) OR TS=(ET)) OR TS=(CT)) OR TS=(LCT)) OR TS=(HVT)) OR TS=(SCT)) OR TS=(ACT)) OR TS=(SST)) OR TS=(VT)) OR TS=(CET) AND ((TS=(Interval Training)) OR TS=(High-Intensity Interval Training)) OR TS=(High Intensity Interval Training)) OR TS=(High-Intensity Interval Trainings)) OR TS=(Interval Training, High-Intensity)) OR TS=(Interval Trainings, High-Intensity)) OR TS=(Trainings, High-Intensity Interval)) OR TS=(High-Intensity Intermittent Exercise)) OR TS=(Exercise, High-Intensity Intermittent)) OR TS=(Exercises, High-Intensity Intermittent)) OR	3960

	TS=(High-Intensity Intermittent Exercises)) OR TS=(Sprint Interval Training)) OR TS=(Sprint Interval Trainings)) OR TS=(Aerobic Interval Training)) OR TS=(High-Volume Interval Training)) OR TS=(Repeated Sprint Training)) OR TS=(Intermittent Exercise Training)) OR TS=(HIIT)) OR TS=(SIT)) OR TS=(HIT)) OR TS=(HIIE)) OR TS=(AIT)) OR TS=(RST)) OR TS=(IET)	
CNKI	（主题：间歇训练）OR（主题：重复冲刺）OR（主题：间歇运动）AND（主题：持续训练）OR（主题：容量训练）OR（主题：耐力训练）OR（主题：持续运动）OR（主题：有氧训练）	595

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Supplementary Table 2 Subgroup Analysis of Relative Maximal Oxygen Uptake

Subgroup	*k*	*g*	95% CI	95% PI	*p*-value	I^2	*p*-subgroup
Training Level							0.41
Tier 0	96	0.3429	0.21 to 0.48	-0.61 to 1.30	<0.01	53%	
Tier 1	9	0.5647	0.06 to 1.07	-0.51 to 1.63	0.03	58%	
Tier 2	14	0.3891	0.00 to 0.78	-0.63 to 1.41	0.05	0%	
Tier 3	8	0.8293	0.30 to 1.36	-0.25 to 1.91	<0.01	71%	
Tier 4	4	0.6213	-0.12 to 1.36	-0.58 to 1.82	0.10	12%	
Age Group							0.02
Adolescents	12	0.7532	0.40 to 1.11	-0.21 to 1.72	<0.01	72%	
Young Adults	94	0.2780	0.14 to 0.42	-0.63 to 1.19	<0.01	47%	
Middle-aged Adults	17	0.4033	0.10 to 0.71	-0.55 to 1.35	0.01	0%	
Older Adults	6	0.8205	0.30 to 1.34	-0.22 to 1.86	<0.01	82%	
Sex							0.54
Male	56	0.4318	0.24 to 0.63	-0.54 to 1.41	<0.01	33%	
Female	14	0.1366	-0.23 to 0.50	-0.89 to 1.16	0.46	0%	
Mixed	56	0.4152	0.24 to 0.59	-0.56 to 1.39	<0.01	33%	
Interval Type							0.01
Sprint Intervals	31	0.1089	-0.10 to 0.32	-0.71 to 0.92	0.31	56%	
Small-sided Games	4	0.2473	-0.39 to 0.88	-0.76 to 1.26	0.44	35%	
Short Intervals	14	0.5513	0.25 to 0.85	-0.29 to 1.39	<0.01	33%	
Repeated Sprints	13	-0.1361	-0.47 to 0.20	-0.99 to 0.72	0.42	20%	
Long Intervals	69	0.5661	0.42 to 0.71	-0.23 to 1.36	<0.01	37%	
Interval Intensity							0.01
High intensity	64	0.6118	0.46 to 0.77	-0.25 to 1.47	<0.01	43%	
Very High intensity	67	0.1807	0.03 to 0.33	-0.68 to 1.04	0.02	46%	
Exercise Modalities							0.29
Upper-body Handgrip	2	1.1497	0.16 to 2.14	-0.23 to 2.53	0.02	17%	
Rowing	6	0.7143	0.11 to 1.32	-0.42 to 1.85	0.02	0%	
Multiple Exercise Modalities	7	0.1613	-0.28 to 0.60	-0.89 to 1.21	0.47	79%	
Boxing	1	1.1779	-0.39 to 2.74	-0.66 to 3.01	0.14	0%	
Swimming	2	0.3938	-0.43 to 1.22	-0.87 to 1.66	0.35	0%	
Stair Climbing	1	0.4422	-0.79 to 1.67	-1.12 to 2.00	0.48	0%	
Football	2	-0.2522	-1.50 to 0.99	-1.82 to 1.32	0.69	0%	
Running	41	0.5286	0.32 to 0.74	-0.45 to 1.51	<0.01	44%	
Cycling	69	0.2900	0.12 to 0.46	-0.68 to 1.26	<0.01	55%	

Supplementary Table 3 Subgroup Analysis of Absolute Maximal Oxygen Uptake

Subgroup	*k*	*g*	95% CI	95% PI	*p*-value	I^2	*p*-subgroup
Training Level							0.46
Tier 0	45	0.2666	0.11 to 0.42	-0.29 to 0.83	<0.01	27%	
Tier 1	5	0.5142	-0.06 to 1.09	-0.28 to 1.30	0.08	70%	
Tier 2	6	0.0804	-0.40 to 0.56	-0.64 to 0.80	0.74	0%	
Tier 3	3	0.5995	-0.16 to 1.36	-0.33 to 1.53	0.12	0%	
Tier 4	3	0.7495	0.02 to 1.48	-0.16 to 1.66	0.05	0%	
Age Group							0.49
Adolescents	7	0.6035	0.21 to 0.99	-0.08 to 1.28	<0.01	51%	
Young Adults	43	0.2570	0.08 to 0.43	-0.33 to 0.84	<0.01	28%	
Middle-aged Adults	9	0.1512	-0.21 to 0.51	-051 to 0.82	0.40	0%	
Older Adults	2	0.4236	-0.29 to 1.14	-0.49 to 1.33	0.24	0%	
Sex							0.87
Male	28	0.2616	0.02 to 0.50	-0.38 to 0.90	0.03	46%	
Female	4	0.1755	-0.36 to 0.71	-0.63 to 0.98	0.51	0%	
Mixed	28	0.3412	0.14 to 0.54	-0.28 to 0.97	<0.01	0%	
Interval Type							0.28
Sprint Intervals	13	0.1726	-0.13 to 0.47	-0.43 to 0.77	0.25	47%	
Small-sided Games	2	-0.2732	-1.23 to 0.68	-1.36 to 0.81	0.57	0%	
Short Intervals	7	0.3680	0.02 to 0.71	-0.26 to 0.99	0.04	23%	
Repeated Sprints	5	-0.0157	-0.48 to 0.45	-0.71 to 0.68	0.95	0%	
Long Intervals	35	0.3836	0.20 to 0.56	-0.16 to 0.93	<0.01	14%	
Interval Intensity							0.13
High intensity	31	0.4013	0.21 to 0.60	-0.15 to 0.95	<0.01	28%	
Very High intensity	31	0.1972	0.01 to 0.38	-0.35 to 0.75	0.04	15%	
Exercise Modalities							0.76
Upper-body Handgrip	1	0.5175	-0.57 to 1.61	-0.73 to 1.76	0.35	n/a	
Rowing	5	0.7143	0.17 to 1.26	-0.10 to 1.52	0.01	0%	
Multiple Exercise Modalities	1	0.2436	-0.58 to 1.07	-0.78 to 1.27	0.56	n/a	
Boxing	1	0.7037	-0.63 to 2.04	-0.76 to 2.17	0.30	n/a	
Swimming	1	0.4812	-0.52 to 1.48	-0.68 to 1.65	0.34	n/a	
Stair Climbing	1	0.4246	-0.56 to 1.41	-0.73 to 1.58	0.39	n/a	
Football	2	-0.2732	-1.28 to 0.73	-1.44 to 0.89	0.59	0%	
Running	11	0.2921	-0.07 to 0.65	-0.41 to 0.99	0.11	25%	
Cycling	39	0.2429	0.06 to 0.42	-0.38 to 0.87	<0.01	34%	

Supplementary Table 4 Subgroup Analysis of Maximal Aerobic Power/Speed

Subgroup	*k*	*g*	95% CI	95% PI	*p*-value	I^2	*p*-subgroup
Training Level							0.05
Tier 0	40	0.2090	0.05 to 0.37	-0.39 to 0.80	0.01	36%	
Tier 2	9	0.7052	0.31 to 1.10	0.01 to 1.40	<0.01	0%	
Tier 3	7	0.6549	0.21 to 1.10	-0.07 to 1.38	<0.01	26%	
Tier 4	2	0.1138	-0.72 to 0.95	-0.90 to 1.13	0.79	0%	
Age Group							0.19
Adolescents	4	0.8044	0.31 to 1.30	0.01 to 1.60	<0.01	81%	
Young Adults	48	0.2491	0.08 to 0.41	-0.39 to 0.89	<0.01	22%	
Middle-aged Adults	5	0.4546	-0.03 to 0.94	-0.33 to 1.24	0.07	0%	
Sex							0.11
Male	29	0.4422	0.22 to 0.66	-0.21 to 1.10	<0.01	47%	
Female	1	-0.8257	-1.99 to 0.34	-2.14 to 0.49	0.16	n/a	
Mixed	26	0.2263	0.01 to 0.44	-0.43 to 0.88	0.04	3%	
Interval Type							0.12
Sprint Intervals	17	0.1070	-0.17 to 0.38	-0.58 to 0.79	0.43	20%	
Short Intervals	5	0.5249	0.05 to 1.00	-0.26 to 1.31	0.03	51%	
Repeated Sprints	6	0.0579	-0.40 to 0.51	-0.72 to 0.83	0.80	71%	
Long Intervals	30	0.4441	0.24 to 0.65	-0.22 to 1.10	<0.01	18%	
Interval Intensity							0.01
High intensity	20	0.5598	0.32 to 0.80	-0.06 to 1.18	<0.01	19%	
Very High intensity	38	0.1910	0.01 to 0.37	-0.41 to 0.80	0.04	33%	
Exercise Modalities							0.01
Upper-body Handgrip	2	0.6211	-0.14 to 1.39	-0.27 to 1.51	0.11	38%	
Rowing	6	0.2023	-0.24 to 0.64	-0.43 to 0.84	0.36	0%	
Multiple Exercise Modalities	1	-1.2404	-2.22 to -0.27	-2.32 to -0.16	0.01	n/a	
Stair Climbing	1	0.8231	-0.10 to 1.75	-0.21 to 1.86	0.08	n/a	
Running	13	0.6248	0.34 to 0.91	0.10 to 1.16	<0.01	37%	
Cycling	35	0.2218	0.06 to 0.39	-0.26 to 0.71	0.01	16%	

1618 **Supplementary Table 5 Subgroup Analysis of Mean Anaerobic Power**

Subgroup	*k*	*g*	95% CI	95% PI	*p*-value	I^2	*p*-subgroup
Training Level							0.05
Tier 0	6	0.2602	-0.11 to 0.63	-0.11 to 0.63	0.14	0%	
Tier 4	4	1.0070	0.37 to 1.64	0.37 to 1.64	<0.01	0%	
Sex							0.79
Male	7	0.5182	-0.07 to 1.11	-0.45 to 1.49	0.08	43%	
Mixed	3	0.4062	-0.35 to 1.16	-0.67 to 1.48	0.25	0%	
Interval Type							0.15
Sprint Intervals	4	0.1316	-0.35 to 0.61	-0.35 to 0.61	0.54	0%	
Repeated Sprints	1	0.5268	-0.23 to 1.29	-0.23 to 1.29	0.15	n/a	
Long Intervals	5	0.8189	0.27 to 1.37	0.27 to 1.37	<0.01	0%	
Interval Intensity							0.82
High intensity	1	0.3601	-0.86 to 1.58	-1.05 to 1.77	0.51	n/a	
Very High intensity	9	0.4914	0.01 to 0.97	-0.36 to 1.35	0.05	29%	
Exercise Modalities							0.05
Rowing	4	1.0070	0.37 to 1.64	0.37 to 1.64	<0.01	0%	
Cycling	6	0.2602	-0.11 to 0.63	-0.11 to 0.63	0.14	0%	

1619 **Supplementary Table 6 Subgroup Analysis of Peak Anaerobic Power**

Subgroup	*k*	*g*	95% CI	95% PI	*p*-value	I^2	*p*-subgroup
Training Level							0.18
Tier 0	6	0.1160	-0.29 to 0.52	-0.43 to 0.67	0.53	35%	
Tier 3	1	0.1269	-1.09 to 1.34	-1.14 to 1.40	0.82	n/a	
Tier 4	4	0.7939	0.15 to 1.44	0.05 to 1.54	0.02	0%	
Interval Type							0.48
Sprint Intervals	5	0.1594	-0.40 to 0.71	-0.76 to 1.08	0.53	48%	
Repeated Sprints	1	0.1219	-0.91 to 1.16	-1.15 to 1.39	0.80	n/a	
Long Intervals	5	0.5842	-0.04 to 1.21	-0.38 to 1.55	0.06	16%	
Interval Intensity							0.21
High intensity	1	-0.0295	-1.22 to 1.16	-1.41 to 1.36	0.96	n/a	
Very High intensity	10	0.3570	-0.06 to 0.78	-0.46 to 1.18	0.09	30%	
Exercise Modalities							0.12
Rowing	5	0.6464	0.08 to 1.21	-0.04 to 1.33	0.03	0%	
Cycling	6	0.1167	-0.28 to 0.52	-0.44 to 0.68	0.53	35%	

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Supplementary Table 7 Subgroup Analysis of Intensity Threshold 1

Subgroup	*k*	*g*	95% CI	95% PI	*p*-value	I^2	*p*-subgroup
Training Level							0.78
Tier 0	10	0.7215	-0.61 to 2.05	-2.66 to 4.10	0.26	94%	
Tier 1	5	0.0546	-2.19 to 2.30	-3.78 to 3.89	0.96	0%	
Tier 2	3	-0.1412	-2.03 to 1.75	-3.78 to 3.49	0.88	80%	
Tier 3	1	1.3073	-1.98 to 4.60	-3.22 to 5.83	0.41	n/a	
Age Group							0.79
Young Adults	15	0.4979	-0.51 to 1.50	-2.53 to 3.52	0.31	92%	
Middle-aged Adults	4	0.2610	-1.46 to 1.98	-3.07 to 3.59	0.75	0%	
Sex							0.98
Male	9	0.4488	-0.79 to 1.69	-2.67 to 3.57	0.46	94%	
Mixed	10	0.4268	-0.79 to 1.64	-2.68 to 3.54	0.47	0%	
Interval Type							0.44
Sprint Intervals	2	0.6366	-0.49 to 1.76	-2.18 to 3.45	0.25	37%	
Short Intervals	2	0.9203	-0.30 to 2.14	-1.93 to 3.77	0.13	0%	
Repeated Sprints	1	-1.4714	-4.33 to 1.39	-5.33 to 2.38	0.29	n/a	
Long Intervals	14	0.5701	-0.26 to 1.40	-2.14 to 3.28	0.16	88%	
Interval Intensity							0.80
High intensity	12	0.4678	-0.39 to 1.33	-2.34 to 3.28	0.27	90%	
Very High intensity	7	0.3784	-0.56 to 1.32	-2.46 to 3.22	0.41	78%	
Exercise Modalities							0.57
Rowing	1	1.3073	-1.75 to 4.36	-2.88 to 5.49	0.38	n/a	
Running	8	-0.0571	-1.40 to 1.28	-3.22 to 3.10	0.93	48%	
Cycling	10	0.7144	-0.52 to 1.95	-2.40 to 3.83	0.24	94%	

Supplementary Table 8 Subgroup Analysis of Intensity Threshold 2

Subgroup	*k*	*g*	95% CI	95% PI	*p*-value	I^2	*p*-subgroup
Training Level							0.69
Tier 0	15	0.1344	-0.25 to 0.52	-0.97 to 1.24	0.47	62%	
Tier 1	2	0.3432	-0.60 to 1.29	-1.06 to 1.75	0.46	0%	
Tier 2	4	-0.0673	-0.80 to 0.66	-1.34 to 1.20	0.85	49%	
Tier 3	2	-0.4032	-1.48 to 0.67	-1.90 to 1.09	0.44	48%	
Age Group							0.76
Young Adults	21	0.0614	-0.26 to 0.38	-0.98 to 1.10	0.69	55%	
Middle-aged Adults	2	0.2085	-0.71 to 1.20	-1.14 to 1.56	0.64	0%	
Sex							0.03
Male	11	-0.2479	-0.63 to 0.14	-1.10 to 0.61	0.20	58%	
Mixed	12	0.3198	-0.01 to 0.65	-0.51 to 1.15	0.06	0%	
Interval Type							0.07
Sprint Intervals	7	-0.1858	-0.67 to 0.30	-1.09 to 0.72	0.43	25%	
Repeated Sprints	3	-0.4425	-1.14 to 0.25	-1.48 to 0.60	0.20	79%	
Long Intervals	13	0.3172	-0.01 to 0.65	-0.52 to 1.16	0.06	17%	
Interval Intensity							0.07
High intensity	10	0.3429	-0.04 to 0.73	-0.54 to 1.22	0.08	49%	
Very High intensity	13	-0.1396	-0.49 to 0.21	-1.01 to 0.73	0.41	44%	
Exercise Modalities							0.05
Rowing	3	-0.2779	-1.11 to 0.56	-1.58 to 1.02	0.49	0%	
Multiple Exercise Modalities	1	-1.3057	-2.46 to -0.15	-2.83 to 0.22	0.03	0%	
Running	4	0.1947	-0.47 to 0.86	-1.00 to 1.39	0.55	64%	
Cycling	15	0.2627	-0.20 to 0.73	-0.84 to 1.36	0.25	56%	

1638 **Supplementary Table 9 Subgroup Analysis of Exercise Economy**

Subgroup	*k*	*g*	95% CI	95% PI	*p*-value	I^2	*p*-subgroup
Training Level							0.67
Tier 0	4	0.3900	-0.30 to 1.08	-0.62 to 1.40	0.25	0%	
Tier 1	8	0.3439	-0.27 to 0.95	-0.61 to 1.30	0.25	13%	
Tier 2	8	0.010	-0.51 to 0.53	-0.89 to 0.91	0.97	57%	
Tier 3	5	0.4369	-0.22 to 1.10	-0.55 to 1.42	0.18	0%	
Age Group							0.56
Young Adults	24	0.2780	-0.02 to 0.58	-0.46 to 1.02	0.07	29%	
Middle-aged Adults	1	-0.0587	-1.21 to 1.09	-1.39 to 1.28	0.92	0%	
Sex							0.71
Male	12	0.2447	-0.16 to 0.65	-0.49 to 0.98	0.22	0%	
Mixed	10	0.1406	-0.28 to 0.56	-0.60 to 0.89	0.49	44%	
Interval Type							0.40
Sprint Intervals	5	0.5651	-0.10 to 1.23	-0.36 to 1.49	0.10	0%	
Short Intervals	2	0.4671	-0.37 to 1.30	-0.59 to 1.52	0.26	46%	
Repeated Sprints	2	0.5807	-0.28 to 1.45	-0.50 to 1.66	0.18	36%	
Long Intervals	16	0.0924	-0.25 to 0.44	-0.64 to 0.82	0.58	21%	
Interval Intensity							0.01
High intensity	14	-0.0284	-0.31 to 0.25	-0.42 to 0.36	0.56	9%	
Very High intensity	11	0.6084	0.29 to 0.93	0.19 to 1.03	<0.01	0%	
Exercise Modalities							0.26
Rowing	5	0.4302	-0.19 to 1.05	-0.47 to 1.33	0.17	0%	
Multiple Exercise Modalities	1	0.9236	-0.08 to 1.93	-0.27 to 2.12	0.08	0%	
Running	19	0.1636	-0.16 to 0.49	-0.56 to 0.88	0.31	31%	

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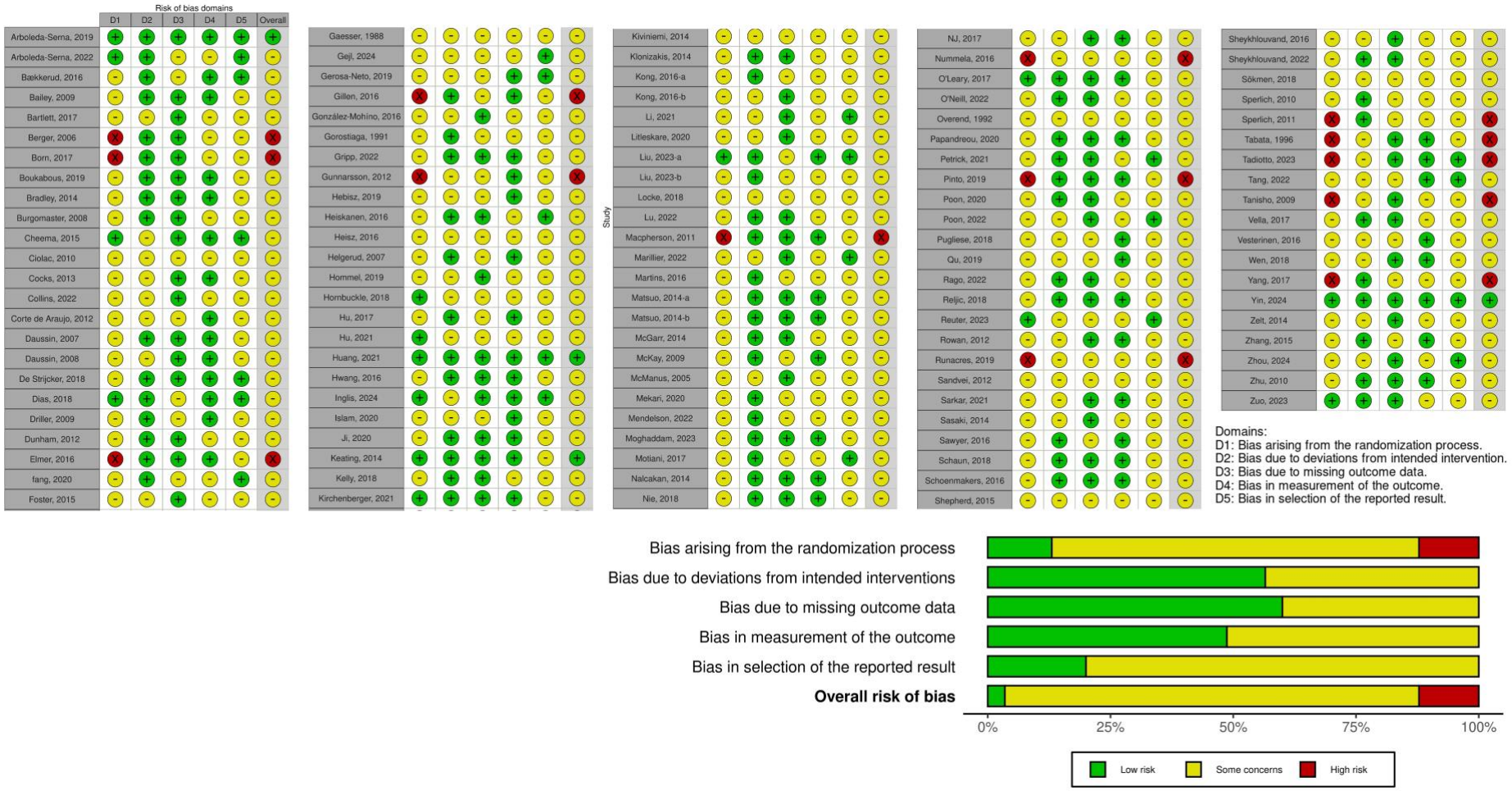
Supplementary Table 10 Subgroup Analysis of Exercise Performance

Subgroup	*k*	*g*	95% CI	95% PI	*p*-value	I^2	*p*-subgroup
Training Level							0.00
Tier 0	3	1.2024	0.48 to 1.92	0.06 to 2.34	0.01	46%	
Tier 2	7	-0.5354	-1.10 to 0.03	-1.58 to 0.51	0.06	56%	
Tier 3	6	0.0153	-0.63 to 0.66	-1.08 to 1.11	0.05	37%	
Tier 4	5	-0.5059	-1.24 to 0.22	-1.65 to 0.64	0.16	0%	
Age Group							0.44
Adolescents	1	-0.1285	-2.06 to 1.81	-2.66 to 2.40	0.89	0%	
Young Adults	18	-0.0877	-0.65 to 0.48	-1.82 to 1.64	0.75	67%	
Middle-aged Adults	2	0.8112	-0.53 to 2.16	-1.30 to 2.93	0.22	75%	
Sex							0.52
Male	12	-0.2518	-1.00 to 0.50	-2.09 to 1.58	0.49	7%	
Female	1	0.4820	-1.63 to 2.60	-2.22 to 3.18	0.64	0%	
Mixed	8	0.2971	-0.46 to 1.06	-1.54 to 2.14	0.42	86%	
Interval Type							0.76
Sprint Intervals	3	-0.2629	-1.48 to 0.96	-2.44 to 1.92	0.66	57%	
Short Intervals	2	-0.4263	-2.37 to 1.51	-3.08 to 2.23	0.65	0%	
Repeated Sprints	1	0.7364	-1.17 to 2.64	-1.89 to 3.36	0.43	0%	
Long Intervals	15	0.0982	-0.56 to 0.76	-1.83 to 2.02	0.76	72%	
Interval Intensity							0.39
High intensity	10	0.2432	-0.45 to 0.94	-1.54 to 2.03	0.47	80%	
Very High intensity	11	-0.1873	-0.93 to 0.56	-1.99 to 1.62	0.60	46%	
Exercise Modalities							0.40
Rowing	10	-0.2069	-0.99 to 0.58	-2.00 to 1.59	0.59	53%	
Multiple Exercise Modalities	1	0.7364	-0.98 to 2.45	-1.62 to 3.09	0.38	0%	
Running	6	-0.2569	-1.18 to 0.66	-2.11 to 1.60	0.56	22%	
Cycling	4	0.6692	-0.43 to 1.76	-1.28 to 2.62	0.21	86%	

Supplementary Figure 1 Risk of bias for the included studies



Supplementary Table 11 Methodological Quality Assessment (PEDro)

Author, year	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11	Total
Gaesser, 1988	Y	1	0	1	0	0	0	0	1	1	1	5
Gorostiaga, 1991	Y	1	0	1	0	0	0	1	1	1	1	6
Overend, 1992	N	1	0	1	0	0	0	0	1	1	1	5
Tabata, 1996	N	0	0	1	0	0	0	0	1	0	1	3
McManus, 2005	N	1	0	1	0	0	0	0	1	1	1	5
Berger, 2006	Y	0	0	1	0	0	0	1	1	1	1	5
Helgerud, 2007	Y	1	0	1	0	0	0	0	1	1	1	5
Daussin, 2007	Y	1	0	1	0	0	0	1	1	1	1	6
Burgomaster, 2008	Y	0	0	1	0	0	0	1	1	1	1	5
Driller, 2009	N	1	0	1	1	0	0	0	1	1	1	6
Bailey, 2009	N	1	0	1	0	0	0	0	1	1	1	5
McKay, 2009	Y	1	0	1	0	0	0	0	1	1	1	5
Ciolac, 2010	Y	1	0	1	0	0	0	0	1	1	1	5
Sperlich, 2010	N	1	0	1	1	0	0	0	1	1	1	6
Macpherson, 2011	N	0	0	1	0	0	0	1	1	1	1	5
Sperlich, 2011	N	0	0	1	0	0	0	0	1	1	1	4
Corte de Araujo, 2012	Y	1	0	1	0	0	0	0	1	1	1	5
Sandvei, 2012	Y	1	0	1	0	0	0	1	1	1	1	6
Dunham, 2012	N	1	0	1	0	0	0	0	1	1	1	5
Cocks, 2013	Y	1	0	1	0	0	0	1	1	1	1	6

Keating, 2014	Y	1	0	1	0	0	0	1	1	1	1	6
McGarr, 2014	N	1	0	1	0	0	0	1	1	1	1	6
Sasaki, 2014	N	1	0	1	0	0	0	0	1	1	1	5
Matsuo, 2014	Y	1	1	1	0	0	1	1	1	1	1	8
Bradley, 2014	N	1	0	1	0	0	0	1	1	1	1	6
Matsuo, 2014	Y	1	1	1	0	0	1	1	1	1	1	8
Kiviniemi, 2014	Y	1	0	1	0	0	0	1	1	1	1	6
Klonizakis, 2014	Y	1	0	1	0	0	0	0	1	1	1	5
Zelt, 2014	N	1	0	1	0	0	0	0	1	1	1	5
Nalcakan, 2014	N	0	0	1	0	0	0	1	1	1	1	5
Cheema, 2015	Y	1	1	1	0	0	0	1	1	1	1	7
Shepherd, 2015	Y	1	0	1	0	0	0	1	1	1	1	6
Zhang, 2015	Y	1	0	1	0	0	0	0	1	1	1	5
Foster, 2015	Y	1	0	1	0	0	0	1	1	1	1	6
Gillen, 2016	Y	0	0	1	0	0	0	1	1	1	1	5
Heisz, 2016	Y	1	0	1	0	0	0	1	1	1	1	6
Kong, 2016	Y	1	0	1	0	0	0	0	1	1	1	5
Kong, 2016	Y	1	0	1	0	0	0	0	1	1	1	5
Schoenmakers, 2016	N	1	0	1	0	0	0	0	1	1	1	5
Bækkerud, 2016	Y	1	0	1	0	0	0	1	1	1	1	6
Elmer, 2016	Y	0	0	1	0	0	0	1	1	1	1	5
Nummela, 2016	Y	0	0	1	0	0	0	0	1	1	1	4
Sheykhlouvand, 2016	N	1	0	1	0	0	0	1	1	1	1	6

González-Mohíno, 2016	N	1	0	1	0	0	0	1	1	1	1	6
Martins, 2016	Y	1	0	1	0	0	0	0	1	1	1	5
Sawyer, 2016	Y	1	0	1	0	0	0	0	1	1	1	5
Vesterinen, 2016	Y	1	0	1	0	0	0	0	1	1	1	5
Hwang, 2016	Y	1	0	1	0	0	1	0	1	1	1	6
Heiskanen, 2016	Y	1	0	1	0	0	0	1	1	1	1	6
Bartlett, 2017	Y	1	0	1	0	0	0	1	1	1	1	6
Born, 2017	N	0	0	1	0	0	0	0	1	1	1	4
Motiani, 2017	Y	1	0	1	0	0	0	1	1	1	1	6
NJ, 2017	N	1	0	1	0	0	0	1	1	1	1	6
Yang, 2017	N	0	0	1	0	0	0	0	1	1	1	4
Vella, 2017	Y	1	0	1	0	0	0	1	1	1	1	6
O'Leary, 2017	Y	1	1	1	0	1	1	1	1	1	1	9
Hornbuckle, 2018	Y	1	0	1	0	0	0	0	1	1	1	5
Dias, 2018	Y	1	1	1	0	0	0	0	1	1	1	6
Sökmen, 2018	N	1	0	1	0	0	0	1	1	1	1	6
Nie, 2018	N	1	0	1	0	0	0	1	1	1	1	6
Reljic, 2018	Y	1	1	1	0	0	1	0	1	1	1	7
De Strijcker, 2018	Y	1	1	1	0	0	0	1	1	1	1	7
Locke, 2018	Y	1	0	1	0	0	0	0	1	1	1	5
Schaun, 2018	Y	1	0	1	0	0	0	0	1	1	1	5
Kelly, 2018	N	1	0	1	0	0	0	1	1	1	1	6
Hommel, 2019	N	1	0	1	0	0	0	1	1	1	1	6

Pinto, 2019	Y	0	0	1	0	0	0	1	1	1	1	5
Gerosa-Neto, 2019	Y	1	0	1	0	0	0	0	1	1	1	5
Arboleda-Serna, 2019	Y	1	1	1	0	0	1	0	1	1	1	7
Runacres, 2019	N	0	0	1	0	0	0	0	1	1	1	4
Boukabous, 2019	Y	1	0	1	0	0	0	1	1	1	1	6
Litleskare, 2020	Y	1	0	1	0	0	0	0	1	1	1	5
Islam, 2020	Y	1	0	1	0	0	0	1	1	1	1	6
Papandreou, 2020	Y	1	0	1	0	0	0	1	1	1	1	6
Poon, 2020	Y	1	0	1	0	0	0	1	1	1	1	6
Mekari, 2020	Y	1	0	1	0	0	0	0	1	1	1	5
Petrick, 2021	Y	1	0	1	0	0	0	1	1	1	1	6
Huang, 2021	Y	1	1	1	0	0	1	0	1	1	1	7
Kirchenberger, 2021	Y	1	0	1	0	0	0	0	1	1	1	5
Hu, 2021	Y	1	1	1	0	0	0	1	1	1	1	7
Li, 2021	Y	1	0	1	0	0	0	1	1	1	1	6
Poon, 2022	Y	1	0	1	0	0	0	1	1	1	1	6
Gripp, 2022	Y	1	0	1	0	0	0	0	1	1	1	5
Arboleda-Serna, 2022	Y	1	1	1	0	0	0	0	1	1	1	6
Lu, 2022	Y	1	0	1	0	0	0	1	1	1	1	6
Mendelson, 2022	Y	1	1	1	0	0	1	0	1	1	1	7
Marillier, 2022	Y	1	0	1	0	0	0	1	1	1	1	6
Tang, 2022	Y	1	0	1	0	0	0	0	1	1	1	5
O'Neill, 2022	Y	1	0	1	0	0	0	1	1	1	1	6

Collins, 2022	Y	1	0	1	0	0	0	1	1	1	1	6
Reuter, 2023	Y	1	0	1	0	0	0	0	1	1	1	5
Liu, 2023	Y	1	1	1	1	0	1	0	1	1	1	8
Tadiotto, 2023	Y	0	0	1	0	0	0	1	1	1	1	5
Moghaddam, 2023	Y	1	0	1	0	0	0	0	1	1	1	5
Zuo, 2023	Y	1	0	1	0	0	0	1	1	1	1	6
Zhou, 2024	Y	1	0	1	0	0	0	0	1	1	1	5
Yin, 2024	Y	1	1	1	0	0	0	1	1	1	1	7
Gejl, 2024	Y	1	0	1	0	0	1	0	1	1	1	6
Rowan, 2012	N	1	0	1	0	0	0	1	1	1	1	6
Pugliese, 2018	N	1	0	1	0	0	0	1	1	1	1	6
Hebisz, 2019	N	1	0	1	0	0	0	0	1	1	1	5
Sarkar, 2021	Y	1	0	1	0	0	0	1	1	1	1	6
Rago, 2022	Y	1	1	1	0	0	0	1	1	1	1	7
Sheykhlouvand, 2022	N	1	0	1	0	0	0	1	1	1	1	6
Tanisho, 2009	N	0	0	1	0	0	0	1	1	1	1	5
Zhu, 2010	N	1	0	1	0	0	0	0	1	1	1	5
Hu, 2017	N	1	0	1	0	0	0	0	1	1	1	5
Wen, 2018	N	1	0	1	0	0	0	1	1	1	1	6
Qu, 2019	Y	1	0	1	0	0	0	1	1	1	1	6
fang, 2020	Y	1	0	1	0	0	0	1	1	1	1	6
Ji, 2020	Y	1	0	1	0	0	0	1	1	1	1	6
Liu, 2023	Y	1	0	1	0	0	0	1	1	1	1	6

Gunnarsson, 2012	N	0	0	1	0	0	0	0	1	1	1	4
Daussin, 2008	Y	1	0	1	0	0	0	1	1	1	1	6
Inglis, 2024	Y	1	0	1	0	0	0	1	1	1	1	6

Note: studies scoring ≥6 are considered **high quality**, those scoring 4-5 are considered **moderate quality**, and those scoring ≤3 are considered **low quality**.

1. eligibility criteria were specified (not included in the total score)
2. subjects were randomly allocated to groups (in a crossover study, subjects were randomly allocated an order in which treatments were received)
3. allocation was concealed
4. the groups were similar at baseline regarding the most important prognostic indicators
5. there was blinding of all subjects
6. there was blinding of all therapists who administered the therapy
7. there was blinding of all assessors who measured at least one key outcome
8. measures of at least one key outcome were obtained from more than 85% of the subjects initially allocated to groups
9. all subjects for whom outcome measures were available received the treatment or control condition as allocated or, where this was not the case, data for at least one key outcome was analysed by "intention to treat"
10. the results of between-group statistical comparisons are reported for at least one key outcome
11. the study provides both point measures and measures of variability for at least one key outcome

Supplementary Figure 2 GRADE

Outcome	No of participants (studies)	Certainty Assessment					Standardized Mean effect (95% CI) †	GRADE*
		Risk of Bias	Inconsistency	Indirectness	Imprecision	Other		
High-Frequency *versus* Low-Frequency								
Relative Maximal/peak Oxygen Uptake	3132 (110RCT)	Serious	Some serious	Not serious	Not serious	None	0.39 (0.27 to 0.51)	⊕⊕◯◯ LOW
Absoulute Maximal/peak Oxygen Uptake	1394 (48RCT)	Serious	Some serious	Not serious	Not serious	None	0.29 (0.15 to 0.43)	⊕⊕◯◯ LOW
Maximal Aerobic Power/Speed	1308 (46 RCT)	Serious	Some serious	Not serious	Not serious	None	0.32 (0.17 to 0.47)	⊕⊕◯◯ LOW
Mean Anaerobic Power	220 (6 RCT)	Some serious	Not serious	Not serious	Some serious	None	0.47 (0.08 to 0.86)	⊕⊕◯◯ LOW
Peak Anaerobic Power	236 (7 RCT)	Some serious	Not serious	Not serious	Serious	None	0.31 (-0.06 to 0.68)	⊕◯◯◯ Very Low
First Intensity Threshold	455 (12 RCT)	Serious	Not serious	Some serious	Serious	None	0.43 (-0.38 to 1.25)	⊕◯◯◯ Very Low

Second Intensity Threshold	**542 (14 RCT)**	**Serious**	**Not serious**	**Some serious**	**Serious**	**None**	**0.08 (-0.20 to 0.36)**	**⊕○○○ Very Low**
Exercise Economy	**490 (11 RCT)**	**Some serious**	**Some serious**	**Not serious**	**Serious**	**None**	**0.26 (-0.03 to 0.54)**	**⊕○○○ Very Low**
physical Performance	**371 (13 RCT)**	**Some serious**	**Serious**	**Not serious**	**Serious**	**None**	**0.04 (-0.46 to 0.54)**	**⊕○○○ Very Low**

*** Certainty of evidence according to Grading of Recommendations, Assessment, Development, and Evaluations (GRADE):**

High: We are very confident in the estimated effect

Moderate: Our confidence in the estimated effect is moderate

Low: We have limited confidence in the estimated effect

Very low: We have very little confidence in the estimated effect

No of participants: Total number of participants with pooled effects

Supplementary Table 12 Summary of Related Meta-analyses

Reference	Included Studies and Populations	Main findings	Exercise Intervention Characteristics	Limitations
Bonafiglia et al.,2022	N=27(CCTs); Age:18-65 Without specific diseases	There was no significant difference between SIT and MICT in improving VO_{2max}（ *g*=-0.004 ， 95% CI [-0.08 , 0.07]， I^2=72%）	1.The pooled effect of SIT versus MICT on $\dot{V}O_{2max}$ included 30 comparisons.；SIT：360，MICT：359； 2.Intensity：SIT：＞100% VO_{2max}，MICT：<80% VO_{2max}； 3.Duration:2-16weeks ；Frequency:2.7-5times/week	The overall reporting quality of the included studies was poor, with the risk of bias mostly rated as “unclear”； between-study heterogeneity was high; prediction intervals were not reported.
Bouaziz et al.,2020	N=15(RCTs); Age:≧65； Including both healthy and clinical populations	HIIT was significantly more effective than MICT in improving VO_{2peak}（ MD=3.76 ； 95% CI [2.96 , 4.56]， I^2=0%）	1.The pooled effect of HIIT versus MICT on $\dot{V}O_{2peak}$ included only 3 comparisons ；Total:480； 2.Intensity：HIIT：90%–95% HR_{max}；MICT：60%–80% HR_{max}； 3.Duration: 4-28 weeks ； Frequency: 2-4 times/week 4.session duration: MICT: 15-20min；	The number of comparisons included in the pooled analysis for $\dot{V}O_{2peak}$ was very small (only 3 comparisons). The $\dot{V}O_{2peak}$ testing protocols were not clearly reported, limiting the comparability of the outcome measures. The study population consisted of older adults, which restricts the generalizability of the findings. Prediction intervals were not reported.
Gist et al.,2014	N=16(CCTs); Age:23.5±4.3 Healthy, young individuals	There was no significant difference between SIT and MICT in improving $\dot{V}O_{2max}$（Cohen’s *d*=0.04，95% CI [-0.17 , 0.24]； *P*=0.72）	1.The pooled effect of HIIT versus MICT on $\dot{V}O_{2max}$ included 10 comparisons；Total:318； 2.Intensity ： SIT ： Intensity: all-out/supramaximal； 3.work interval duration：SIT：30s；session	The number of comparisons included in the pooled analysis was small. Specific protocols for VO_{2max} testing were not reported. No systematic assessment of methodological

			duration：MICT: 15-60min； 4.Duration: 2-10 weeks； 5.Frequency: 2-3.5 times/week； 6.Mode:cycling、running、rowing；	quality or risk of bias was conducted. The intervention duration was relatively short, which may be insufficient to reflect long-term adaptations. Prediction intervals were not reported.
Guo et al.,2023	N=29(RCTs) Age:18-60(mean:33.82±11.6) No restriction on medical comorbidities	HIIT was significantly more effective than MICT in improving VO_{2peak}（SMD=0.19, 95% CI [0.03 , 0.34], p=0.0211）	1.The pooled effect of HIIT versus MICT on VO_{2peak} included 27 comparisons；HIIT：404，MICT：403； 2.Intensity：HIIT：80%–100% HR_{max}/$\dot{V}O_{2peak}$，or RPE＞15，MICT：40%–80% HR_{max}/$\dot{V}O_{2peak}$，or RPE：12-15； 3.session duration: MICT: ＞15min； 4.Duration: 2 weeks - 6 months； 5.Frequency: 1-5 times/week； 6.Mode: cycling、running、home-based HIIT、boxing；	The included populations were heterogeneous in health status (healthy and clinical populations); Not all studies clearly reported the VO_{2peak} testing protocol; Prediction intervals were not reported.
Jelleyman et al.,2015	N=50(controlled and Uncontrolled trials) Age: 21-68 With normal weight，overweight/obesity	HIIT was significantly more effective than MICT in improving VO_{2peak}（WMD=0.16, 0.07 to 0.25, p=0.001，I^2=76.3%）	1.The pooled effect of HIIT versus MICT on VO_{2peak} included 23 comparisons；Total: 2033； 2.Intensity：HIIT：65% HR_{max} to all-out effor，或 RPE＞15，MICT：55% HR_{max}/$\dot{V}O_{2peak}$ to 80% HR_{max}； 3.session duration: HIIT：4s-5min；MICT:30-120min； 4.Duration: 2-16 weeks； 5.Frequency: NR；	Between-study heterogeneity was high (I^2 > 70%); Overall methodological quality was low (median quality score 1/5); VO_{2peak} testing protocols were not clearly reported; Prediction intervals were not reported.

			6.Mode: cycling、running、walking；	
Kramer et al.,2023	N=11(RCTs) Age:≥18 overweight/obesity	HIIT was superior to MICT in improving VO_{2max}（SMD=0.30，95% CI [0.09 , 0.52]，p=0.005）；95% PI [0.07, 0.55]	1.The pooled effect of HIIT versus MICT on $\dot{V}O_{2max}$ included 10 comparisons；Total: 379； 2.Intensity：HIIT：85%-120% HR_{max}/HRR/$\dot{V}O_{2max}$；MICT：50%-65% HR_{max}/HRR/$\dot{V}O_{2max}$； 3.session duration: HIIT：26.6min；MICT:44min； 4.Duration: 5-16 weeks； 5.Frequency: 3-5 times/week；	The study population was limited to overweight/obese individuals, restricting the generalizability of the results. The number of comparisons included in the pooled effect was small. Specific protocols for VO_{2max} testing were not reported. All included studies were rated as having a “some risk of bias.”
Liang et al.,2024	N=8(RCTs) Age:≥18 Including both healthy and clinical populations	MICT is more effective than SIT in improving VO_{2peak}（MD=−1.36 mL/kg/min，95% CI [−2.31 , 0.40]，p=0.56，I^2=0%）	1.The pooled effect of SIT and MICT on $\dot{V}O_{2max}$ included 6 comparisons；SIT：84，MICT：85； 2.Intensity：SIT：>100% VO_{2max}/HR_{max}；MICT：46-64% VO_{2max}/HR_{max}； 3.session duration: SIT：4-6*30s；MICT:25-60min； 4.Duration: 2-12 weeks； 5.Frequency: 3-5 times/week；	The included populations were heterogeneous in health status (healthy and clinical populations); the number of pooled comparisons was small; the training volume of MICT was substantially higher than that of SIT; specific VO_{2max} testing protocols were not reported; the intervention duration was relatively short; prediction intervals were not reported.
Lindner et al.,2023	N=20(RCTs) Age:≥18（mean:20-67） Women only	MVICT and HIIT showed no significant difference in their effects on VO_{2max} in females（MD：−0.42，95%	1.The pooled effect of HIIT versus MVICT on VO_{2max} included 8 comparisons；HIIT：235，MVICT：234； 2.session duration: HIIT：30s-4min；	Only female participants were included; The number of pooled comparisons was small; The intervention intensity of HIIT and

		CI [1.43 , 0.60], $chi^2 = 6.0$, $I^2 = 0\%$, $p=0.42$）	MICT:20-75min； 3.Mode:cycling 、 running 、 rowing 、 water-based exercise 、 free weight 、 bodyweight exercises and sprinting；	MVICT was not clearly reported; Prediction intervals were not reported.
Maturana et al.,2021	N=55(RCTs) Age: no restrictions； Including both healthy and clinical populations	HIIT is significantly more effective than MICT in improving VO_{2max}（d=0.40, 95% CI [0.24-0.57], P<0.001, I^2=47%,）	1.The pooled effect of HIIT versus MICT on VO_{2max} included 48 comparisons； Total: 1529； 2.Intensity ： HIIT ： 75-120%$\dot{V}O_{2max}$ /80%-100%HR_{max} or HRR/85%-100% PPO； MICT： 50-79%$\dot{V}O_{2max}$ /60%-80%HR_{max}/50%-85%HRR； 3.session duration: HIIT： 25.1±9.5min； MICT:42.3±13.2min； 4.Duration: 2-24 weeks； 5.Frequency: 2-5 times/week； 6.Mode: cycling、running；	The included populations were heterogeneous in health status (healthy and clinical populations); the specific VO_{2max} testing protocols were not reported; prediction intervals were not reported.
Milanović et al.,2015	N=55(RCTs, non-RCTs) Age:18-45 Healthy individuals	Compared with MVICT, HIIT shows a significant advantage in improving $\dot{V}O_{2max}$ （ 1.2±0.9 $mL \cdot kg^{-1} \cdot min^{-1}$）	1.The pooled effect of HIIT versus MVICT on VO_{2max} included 19 comparisons；Total: 723； 2.Intensity：HIIT：90%–95% HR_{max} or all-out effor；MVICT：60%–85% HR_{max}； 3.Duration: 3-24 weeks； 4.Frequency: 2-5 times/week； 5.Mode: NR；	The VO_{2max} testing protocol was not reported. Intervention protocols were insufficiently described. No systematic assessment of methodological quality or risk of bias was conducted. Prediction intervals were not reported.

Poon et al.,2021	N=14(RCTs) Age:≥40 Healthy men and women not suffering from any kind of acute or chronic diseas	HIIT is significantly more effective than MICT in improving VO_{2max}（ MD=1.10 $mL \cdot kg^{-1} \cdot min^{-1}$； 95% CI [0.55，1.64]，$p < 0.001$，$I^2$=65%）	1.The pooled effect of HIIT versus MICT on VO_{2max} included 15 comparisons；HIIT：215，MICT：228； 2.Intensity：HIIT：≧80% HR_{max}/＞100%%$\dot{V}O_{2max}$ /or all-out effor；MICT：60%–79% HR_{max}； 3.session duration: HIIT：30s-5min；MICT:20-60min； 4.Duration: 2-52 weeks； 5.Frequency: 3 times/week； 6.Mode: cycling；	Between-study heterogeneity was high (I^2 = 65%); the overall risk of bias was high in multiple studies; the intervention duration varied widely (2–52 weeks); prediction intervals were not reported.
Rugbee et al.,2021	N=26(RCTs) Age:18-60 With overweight/obesity	SIT was significantly more effective than MICT in improving VO_{2max}/VO_{2peak}（ MD=-0.92； 95% CI [-1.63，-0.21]，p=0.01，I^2=10%）；HIIT showed no significant difference compared with MICT in improvingVO_{2max}/VO_{2peak}（ MD=-0.52； 95% CI [-1.18, 0.31]， p=0.12，I^2=23%）	1.The pooled effects of HIIT versus MICT on VO_{2max}/VO_{2peak} included 18 comparisons, while the pooled effects of SIT versus MICT on VO_{2max}/VO_{2peak} included 10 comparisons；Total: 784； 2.Intensity：HIIT：≧60%$\dot{V}O_2R$ /HRR or ≧77%%HR_{max}；MICT：40%–59% $\dot{V}O_2R$ /HRR or 64-76%%HR_{max}； 3.session duration: HIIT：20-30min；SIT：17-30min；MICT:20-40min； 4.Duration: 2-15 weeks； 5.Frequency: 3-5 times/week； 6.Mode: cycling、walking、jogging；	The results are primarily applicable to overweight/obese populations; the VO_{2max}/VO_{2peak} testing protocols were not reported; prediction intervals were not reported.
Sultana et al.,2019	N=47(RCTs，non-RCTs) Age:≥18	HIIT has a significant advantage over MICT in	1.The pooled effect of HIIT versus MICT on $\dot{V}O_{2max}/VO_{2peak}$ included 27 comparisons；	The included populations were heterogeneous in health status (healthy and

	With normal-weight, overweight and obesity, regardless of physical activity and health status	improving $\dot{V}O_{2max}/VO_{2peak}$（*g*=-0.175，95% CI [-0.318,-0.031]；*p*=0.017））	Total: 1458； 2.Low-volume HIIT was defined as ≤500 MET-min/week, while the MICT control group was defined as ≥ 500 MET-min/week； 3.Intensity：75%-100% $HR_{max/peak/reserve}$/ 80%-170% $\dot{V}O2_{max/peak}$/ 60%-140% PPO or all-out effor；MICT：40%-80% $HR_{max/peak/reserve}$/ 40%-85% $\dot{V}O_{2max/peak}$/ 50%-70%PPO/$W_{max/peak}$； 4.session duration: HIIT：8-240s；SIT：17-30min；MICT:20-60min； 5.Duration: 4-16 weeks； 6.Frequency: 2-5 times/week； 7.Mode: cycling、running、walking；	clinical populations); there were substantial differences in the interval training protocols, increasing potential between-study heterogeneity; some studies had small sample sizes, reducing the statistical power to detect differences between groups; prediction intervals were not reported.
Tsuji et al.,2023	N=15(RCTs) Age:≥18 Adults regardless of disease or handicap status	Home-based HIIT showed no significant difference compared with MICT in improving $\dot{V}O_{2peak}$（SMD=0.34；95% CI [-0.05，0.73]；I^2=32%；*p*=0.09）	1.The pooled effect of HIIT versus MICT on VO_{2peak} included 3 comparisons；Total: 770； 2.The intervention group performed home-based HIIT, while the control group performed either home-based or laboratory-based MICT； 3.Intensity：HIIT：≧80%$\dot{V}O2_{max/peak}$/MAP or RPE≧15/20；MICT：40%–70% HR_{max} /MAP or RPE：11-13； 4.Duration: 4weeks-12months； 5.Frequency: 1-6 times/week；	The number of comparisons included in the pooled analysis of VO_{2peak} was small (only 3 comparisons); the included populations were heterogeneous, encompassing both athletes and individuals with medical conditions; in some studies, exercise intensity was unclear or variable; prediction intervals were not reported.

			6.Mode: weight-bearing exercise、stationary cycling, or use of outdoor/indoor equipment；	
Weston et al.,2014	N=10(RCTs)； Age: no restrictions； Individuals with metabolic chronic diseases	HIIT was significantly more effective than MICT in improving $\dot{V}O_{2peak}$（ MD=3.03 $mL \cdot kg^{-1} \cdot min^{-1}$ ； 95% CI [2.00 , 4.07]， $p < 0.001$， I^2=9%）	1.The pooled effect of HIIT versus MICT on $\dot{V}O_{2peak}$ included only 10 comparisons；HIIT：137，MICT：136； 2.The training volume of HIIT and MICT was matched 3.Intensity： HIIT： 85%–95% $HR_{max,}$， 80%–100% PPO/$W_{max/peak}$；MICT：60%–75% HR_{max} 4.Duration: 4-16 weeks； Frequency: 3-6 times/week 5.session duration: HIIT：38min，MICT: 46min； 6.Mode:cycling、running；	The number of pooled comparisons was limited; There were differences in interval protocols, intensity, and session duration across studies; The studies were limited to specific clinical populations, restricting the generalizability of the results; Six out of the ten studies came from the same research group, so these findings need to be confirmed by follow-up studies from other institutions; Prediction intervals were not reported.
Weston et al.,2014	N=38(RCTs，non-RCTs) Age:≥18 Healthy adults	The effect of HIIT compared with ET on improving $\dot{V}O_{2max}$ is unclear（-1.6 %，90% CI ±4.3 %）	1.The pooled effect of HIIT versus ET on $\dot{V}O_{2max}$ included only 10 comparisons；HIIT：137，ET：136； 2.HIIT：Intensity：maximal or near-maximal；repetition duration：30-60 s；work/rest ratio <1.0； mean： 13 sessions； Duration ≥2 weeks；Mode：cycling；ET：NR	The number of pooled comparisons was small. The conclusions comparing HIIT and ET were inconclusive. The intervention protocol for the endurance training group was not clearly reported. Prediction intervals were not reported.
Wu et al.,2021	N=29(RCTs and CCTs) Age:≥60 Healthy subjects not restricted by BMI, sex,	HIIT was significantly superior to MICT in improving VO_{2max}（ WMD=1.74, 0.80 to	1.The pooled effect of HIIT versus MICT on VO_{2max} included six comparisons；Total：1156； 2.Intensity：HIIT：≧100%%$\dot{V}O_{2max}$ /≧75%	The number of comparisons contributing to the pooled effect was small; The study population consisted of older adults, limiting generalizability;

	pathologie, or ethnic origin	2.69, p<0.001，I^2=76.3%）	HRR/ ≧ 85% HR_{max} ； MICT ： 55-70% HR_{max}/55-70% PPO； 3.session duration: 20-40min； 4.Duration: 4-24 weeks； 5.Frequency: 2-5 times/week； 6.Mode: elliptical devices, cycling, circuit-based interval exercise, Xbox 360s；	Substantial between-study heterogeneity was present (I^2 > 70%); Exercise modalities varied widely (e.g., equipment-based training, gamified exercise); Prediction intervals were not reported.
Yin et al.,2024	N=21(RCTs) Age:≥18 Including both healthy and clinical populations	There was no significant difference between LV-HIIT and MICT in improving $\dot{V}O_{2max}$（ SMD=0.18 ； 95% CI [−0.06, 0.42]；p=0.15；I^2 = 11%；p=0.35）；PI [-0.19, 0.54]	1.The pooled effect of HIIT versus MICT on $\dot{V}O_{2max}$ included 10 comparisons； 2.LV-HIIT was defined as including at least one high-intensity interval (≥77% HR_{max} or RPE ≥ 14), with a total duration of “all-out” exercise ≤5 minutes per session and a total session duration (including warm-up, cool-down, and recovery periods) not exceeding 15 minutes; MICT was performed at an intensity of 60 – 75% HR_{max} with a total duration of 30-50 minutes 3.Duration: 2-24 weeks； 4.Frequency: 2-4 times/week；	The number of comparisons contributing to the pooled effect was small; There were differences in how exercise intensity was quantified across study protocols; The operational definition of low-volume HIIT varied between studies; Some studies had small sample sizes, which may have limited the overall statistical power of the meta-analysis.