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SYSTEMATIC REVIEW

Effect of High-Intensity Interval Training Versus Sprint Interval Training on Time-Trial Performance: A Systematic Review and Meta-analysis

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Abstract

Background Two forms of interval training commonly discussed in the literature are high-intensity interval training (HIIT) and sprint interval training (SIT). HIIT consists of repeated bouts of exercise that occur at a power output or velocity between the second ventilatory threshold and maximal oxygen consumption (VO_{2max}). SIT is performed at a power output or velocity above those associated with VO_{2max}.
Objective The primary objective of this study is to systematically review published randomized and pair-matched trials to determine which mode of interval training, HIIT versus SIT, leads to a greater improvement in TT performance in active and trained individuals. The second objective of this review is to perform a subgroup analysis to determine if there is a distinction between HIIT programs that differ in work-bout duration.
Data Sources SPORTDiscus (1800–present) and Medline with Full Text (1946–present) were used to conduct a systematic literature search.
Study Selection Studies were selected for the review if they met the following criteria: (1) individuals (males and females) who were considered at least moderately trained (~ 3-h per week of activity) as specified by the authors of the included studies; (2) between the ages of 18 and 45 years; (3) randomized or pair-matched trials that included a HIIT and a SIT group; (4) provided detailed information about the interval training program; (5) were at least 2 weeks in duration; (6) included a TT test that required participants to complete a set distance.
Results A total of 6 articles met the inclusion criteria for the subjective and objective analysis. The pooled analysis was based on a random-effects model. There was no difference in the change in TT performance when comparing all HIIT versus SIT (0.9%; 90% CI − 1.2–1.9%, $p = 0.18$). However, subgroup analysis based on duration of work interval indicated a 2% greater improvement in TT performance following long-HIIT (≥ 4 min) when compared to SIT. There was no difference in change in $VO_{2max}/_{peak}$ oxygen consumption (VO_{2peak}) between groups. There was a moderate effect (ES = 0.70) in favor of HIIT over SIT in maximal aerobic power (MAP) or maximal aerobic velocity (MAV).
Conclusion The results of the meta-analysis indicate that long-HIIT may be the optimal form of interval training to augment TT performance. Additional research that directly compares HIIT exercise differing in work-bout duration would strengthen these results and provide further insight into the mechanisms behind the observed benefits of long-HIIT.

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1 Introduction

Endurance training programs should be optimized to improve athletic performance while limiting the development of fatigue or risk of injury. One of the most important variables to consider when prescribing exercise is the intensity at which an athlete trains as this metric strongly influences physiological and performance adaptations [1]. The distribution of exercise intensity within a training program has provoked great interest over the past decade [2]. The results of a recent meta-analysis of randomized controlled trials examining intensity distribution suggests that

Key Points

There was approximately a 2% greater improvement in time-trial performance following long-duration high-intensity interval training (HIIT) that consisted of work-bouts that are 4 minutes or greater when compared to sprint interval training (SIT).

There was no difference in change in maximal or peak oxygen consumption between HIIT and SIT.

There was a moderate effect (ES = 0.70) in favor of HIIT over SIT in maximal aerobic power/velocity, with long-duration HIIT producing the greatest increase in performance, a 4% greater change when compared to SIT.

a polarized training model, which includes approximately 20% of total training volume in the high-intensity exercise domain and 80% in the low-intensity domain, may lead to a greater improvement in endurance sport performance when compared to other intensity distribution models [3].

However, there remains equivocal evidence regarding the best method to program high-intensity training sessions and, in particular, the variables defining interval training stimuli. Interval training consists of repeated bouts of exercise followed by rest or low-intensity exercise, each of which can last from seconds to minutes in duration. Prescribing interval training can be quite complex since performance improvements may be influenced through the manipulation of a number of programming variables including exercise mode, duration, intensity, recovery, number of intervals, and the frequency and distribution of interval training [4, 5]. In addition to the variables required for programming a specific exercise session, population characteristics such as age, sex, training status and background can also impact performance gains [4].

Two forms of interval training commonly discussed in the literature are high-intensity interval training (HIIT) and sprint interval training (SIT). HIIT consists of repeated bouts of exercise that occur at a power output or velocity within the severe-intensity domain [6], which occurs between the second ventilatory threshold (VT_2) and maximal oxygen consumption ($\dot{V}O_{2max}$) [7]. In the case when an individual's $\dot{V}O_{2max}$ cannot be determined through exercise testing, peak oxygen consumption ($\dot{V}O_{2peak}$) is used to indicate the upper border of the domain. SIT is performed at a power output or velocity above those associated with $\dot{V}O_{2max}$ [8]. As such, it can be considered to be completed in the extreme exercise domain.

Gaps in our understanding of the effects of interval training may remain in part due to the lack of standardization for developing HIIT and SIT protocols. This concern was addressed in the review by Viana et al., where the authors explain that it may be difficult to generalize the results of interval training programs due to inconsistent exercise protocols [9]. There are a number of interval training studies that use HIIT programs that more closely represent SIT exercise [10–15]. Those programs include work-bouts that are between 15 s and two min in duration. Due to the short work-bout duration, a large portion of total energy production is through anaerobic energy sources [16]. Previous investigations examining SIT protocols including short-interval rest periods (e.g., 15 s) have demonstrated similar responses to that of HIIT, requiring a greater proportion of aerobic metabolism [17–20]. While these SIT protocols have been shown to improve exercise performance, they may be less effective for improving $\dot{V}O_{2max}$ than HIIT protocols incorporating longer rest intervals [19]. In addition, confounding evidence may arise as a consequence of SIT protocols that incorporate a one-to-one work–rest ratio, whereby power or velocity is decreased over multiple intervals, yet heart rate remains elevated. As such, by definition, these intervals digress to a typically HIIT protocol, with power or velocity falling below $\dot{V}O_{2max}$.

Both HIIT and SIT produce adaptations that are beneficial for endurance performance. A meta-analysis by Milanović et al. shows that interval training can lead to improvements in $\dot{V}O_{2max}$ and can do so to a greater extent than moderate-intensity continuous training (MICT) [21]. However, that analysis did not differentiate between modes of interval training, including HIIT and SIT in the same analysis group. In addition, most reviews that address aerobic performance use $\dot{V}O_{2max}$ as the primary outcome measure. Although $\dot{V}O_{2max}$ has been correlated with race performance [22], strong evidence suggest other variables may positively influence performance outcomes [23, 24]. An alternative measure, time-trial (TT) performance, has demonstrated a high correlation with endurance performance, and may directly simulate the physiological responses required during competition [25, 26]. Time-to-exhaustion (TTE) tests have also been used as substitute measures for $\dot{V}O_{2max}$. However, TTE tests have a wider variability in results when compared to TT tests [27].

Previous reviews have compared interval training (HIIT, SIT or combined) with either a non-exercising control or MICT [21, 28]. There is sufficient evidence that interval training can enhance performance to a greater extent than other modes of endurance training. Currently, there remains a paucity of reviews that compare the effects of HIIT versus SIT on markers of endurance sport performance. As such, the primary objective of this study is to systematically review published randomized and pair-matched trials to determine which mode of interval training, HIIT versus SIT, leads to a greater improvement in TT performance in active and trained individuals. Various studies have employed HIIT work-bout durations ranging from 1 min to 6 min [10, 29]. In addition to the limited research comparing HIIT and SIT, there are no reviews that compare the effects of HIIT exercise protocols which differ in work-bout duration with SIT protocols on endurance performance. Therefore, the second objective of this review is to perform a subgroup analysis to determine if there is a distinction between HIIT programs that differ in work-bout duration.

2 Methods

2.1 Protocol and Registration

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) was used as the protocol for the design of the review [30]. The PRISMA guidelines include a 27-item checklist considered to improve reporting transparency, limiting the risk of publication and selection bias [30].

2.2 Eligibility Criteria

2.2.1 Inclusion Criteria

Studies were selected for the review if they met the following criteria: (1) Individuals (males and females) who were considered at least moderately trained (~ 3 h per week of activity) as specified by the authors of the included studies; (2) between the ages of 18 and 45 years; (3) randomized or pair-matched trials that included a HIIT and a SIT group; (4) provided detailed information about the interval training program; (5) were at least 2 weeks in duration; and (6) included a TT test that required participants to complete a set distance.

2.2.2 Exclusion Criteria

Studies were excluded if participants had pathology or if interventions included the following: (1) nutritional interventions (supplements, hydration, fed state, etc.), (2) change in environmental conditions (heat/cold, altitude, hypoxia/hyperoxia, etc.), (3) inclusion of modalities (cryotherapy, compression garments, etc.), and (4) pharmacological agents,

2.3 Information Sources

An electronic search was conducted that included all publication years (up to and including December 2018). To minimize selection bias and to perform a comprehensive search, two databases were used to conduct a systematic literature search and included SPORTDiscus (1800–present) and Medline with Full Text (1946–present).

2.4 Search

2.4.1 Search String

Key search terms that were produced from reviewing previous literature and using a number of synonyms of the different forms of interval training were grouped and searched within the article title and abstract, and keywords using the search conjunction 'OR'. Combinations of the following terms were used as search terms: 'interval training', 'interval exercise' 'anaerobic interval*' 'aerobic interval*' 'high intensity interval*' 'sprint interval*' 'intermittent exercise' 'intermittent training' 'repeated sprint*'.

2.4.2 Search Limits

To provide a more accurate search, the following limits were selected: (1) English language, (2) humans, and (3) journal article, all publications up to and including the year 2018.

2.5 Study Selection

The titles and abstracts of the search results were independently assessed for suitability by two authors. Full-text articles were retrieved if the titles or abstracts met the eligibility criteria or if there was uncertainty. Disagreements were resolved through a discussion between the two authors, with a third to be consulted if the first two authors could not reach agreement. The rationale for excluding articles was documented.

2.6 Data Collection Process

A data collection form was created using the Cochrane Data Extraction and Assessment Form template. One author was responsible for collecting the data and the second author checked the extracted data. Disagreements were discussed between the two authors, with a third to be consulted if the first two authors could not reach agreement.

2.7 Data Items

The following data were extracted from each of the articles that were included in the review: study methodology (study design and duration); the participant characteristics (sex, age, height, mass, $\dot{V}O_{2max}$/$\dot{V}O_{2peak}$); intervention description (exercise mode, training program duration, interval sessions performed each week, interval work-bout duration, interval work-bout intensity (expressed as a percentage of the power or velocity associated with VO_{2max}/VO_{2peak}); and outcomes measures (VO_{2max}/VO_{2peak}, power at maximal oxygen uptake (MAP), velocity at maximal oxygen uptake (MAV), and TT performance). The correction factor used by Granata et al. was used to standardized exercise intensity obtained from testing protocols that exceeded 12 min in duration [31].

2.8 Risk of Bias of Individual Studies

Two reviewers used the PEDro scale to assess the quality of the studies included in the review. The PEDro scale is a 10-point ordinal scale used to determine the internal validity of a study. The specific methodological components assessed include: (1) randomization, (2) concealed allocation, (3) baseline comparison, (4) blind participants, (5) blind therapists, (6) blind assessors, (7) adequate follow-up, (8) intention-to-treat analysis, (9) between group comparisons, and (10) point estimates and variability [32]. Participant eligibility is also a component of the PEDro scale; however, it is not included in the final 10-point score.

2.9 Summary of Measures

The primary outcome assessed in this review is TT performance. Secondary outcome measures include VO_{2max}/VO_{2peak} and MAP/MAV.

2.10 Synthesis of Results

Group data are reported as means and standard deviations with pooled data reported as the standardized mean difference and its 90 percent confidence intervals. The standardized mean difference, adjusted to account for small sample size bias, was calculated to establish an effect size, (Hedges' adjusted g) [33]. Effect size values of 0.2, 0.6 and 1.2 were interpreted as small, moderate and large effect sizes, respectively [34].

The authors of the included studies were contacted for data that were not presented in their publications (e.g., pre- and post-test data). Data expressed using the standard error of the mean (SEM) were converted to the standard deviation (SD) using the following formula: $\mathrm{SD} = \mathrm{SEM}\sqrt{n}$. The SD was estimated using the p value in instances, where the SEM or SD was not available using the following formula: $\mathrm{SD} = \sqrt{n}\left(\frac{\bar{x}_1 - \bar{x}_2}{t}\right)$. A p value expressed using an inequality (e.g. '<') was discussed as an equality (e.g., '='), providing a more conservative estimate of the SD. The mean value for a training load characteristic in the respective subgroup was used to provide an objective value where only a subjective description was given. Where possible, between-group comparisons were made using the difference of means with the standard error expressed as a 90 percent confidence interval.

Individual study results were combined using Review Manager 5.3 with a random-effect meta-analysis model. This method considers both within- and between-study variability and was used to accommodate for the differences in the interventions in the individual studies [35]. The consistency of the meta-analysis was assessed to determine the variability in excess of that due to chance. A Chi-squared statistic (Cochrane Q) was used to evaluate the level of heterogeneity. The I^2 statistic was used to determine the percentage of the total variation in the estimated effect across studies.

To perform a sub-group analysis, studies were divided into HIIT groups that differed in work-bout duration based on oxygen uptake kinetics. Short-HIIT was defined as interval bouts less than 2 min in duration to coincide with the approximate time to reach peak oxygen consumption [36]. Long-HIIT was considered bouts 4 min or greater to ensure that at least 50% of the total work-bout was completed at VO_{2max}. Medium-HIIT would fall between the subgroups with work-bouts between 2 min and less than 4 min. Session external work was defined as the product of interval intensity, interval work-bout duration, and interval repetitions. Total external work was defined as the product of session external work, sessions per week and number of weeks. Both measures of external work were described in arbitrary units (a.u.)

2.11 Risk of Bias Across all Studies

The relationship between the effect size and the sample size was determined visually using a funnel plot. Egger's test was used to quantitatively assess for small sample size bias.

3 Results

3.1 Study Selection

The literature search was conducted on December 28, 2018. The databases SPORTDiscus and Medline were used to perform the search which yielded a total of 6994 results. Following the removal of 1678 duplicates, 5316 titles and abstracts were screened. A total of 28 full-text articles were screened for eligibility. Six studies met the inclusion criteria for the qualitative and quantitative analysis (Fig. 1).

3.2 Study Characteristics

The studies included only male participants with a mean range of 19–32 years of age. Five of the studies included participants who were endurance-trained individuals (VO_{2max}/VO_{2peak} = 51.6–64.5 mL·kg^{-1}·min^{-1}) who participated in sports such as cycling, rowing, running and triathlon [29, 37–40] and one moderately trained individual (VO_{2peak} = 46.0 mL·kg^{-1}·min^{-1}) [41]. The full details of study characteristics can be found in Table 1.

All six studies included a HIIT and a SIT group. The HIIT group had interval bouts ranging from 1 to 6 min in duration and at intensities between 73% and 100% MAP. The SIT groups consisted of 30-s all-out sprints and ranged from 114% to 175% MAP. Two of the studies included more than one HIIT group [39, 40]. Overall, there was one short-HIIT interval group [40], 5 that included medium-HIIT intervals [37–40], and 3 that comprised of long-HIIT bouts [29, 40, 41]. See Table 2 for additional details.

3.3 Risk of Bias Within Studies

Two studies scored a 4 on the PEDro scale and four scored a 5, with a mean score of 4.7 out of 10 (Table 3). There were no studies that included subject blinding or assessor blinding. In addition, only one study included concealed allocation. See Table 3 for full details.

3.4 Results of Individual Studies

Three of the studies found a significantly greater improvement in TT performance following HIIT when compared

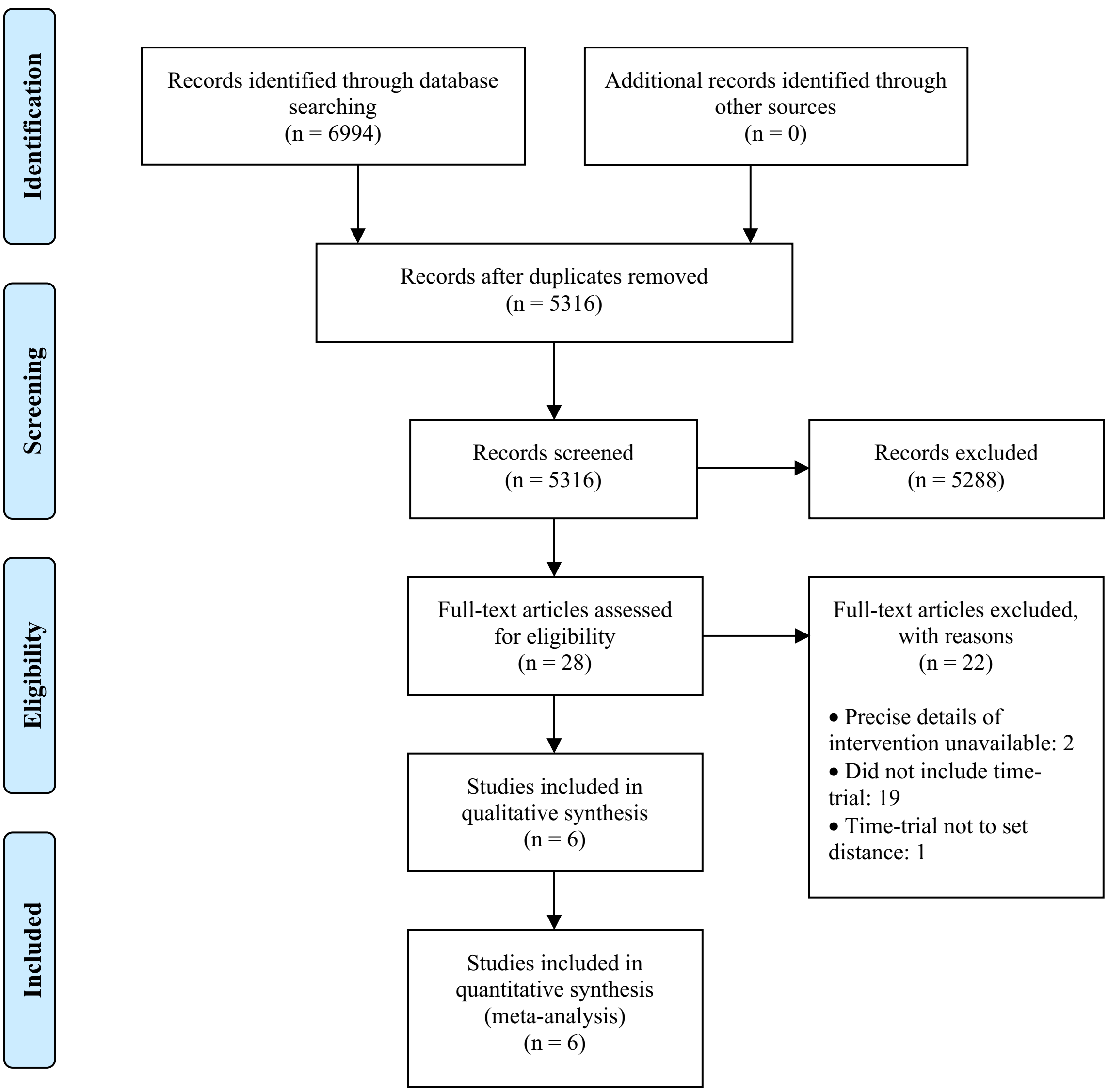

Fig. 1 PRISMA diagram

Table 1 Study characteristics

Study	Study design	Participant characteristics (mean ± SD)	Intervention		Outcome
Akca and Aras [37]	Randomized controlled trial, matched (4 weeks)	Rowers (national level), sex = male, age (years) = 21.8 ± 2.4, body mass (kg) = 79.3 ± 9.1, height (cm) = 178.4 ± 6.0, VO_{2peak} (mL·kg^{-1}·min^{-1}) = 56.6 ± 5.7	Medium-HIIT (n = 10)	8 repetitions of 2.5 min at 75% MAP with 3 min of active recovery, 3 times per week	2-km rowing TT, VO_{2peak}, MAP
			SIT (n = 10)	10 repetitions of 30 s at 125% MAP with 4 min of active recovery, 3 times per week	
Esfarjani and Laursen [38]	Controlled trial, matched (10 weeks)	Runners (moderately trained), sex = male, age (years) = 19.0 ± 2.0, body mass (kg) = 73 ± 3, height (cm) = 172 ± 4, VO_{2max} (mL·kg^{-1}·min^{-1}) = 51.6 ± 2.7	Medium-HIIT (n = 6)	8 repetitions of intervals for 60% of time at 87% MAV with 3.5 min of active recovery, 2 times per week	3-km running TT, VO_{2max}, MAV
			SIT (n = 6)	12 repetitions of 30 s at 114% MAV with 4.5 min of active recovery, 2 times per week	
			Control (n = 5)	60 min of continuous exercise, 4 times per week	
Granata et al. [41]	Randomized controlled trial, matched (4 weeks)	Active (moderately trained), sex = male, age (years) = 20.9 ± 2.0, body mass (kg) = 82.1 ± 16.2, height (cm) = 180.2 ± 9.1, VO_{2peak} (mL·kg^{-1}·min^{-1}) = 46.0 ± 7.3	Long-HIIT (n = 11)	4–7 repetitions of 4 min at 73% MAP with 2 min of active recovery, 3 times per week	20-km cycling TT, VO_{2peak}, MAP
			SIT (n = 10)	4–10 repetitions of 30 s at 168% MAP with 4 min of passive recovery, 3 times per week	
			Control (n = 10)	20–36 min of continuous exercise between 92 and 97% of the second lactic threshold, 3 times per week	
Inoue et al. [29]	Randomized controlled trial (6 weeks)	Cyclists (trained), sex = male, age (years) = 32.1 ± 6.5, body mass (kg) = 69.1 ± 5.3, height (cm) = 175.6 ± 5.4, VO_{2max} (mL·kg^{-1}·min^{-1}) = 63.4 ± 4.5	Long-HIIT (n = 7)	7–10 repetitions of 4–6 min at maximal sustained effort with 4 min of active recovery, 3 times per week	40-km cycling TT, VO_{2max}, MAP
			SIT (n = 9)	8–12 repetitions of 30-s all-out sprints with 4 min of active recovery, 3 times per week	

Table 1 (continued)

Study	Study design	Participant characteristics (mean ± SD)	Intervention		Outcome
Laursen et al. [39]	Controlled trial, matched (4 weeks)	Endurance athletes (highly trained), sex = male, age (years) = 25 ± 6, body mass (kg) = 75 ± 7, height (cm) = 180 ± 5, VO_{2peak} (mL·kg^{-1}·min^{-1}) = 64.5 ± 5.2	Medium-HIIT-1 (n = 10)	8 repetitions at 60% of time at MAP, with 1:2 work-active-recovery ratio, 2 times per week	40-km cycling TT, VO_{2peak}, MAP
			Medium-HIIT-2 (n = 10)	8 repetitions at 60% of time at MAP, with active recovery based on heart rate recovery, 2 times per week	
			SIT (n = 10)	12 repetitions of 30-s at 185% MAP with 4.0 min of active recovery, 2 times per week	
			Control (n = 11)	Regular, low-intensity base training program	
Stepto et al. [40]	Randomized controlled trial (3 weeks)	Cyclists (trained), sex = male, age (years) = 26.3 ± 4.6, body mass (kg) = 76.1 ± 11.1, height (cm) = n/a, VO_{2peak} (mL·kg^{-1}·min^{-1}) = 63.1 ± 6.6	Short-HIIT (n = 4)	12 repetitions of 1.0 min at 100% MAP with 4 min of active recovery, 2 times per week	40-km cycling TT, VO_{2peak}, MAP
			Medium-HIIT (n = 4)	12 repetitions of 2 min at 90% MAP with 3 min of active recovery, 2 times per week	
			Long-HIIT (n = 4)	8 repetitions of 4 min at 85% MAP with 1.5 min of active recovery, 2 times per week	
			MIIT (n = 4)	4 repetitions of 8.0 min at 80% MAP with 1.0 min of active recovery, 2 times per week	
			SIT (n = 4)	12 repetitions of 30 s at 175% MAP with 4.5 min of active recovery, 2 times per week	

High-intensity interval training (HIIT), maximal aerobic power (MAP), maximal aerobic velocity (MAV), moderate-intensity interval training, not available (n/a), peak oxygen uptake (VO_{2peak}), sprint interval training (SIT), time-trial (TT)

Table 2 Interval training program description

Study	Group	Interval type	Program duration (weeks)	Session frequency	Interval repeti-tions	Work duration (min)	Work intensity (%)	Recovery mode	Recovery duration (min)	Session external work (a.u.)	Total external work (a.u.)
Akca and Aras [37]	Medium-HIIT	HIIT	4	2.0	8.0	2.5	75	Active	3.0	1500	12,000
	SIT	SIT	4	2.0	10.0	0.5	125	Active	4.0	625	5000
Esfarjani and Laursen [38]	Medium-HIIT	HIIT	10	2.0	8.0	3.3	87	Active	3.5	2296	45,936
	SIT	SIT	10	2.0	12.0	0.5	114	Active	4.5	684	13,680
Granata et al. [41]	Long-HIIT	HIIT	4	3.0	5.5	4.0	73	Active	2.0	1606	19,272
	SIT	SIT	4	3.0	6.6	0.5	168	Passive	4.0	554	6653
Inoue et al. [29]	Long-HIIT	HIIT	6	2.8	6.3	4.7	79[a]	Active	4.0	2339	39,298
	SIT	SIT	6	2.8	7.5	0.5	153[a]	Active	4.0	575	9664
Laursen et al. [39]	Medium-HIIT-1	HIIT	4	2.0	8.0	2.4	100	Passive	4.8	1920	15,360
	Medium-HIIT-2	HIIT	4	2.0	8.0	2.6	100	Passive	4.0	2640	16,640
	SIT	SIT	4	2.0	12.0	0.5	185	Passive	4.5	1110	8880
Stepto et al. [40]	Short-HIIT	HIIT	3	2.0	12.0	1.0	100	Active	4.0	2720	7200
	Medium-HIIT	HIIT	3	2.0	12.0	2.0	90	Active	3.0	2160	12,960
	Long-HIIT	HIIT	3	2.0	8.0	4.0	85	Active	1.5	1200	16,320
	SIT	SIT	3	2.0	12.0	0.5	175	Active	4.5	1050	6300

All values represent the mean value for each category; session external work is a product of interval repetitions, work duration and work intensity; total external work is a product of session external work, program duration and session frequency

[a]The average training intensity for the respective subgroup was used due to missing data

Table 3 Risk of bias of individual studies

Study	Eligibility	Random allocation	Concealed allocation	Baseline comparison	Blind subjects	Blind therapists	Blind assessors	Adequate follow-up	Intention-to-treat	Between-group comparison	Point estimates/variability	Score
Akca and Aras [37]	0	1	0	1	0	0	0	0	0	1	1	4
Esfarjani and Laursen [38]	0	0	0	1	0	0	0	1	1	1	1	5
Granata et al. [41]	0	1	0	1	0	0	0	1	0	1	1	5
Inoue et al. [29]	0	1	1	1	0	0	0	0	0	1	1	5
Laursen et al. [39]	0	0	0	1	0	0	0	1	0	1	1	4
Stepto et al. [40]	0	1	0	1	0	0	0	1	0	1	1	5
Mean score												4.7

Eligibility is not included in the final 10-point score

to SIT (Table 4). There was no significant difference in VO_{2max}/VO_{2peak} between the HIIT and SIT groups in any of the studies (Table 5). With respect to MAP/MAV, there was a significantly greater improvement following HIIT when compared to SIT in 4 of the subgroups (Table 6).

3.5 Synthesis of Results

3.5.1 Training Load

Three of the studies used incremental tests that were greater than 12 min to determine VO_{2max}/VO_{2peak} [37, 38, 41]; therefore, the correction factor was applied to standardize exercise intensity. The average session external work was significantly different between the HIIT and SIT groups ($p < 0.0001$), with average values of 1980 ± 475 (a.u.) and 766 ± 248 (a.u.), respectively. However, there was no statistically significant difference in average total external work between HIIT and SIT, with 20,554 ± 13,070 (a.u.) and 8363 ± 3122 (a.u.). The average intensity performed by the HIIT groups was 88% ± 11% MAP/MAV with an average interval work duration of 2.9 ± 1.2 min per work-bout. The SIT group's average training intensity was 153% ± 28 MAP/MAV with an average work-bout duration of 30 s. The total external work was 7200 ± 0 (a.u.), 20,579 ± 13,904 (a.u.), and 24,963 ± 12,502 (a.u.), for the short-HIIT, medium-HIIT and long-HIIT groups, respectively. There was no difference in session external work or total external work between the medium-HIIT and long-HIIT subgroups.

3.5.2 Time-Trial

There was no difference in the change in TT performance when comparing HIIT versus SIT (0.9%; 90% CI − 0.2% to 1.9%, $p = 0.18$) (Fig. 2). The subgroup analysis indicates that there was approximately a 2% greater improvement following long-HIIT when compared to SIT (2.0%; 90% CI: 0.7% to 3.3%, $p = 0.01$), producing a large effect (ES = 0.88). There was a significant difference between subgroups ($p = 0.009$), with longer HIIT bouts producing a greater improvement in performance.

3.5.3 Maximal Oxygen Consumption/Peak Oxygen Consumption

There was no difference in change in VO_{2max}/VO_{2peak} between any of the groups, including subgroups (Fig. 3).

3.5.4 Maximal Aerobic Power/Maximal Aerobic Velocity

There was a moderate effect (ES = 0.70) in favor of HIIT over SIT in MAP/MAV. This equates to a 2.4% greater improvement following HIIT (2.4%; 90% CI 1.3–3.6%,

Table 4 Time-trial results

Study	Measurement	Group	*n*	Pre (sec ± SD)	Post (sec ± SD)	Within-group change (% ± SD)	Between-group difference (%; 90% CI)	Cohen's *d*
Akca and Aras [37]	2-km rowing	Medium-HIIT	10	411.6 ± 7.5	406.6 ± 7.0	1.2 ± 1.2	− 0.2; − 1.1 to 0.8	− 0.13
		SIT	10	412.0 ± 7.7	406.3 ± 7.1	1.4 ± 1.4		
Esfarjani and Laursen [38]	3-km running	Medium-HIIT	6	679.0 ± 38.5	–	7.4 ± 2.6	4.0; 1.7 to 6.2	1.55
		SIT	6	679.0 ± 32.0	–	3.4 ± 2.1		
Granata et al. [41]	20-km cycling	Long-HIIT	11	2247.7 ± 147.5	2138.1 ± 90.7	4.9 ± 3.2	3.5; 1.4 to 5.6	1.13
		SIT	9	2162.3 ± 143.1	2131.9 ± 165.1	1.4 ± 2.5		
Inoue et al. [29]	40-km cycling	Long-HIIT	7	6091.1 ± 478.3	5785.4 ± 387.3	5.0 ± 2.6	2.1; 0.2 to 4.0	0.9
		SIT	9	6143.1 ± 445.7	5960.7 ± 417.0	3.0 ± 1.7		
Laursen et al. [39]	40-km cycling	Medium-HIIT-1	8	3419.5 ± 188.0	3259.9 ± 211.2	4.8 ± 2.8	0.5; − 1.8 to 2.9	0.17
		Medium-HIIT-2	9	3491.0 ± 202.7	3299.8 ± 267.3	5.5 ± 2.2	− 1.2; − 0.8 to 3.3	0.44
		SIT	10	3451.0 ± 228.6	3304.3 ± 162.5	4.3 ± 3.2		
Stepto et al. [40]	40-km cycling	Short-HIIT	3	3618.4 ± 301.7	3608.2 ± 283.0	0.3 ± 0.7	− 2.1; − 3.8 to − 0.4	1.12
		Medium-HIIT	4	3181.7 ± 39.3	3138.45 ± 106.0	1.4 ± 2.2	− 0.9; − 3.1 to 1.2	− 0.44
		Long-HIIT	4	3356.4 ± 156.5	3258.75 ± 123.9	2.9 ± 1.5	0.6; − 1.4 to 2.6	0.29
		SIT	4	3434.9 ± 209.7	3354.6 ± 165.0	2.3 ± 1.9		

Negative between-group difference favours SIT, positive between-group difference favours HIIT

Table 5 Maximal oxygen consumption and peak oxygen consumption results

Study	Group	*n*	Pre (mL·min^{-1} ± SD)	Post (mL·min^{-1} ± SD)	Within-group change (% ± SD)	Between-group difference (%; 90% CI)	Cohen's *d*
Akca and Aras [37]	Medium-HIIT	10	4100.0 ± 650.0	4290.0 ± 630.0	4.6 ± 4.5	− 0.8; − 4.4 to 2.8	− 0.15
	SIT	10	4080.0 ± 660.0	4300.0 ± 610.0	5.4 ± 5.3		
Granata et al. [41]	Long-HIIT	11	3540.0 ± 298.0	3687.0 ± 348.0	4.2 ± 4.9	− 2.2; − 5.0 to 0.7	− 0.51
	SIT	9	3937.0 ± 718.0	4185.0 ± 707.0	6.3 ± 2.7		
Laursen et al. [39]	Medium-HIIT-1	8	4916.0 ± 485.0	5213.0 ± 470.0	6.0 ± 3.2	2.3; − 0.7 to 5.2	0.55
	Medium-HIIT-2	9	4982.0 ± 341.0	5242.0 ± 217.0	5.2 ± 2.8	1.4; − 1.3 to 4.2	0.37
	SIT	10	4776.0 ± 287.0	4956.0 ± 433.0	3.8 ± 4.4		
Stepto et al. [40]	Short-HIIT	3	4519.0 ± 1373.0	4430.0 ± 1228.0	− 2.0 ± 4.3	− 2.2; − 8.0 to 3.6	− 0.39
	Medium-HIIT	4	5189.0 ± 501.0	5226.0 ± 356.0	0.7 ± 5.2	0.5; − 5.5 to 6.5	0.08
	Long-HIIT	4	4896.0 ± 248.0	5257.0 ± 491.0	7.4 ± 8.0	7.1; − 0.6 to 14.9	0.93
	SIT	4	4698.0 ± 381.0	4709.0 ± 563.0	0.2 ± 5.1		

Negative between-group difference favours SIT, positive between-group difference favours HIIT

$p = 0.0007$) (Fig. 4). There was a trend in HIIT subgroup duration and change in MAP/MAV, similar to that observed in TT performance, indicating a greater improvement in MAP/MAV with longer-duration interval bouts ($p = 0.0003$). Long-HIIT produced the greatest increase in MAP/MAV, with a 4% ($p < 0.00001$) higher change when compared to SIT.

3.6 Risk of Bias Across Studies

A funnel plot of the standard difference in mean versus standard error for TT results indicates that there is no evidence of publication bias ($p = 0.16$) regarding the studies included in the meta-analysis (Fig. 5).

Table 6 Maximal aerobic power and maximal aerobic velocity results

Study	Measurement	Group	*n*	Pre (mean ± SD)	Post (mean ± SD)	Within-group change (% ± SD)	Between-group difference (%; 90% CI)	Cohen's *d*
Akca and Aras [37]	MAP	HIIT	10	336.0 ± 20.0	351.0 ± 21.0	4.5 ± 4.3	− 0.9; − 4.5 to 2.7	− 0.18
		SIT	10	335.0 ± 24.0	353.0 ± 26.0	5.4 ± 5.2		
Esfarjani and Laursen [38]	MAV	Medium-HIIT	6	15.6 ± 0.7	16.6 ± 0.6	6.4 ± 6.1	− 1.4; − 7.8 to 5.1	− 0.19
		SIT	6	15.4 ± 0.5	16.6 ± 0.6	7.8 ± 7.4		
Granata et al. [41]	MAP	Long-HIIT	11	264.1 ± 37.4	293.2 ± 34.3	11.0 ± 3.6	6.6; 2.7 to 10.4	1.27
		SIT	9	280.8 ± 48.2	293.3 ± 51.5	4.5 ± 6.3		
Inoue et al. [29]	MAP	Long-HIIT	7	299.8 ± 24.6	323.1 ± 24.0	7.8 ± 3.3	2.7; − 1.3 to 6.6	0.49
		SIT	9	294.8 ± 22.9	310.0 ± 22.7	5.1 ± 6.1		
Laursen et al. [39]	MAP	Medium-HIIT-1	8	439.0 ± 28.9	459.6 ± 37.4	4.7 ± 3.1	1.7; − 0.7 to 4.1	0.51
		Medium-HIIT-2	9	429.3 ± 23.7	459.1 ± 27.2	6.9 ± 2.1	3.9; 1.9 to 6.0	1.37
		SIT	10	425.5 ± 32.4	438.3 ± 36.1	3.0 ± 3.2		
Stepto et al. [40]	MAP	Short-HIIT	3	349.7 ± 95.2	354.7 ± 91.6	1.4 ± 1.3	1.0; − 0.3 to 2.3	0.94
		Medium-HIIT	4	403.3 ± 21.0	411.0 ± 25.6	1.9 ± 1.5	1.5; 0.2 to 2.9	1.17
		Long-HIIT	4	389.8 ± 24.3	407.5 ± 26.0	4.6 ± 0.7	4.2; 3.4 to 4.9	5.89
		SIT	4	371.8 ± 28.6	373.3 ± 30.0	0.4 ± 0.5		

Maximal aerobic power (MAP) is measured in watts, maximal aerobic velocity is measured in km·h^{-1}, negative between-group difference favours SIT, positive between-group difference favours HIIT

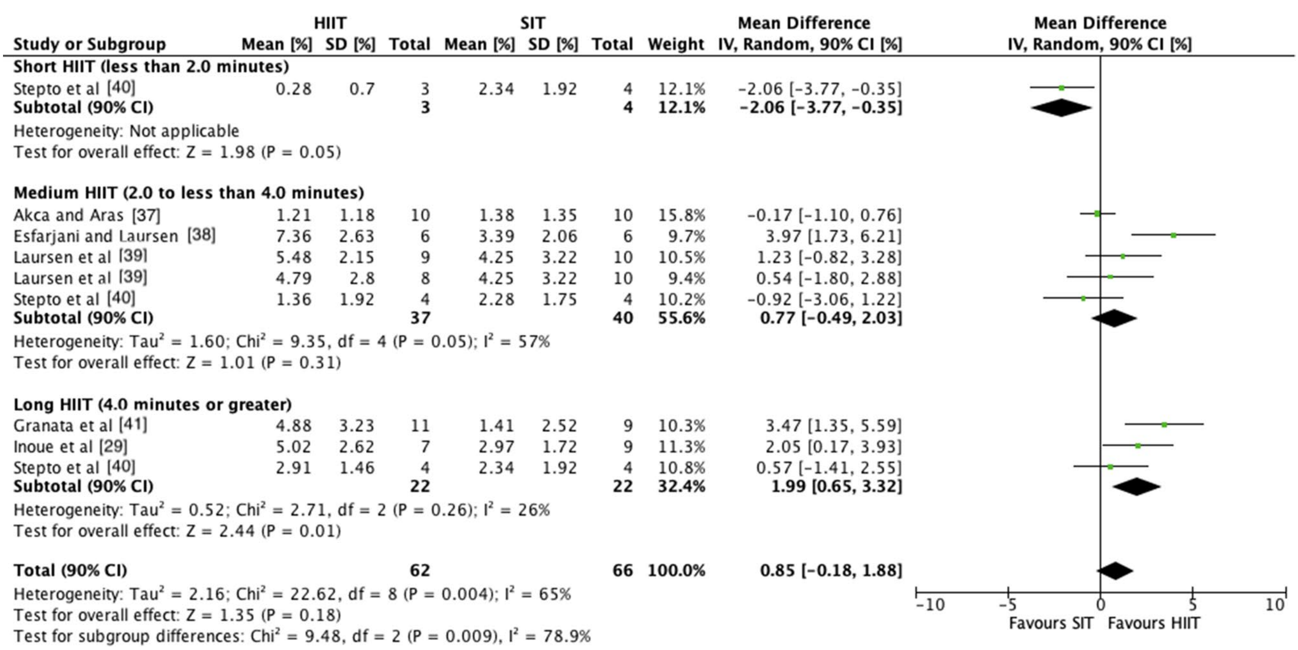

Fig. 2 Forest plot of time-trial results

4 Discussion

4.1 Summary of Evidence

This is the first systematic review to measure changes in TT performance following an interval training program. Previous meta-analyses that studied the effects of interval training have focused solely on VO_{2max} as the primary outcome [21, 28, 42–45]. Performance outcomes such as VO_{2max} may not account for individual physiological differences at submaximal levels [46]. In fact, in a group of athletes with the same VO_{2max}, TT results are up to 10%

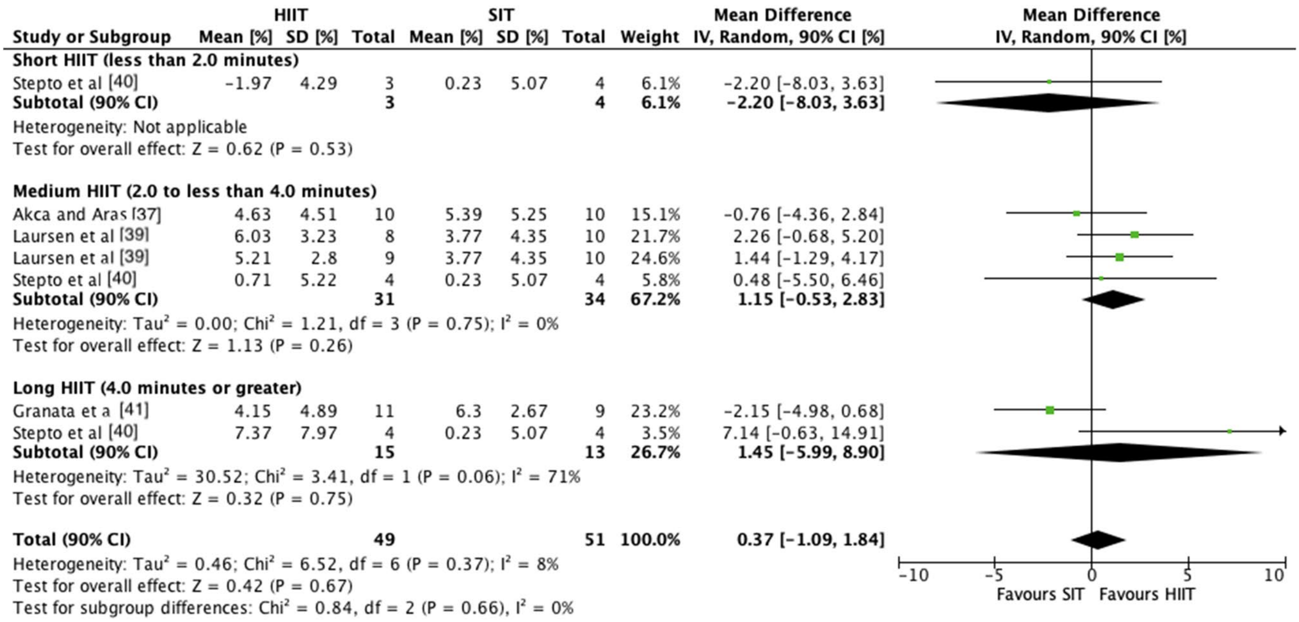

Fig. 3 Forest plot of maximal oxygen consumption and peak oxygen consumption

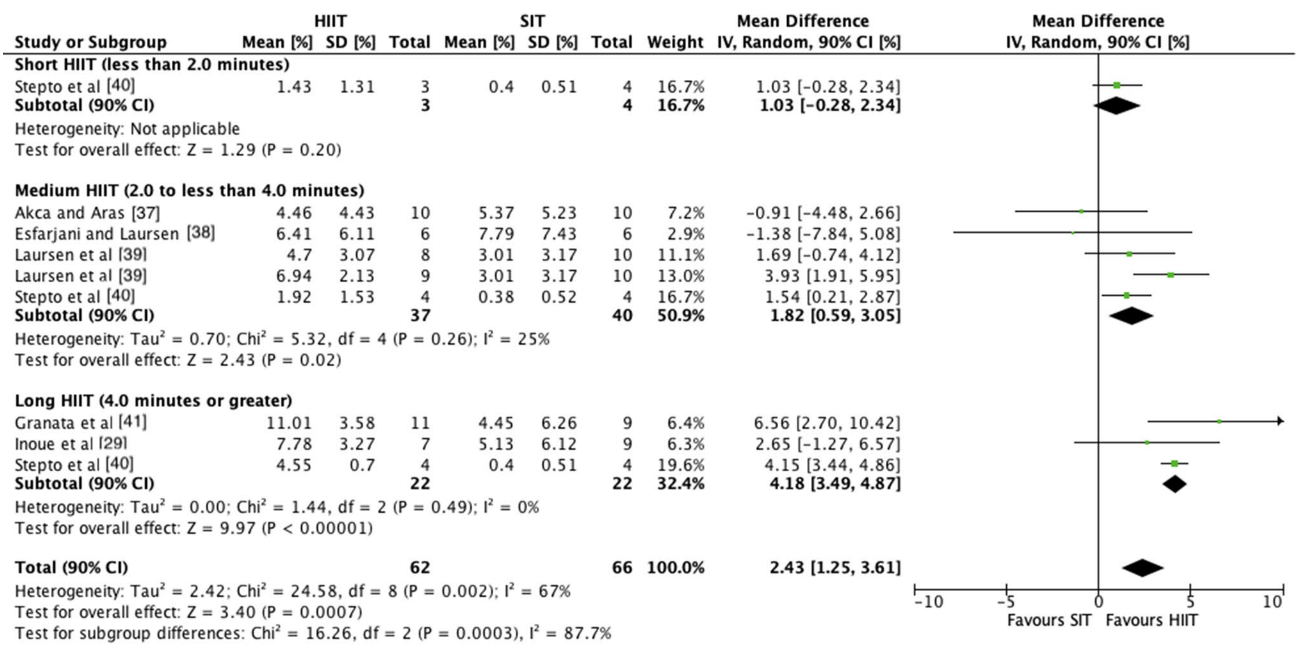

Fig. 4 Forest plot of maximal aerobic power and maximal aerobic velocity

faster in those athletes with higher relative VTs [47]. In a TT test, athletes are expected to complete a set distance in the shortest possible time. This approach may provide a similar experience to endurance events where power output can fluctuate much like a TT assessment, thereby increasing the external validity of the measurement [48]. TT results have been shown to be a reliable measurement (ICC = 0.99) and are highly correlated with cycling ($r = 0.99$, $p < 0.001$) and running ($r = 0.95$, $p = 0.001$) race performance [25, 26]. However, the physiological demands of TT tests may make them impractical for coaches to perform regularly since the potential for athlete fatigue may require alterations in training programs. Nevertheless, in endurance sport science research, these tests may be the best method of evaluating

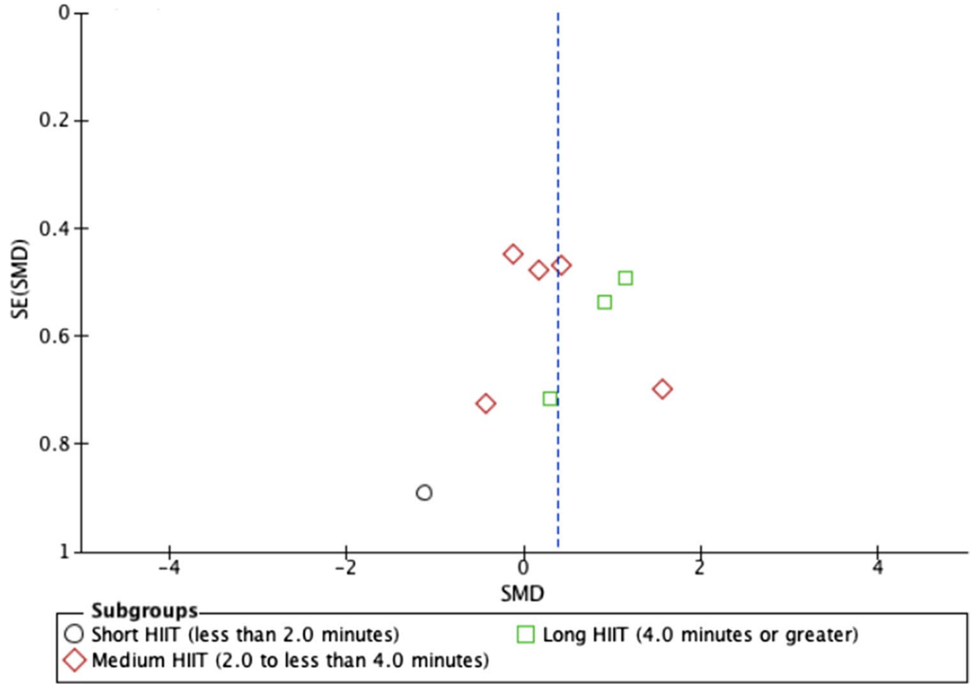

Fig. 5 Funnel plot of standardized mean difference versus standard error of time-trial performance

the effectiveness of training programs. These testing methods can then be translated into actual practice.

The results of this meta-analysis show that there is no significant difference in TT performance change between HIIT and SIT. There is some degree of commonality among the various training programs in the studies making up the meta-analysis. Specifically, all studies compared HIIT with a SIT program that consisted of 30-s work-bouts followed by a recovery period that would allow for full recovery between bouts. However, the studies incorporated HIIT programs that ranged in work-bout duration from 1 to 5 min, making it difficult to generalize the results. Therefore, a subgroup analysis was completed to analyze the results of HIIT programs of similar work-bout duration. This subgroup analysis indicates that longer-duration intervals may have a greater ability to augment TT performance and MAP, when compared to SIT.

VO_{2max}/VO_{2peak} improved following both HIIT and SIT, with no difference between interval subgroups. There were conflicting results concerning the changes in VO_{2max} and TT performance between the studies by Stepto et al. and Granata et al. [40, 41]. The distinction is likely due to the design of the incremental test used to determine VO_{2max}. The Stepto study used 2.5-min stages, whereas the Granata study used 4-min stages. Tests that incorporate longer stages may be more indicative of submaximal performance. Time-to-exhaustion (TTE) at MAP from tests that use 2-min stages is approximately 3.7 min in highly trained cyclists [49]; whereas, TTE at MAP following longer-duration tests (3-min increments) can be as long as 6.8 min in highly trained cyclists [50]. This may be why there was a greater improvement in TT and MAP with a lesser improvement in VO_{2max} in the study by Granata et al. when compared to the study by Stepto et al.

4.2 Classification System for High-Intensity Interval Training

While exercise intensity is the main component that can be used to classify an interval training program as either HIIT or SIT, the duration of the interval itself is a very important consideration. Previous inquiries into interval training have manipulated the work–rest ratio to optimize time spent near or at VO_{2max} [17, 19, 20, 51]. These types of protocols can produce a significant acute increase in oxygen uptake during exercise but to a lesser extent than longer HIIT bouts [17, 20, 52]. With respect to training adaptations, HIIT that consists of very short work-bouts (15–30 s) may not appear to be as effective at improving exercise economy as programs that utilize longer HIIT bouts [19, 51]. Therefore, it may be beneficial to program HIIT intervals using longer-duration work-bouts to optimize endurance performance.

There have been a few attempts to classify HIIT exercise based on the duration of the interval work-bout [4, 28]. In a previous review, short-HIIT was considered to be work-bouts under 30 s, medium-HIIT as 30 s–2 min, and long-HIIT as 2–4 min in duration [28]. However, there remain inconclusive physiological justifications for choosing these ranges. It may be appropriate to identify subgroups of interval training by considering the relative contributions of energy system (anaerobic vs. aerobic) components. Providing an accurate classification for HIIT subgroups based on anaerobic contributions can be challenging as previous literature suggests that there is some difficulty in determining the degree of anaerobic metabolism that takes place during HIIT [5]. Blood lactate levels as well as excess post-exercise oxygen consumption (EPOC) are common methods that have been used to determine anaerobic metabolism during interval exercise although the reliability of such techniques remains questionable [5].

It may be more productive to base categorization of intervals on known oxygen uptake kinetics. Previous measurements of oxygen uptake during high-intensity exercise indicate that VO_{2max} can be reached in as short a time as 117 s in trained individuals, while taking approximately 209 s in untrained individuals [53]. Since there is variability among individuals of different training status, it would be appropriate to use work-bouts of 120 s or less when defining an anaerobic interval (short-HIIT) for trained individuals, as the dominant source of total energy is supplied via anaerobic metabolism. Conversely, to perform an aerobic interval (long-HIIT), more than 50% of the total work completed should consist of exercise at VO_{2max}. Therefore, long-HIIT should comprise of bouts of exercise that are at least 4 min in duration. Finally, medium-HIIT would incorporate interval exercise that is between 2 and 4 min in duration. This method of classification does not provide an individualized approach to interval programming. Nevertheless, it does specify the criteria for athletes and coaches to make an informed decision concerning their training.

With respect to aerobic metabolism, the measurement of oxygen uptake can become delayed in the heavy and severe exercise domains due to the development of the VO_2 slow-component which has been described as the continued increase in oxygen consumption after 3 min of constant-load exercise [54]. Individually determined oxygen kinetics may be a novel approach to classify HIIT but those data are not available in the reviewed studies and as a consequence fixed time points were employed. Future investigations are encouraged to examine this approach for evidence-based decision-making that is specific to sedentary and athletic populations.

4.3 Limitations

There are elements regarding design of the individual studies that may influence the results of the meta-analysis. Three of the studies did not randomize participants into their respective groups [38, 39, 55] and only one included concealed group allocation. These methodological issues increase the possibility that the results will be swayed by confounding variables. In addition, they may influence the decision as to whether a study participant receives treatment [56]. With respect to randomization, four of the studies did not match participants by VO_{2max}/VO_{2peak} or TT results, potentially producing non-homogeneity in the training groups [39]. The lack of assessor and participant blinding in all the studies might introduce significant bias. When subjects are blinded, it is less likely that the results of treatment are due to a placebo effect [56]. Blinding assessors prevents their personal bias from affecting the results [56].

There are a limited number of studies that compare the effects of HIIT and SIT on TT performance in a healthy, active population. Six studies met the inclusion criteria for the qualitative and quantitative analysis (Fig. 1). The subgroup analysis was performed to provide further insight into the effects of HIIT programs differing in duration. There were only data from one study for a comparison of the short-HIIT group, limiting the ability to provide a strong conclusion for this analysis. There were 5 comparisons using medium-HIIT and 3 using long-HIIT (Fig. 2). Previous reviews have included as few as 4 studies with only 2 groups for subgroup analysis [57]. However, while there are reviews that include a small sample size, there is a greater risk of error due to the heterogeneity of the individual studies. In addition, the small sample size of the individual studies, specifically the study by Stepto et al. [40], may skew the results by increasing the variability. Therefore, future investigations should include larger sample sizes when feasible.

There remains some debate around participant characteristics that can influence the response to a training intervention. Participant age and fitness level are two variables that, in theory, can affect the outcome of an intervention. The studies in the current review included participants between the ages of 19 and 32 years of age. Due to the small range, it is unlikely that age differences could have affected the results. A study by Støren et al. directly compared the effects of age on changes in VO_{2max} following an interval training program [58]. They included males ($n = 72$) and females ($n = 22$) between the ages of 20 and 70+ years, and found no difference in relative improvement in VO_{2max} [58].

Training status as determined by baseline VO_{2max} may affect the magnitude of a training response as there are physiological limits of oxygen consumption [59]. There was a broad range of baseline VO_{2max}/VO_{2peak} values in the studies included in this review, with values ranging from 46.0 to 64.5 $mL \cdot kg^{-1} \cdot min^{-1}$. This is meaningful because the study by Støren et al. found a significant difference in individual training response, with those participants who were inactive demonstrating the greatest improvement in performance. In contrast, a recent study of well-trained cyclists ($VO_{2max} = 57.9 \pm 6.8$ $mL \cdot kg^{-1} \cdot min^{-1}$) displayed a 15% improvement in VO_{2max} following an interval training program, indicating that interval training can elicit a substantial response in highly trained individuals [60]. However, changes in VO_{2max} may not appropriately indicate improvements in submaximal endurance performance. The results of study by Granata et al. show the greatest in improvement in MAP and TT performance following long-HIIT when compared to the other studies. Baseline measurements of VO_{2max} for the participants in that study was significantly lower than in the other studies, indicating that initial training status can influence the magnitude of improvements in TT performance. However, there was no significant difference in the results when the data were removed from the meta-analysis.

The studies included in this review incorporated three different modes of exercise including cycling [29, 39–41], rowing [37] and running [38]. Exercise mode may influence the acute physiological responses that occur during interval exercise, producing differences in long-term adaptations. Cycling and running have been shown to elicit different acute responses during exercise such as variations in oxygen uptake kinetics, peak oxygen consumption, skeletal muscle oxidative capacity and neuromuscular responses [61]. There is also literature that demonstrates similar physiological differences between cycling and rowing [62]. To the best of our knowledge, there are no studies that compare the effects of an interval training program using different modes of exercise on measurements of endurance performance. Due to the differences in the acute responses, it is likely that there is a difference in the magnitude of the response between exercise modes, potentially limiting the generalizability of the results. However, further investigations are required to determine if variations in training adaptations occur.

There was a significant difference in training load between the HIIT and SIT groups. However, the variance in training load may not influence performance. A recent meta-analysis showed an inverse relationship between training load and performance following SIT, with a decline in improvement for every two SIT bouts above 4 repetitions [45]. Therefore, it is unlikely that the difference in performance was as a result of variations in external work. There was no difference in total external work between the medium-HIIT and long-HIIT groups. We believe that the greater performance improvement following long-HIIT is likely due to the higher aerobic contribution of a longer interval bout. There was no difference in changes in VO_{2max}/VO_{2peak} between any of the groups. However, there was a greater increase in MAP/MAV following long-HIIT. Since MAP/MAV is an indicator of exercise economy [63], the greater degree of aerobic metabolism that occurs during long-HIIT likely would produce improvements that contribute to submaximal exercise.

The differences in the distance for the TT measures used to assess performance may influence the results of the meta-analysis. Previous inquiry suggests that there is a greater anaerobic contribution to the TTs of shorter duration [64]. The majority of the TTs included in this review incorporated longer-duration tests (between 20 and 40 km) [39–41], which require a greater aerobic contribution [64]. Therefore, it could be postulated that the results of the review would favor long-HIIT due to the aerobic nature of the intervention. Two studies in the meta-analysis included TTs that were between 6 and 12 min in duration [37, 38]. However, there was no significant change in the results when they are removed from the analysis.

4.4 Practical Application

The results of the subgroup analysis show long-HIIT to be the most beneficial form of interval training to augment performance. While exercise intensity is one of the most important variables to consider when programming interval training [1], work-bout duration may be essential to optimize changes in performance. Interval training that includes work-bouts between 4 and 6 min in duration at an intensity between VT_2 and VO_{2max} with 2–4 min of recovery would be best to improve TT performance.

4.5 Future Direction

This is the first analysis to directly compare HIIT and SIT with markers of endurance sport performance. The results of the individual studies indicate that SIT may provide benefits for shorter-duration TTs and HIIT for longer TTs. It may be beneficial to investigate this hypothesis through a direct comparison of HIIT and SIT on short- and long-duration TTs. The subgroup analysis shows that different adaptations may occur as a result of manipulating the interval work-bout duration. The study by Stepto et al. directly compared short-, medium- and long-HIIT groups on TT performance; however, due to small sample size, a statistically significant change in the performance variables was not detected [40]. Future studies with larger sample sizes that directly compare medium-HIIT and long-HIIT could provide additional insight into the benefit of these programs.

5 Conclusion

The subgroup analysis indicates that there was a large effect in TT performance favoring long-HIIT over SIT. Therefore, the results based on the currently available literature suggest that longer-duration HIIT bouts may provide optimal performance adaptation and should be incorporated in an endurance training program. Additional research that directly compares HIIT exercise differing in work-bout duration would strengthen these results and provide further insight into the mechanisms behind the observed benefits of long-HIIT.

Compliance with Ethical Standards

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Conflicts of interest Michael Rosenblat, Andrew Perrotta and Scott Thomas declare that they have no conflicts of interest relevant to the content of this review.

Data availability statement All data supporting the results in this manuscript are available within the results sections or in the cited articles.

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