Sports Medicine (2021) 51:1687–1714
https://doi.org/10.1007/s40279-021-01457-2

SYSTEMATIC REVIEW

Programming Interval Training to Optimize Time-Trial Performance: A Systematic Review and Meta-Analysis

Michael A. Rosenblat[1,2] **· Edward Lin**[1,3] **· Bruno R. da Costa**[4,5,6] **· Scott G. Thomas**[1]

Accepted: 19 March 2021 / Published online: 7 April 2021

Abstract

Background Interval training has become an essential component of endurance training programs because it can facilitate a substantial improvement in endurance sport performance. Two forms of interval training that are commonly used to improve endurance sport performance are high-intensity interval training (HIIT) and sprint interval training (SIT). Despite extensive research, there is no consensus concerning the optimal method to manipulate the interval training programming variables to maximize endurance performance for differing individuals.

Objective The objective of this manuscript was to perform a systematic review and meta-analysis of interval training studies to determine the influence that individual characteristics and training variables have on time-trial (TT) performance.

Data Sources SPORTDiscus and Medline with Full Text were explored to conduct a systematic literature search.

Study Selection The following criteria were used to select studies appropriate for the review: 1. the studies were prospective in nature; 2. included individuals between the ages of 18 and 65 years; 3. included an interval training (HIIT or SIT) program at least 2 weeks in duration; 4. included a TT test that required participants to complete a set distance; 5. and programmed HIIT by power or velocity.

Results Twenty-nine studies met the inclusion criteria for the quantitative analysis with a total of 67 separate groups. The participants included males ($n = 400$) and females ($n = 91$) with a mean group age of 25 (range 19–45) years and mean VO_{2max} of 52 (range 32–70) mL·kg^{-1}·min^{-1}. The training status of the participants comprised of inactive ($n = 75$), active ($n = 146$) and trained ($n = 258$) individuals. Training status played a significant role in improvements in TT performance with trained individuals only seeing improvements of approximately 2% whereas individuals of lower training status demonstrated improvements as high as 6%. The change in TT performance with HIIT depended on the duration but not the intensity of the interval work-bout. There was a dose–response relationship with the number of HIIT sessions, training weeks and total work with changes in TT performance. However, the dose–response was not present with SIT.

Conclusion Optimization of interval training programs to produce TT performance improvements should be done according to training status. Our analysis suggests that increasing interval training dose beyond minimal requirements may not augment the training response. In addition, optimal dosing differs between high intensity and sprint interval programs.

1 Introduction

Interval training has become an essential component of endurance training programs because it can facilitate improvements in cardiovascular fitness and endurance sport performance [1–3]. Interval training consists of repeated bouts of high-intensity work, lasting from seconds to minutes, followed by periods of either active or passive recovery. The work is divided into a set of work/rest repetitions because exercise intensities within the severe or extreme domains can only be sustained for short periods of time [4]. With repeated interval bouts, a greater total time can be accumulated at an appropriately high intensity as compared to exercise performed continuously [5].

High-intensity interval training (HIIT) and sprint interval training (SIT) are often used to improve endurance sport performance. HIIT is performed at a power output or velocity within the severe-intensity domain [6]. There are different measures employed to determine the lower limit of the severe-intensity domain, such as critical power (CP), maximal lactate steady state (MLSS) and the second ventilatory threshold (VT_2) [7, 8]. The upper limit of the severe domain, maximal aerobic power (MAP) or maximal aerobic velocity (MAV), can be described as the highest power that

✉ Michael A. Rosenblat
michael@evidencebasedcoaching.ca

Extended author information available on the last page of the article

Key Points

An individual's training status (inactive, active, trained) is the primary baseline characteristic that can influence subsequent changes in time-trial performance.

HIIT programs should consist of 5 repetitions of 5-min work-bouts at any intensity within the severe domain, with a 2.5-min recovery period (active or passive) between work-bouts, performed twice a week for at least 4 weeks, to optimize time-trial performance in trained individuals.

SIT programs should consist of 4 repetitions of 30-s work-bouts performed at maximal effort, with 4 min of passive recovery, twice a week for 2 weeks, to optimize time-trial performance in trained individuals.

can allow for the attainment of a maximal oxygen consumption (VO_{2max}) [9]. In contrast to HIIT, SIT is performed in the extreme intensity domain which is at power outputs or velocities above those associated with MAP or MAV [10].

Exercise session-specific variables that make up an interval program include exercise mode; work-bout duration and intensity; recovery-bout mode (active vs passive) and duration; and the number of interval repetitions [11–13]. Moreover, there are components that make up the training program, such as session frequency, intensity distribution, and the inclusion of other forms of exercise referred to as cross-training. The combination of these variables can also influence the training response [14]. In addition to programming variables, there are other elements that can influence changes in performance. Of particular note are population characteristics, such as age, sex, baseline VO_{2max} and training status [11]. Extensive research has been dedicated to examining the effect of manipulating modifiable program characteristics on various measures of endurance sport performance [3, 11, 12, 15, 16]. Some of the more notable measures that have been examined are VO_{2max}, time-to-exhaustion (TTE) tests, and time-trial (TT) tests.

VO_{2max} is highly correlated with race performance [17] but has limitations because it does not account for additional physiological differences [18, 19]. The reliability of TTE tests has been shown to be lower than TT tests [20]. In addition, since TTE tests are open-looped tests (test termination is determined by the individual), they might fail to provide a realistic indicator of athletic performance [21]. It has been established that TT tests are highly correlated with race performance and can simulate the physiological responses that occur during competition [22, 23]. The most common type of TT test is one that requires an individual to complete a set distance (e.g. 40-km) in the fastest time possible. Time-based TT tests, where an athlete attempts to travel the furthest distance, or maintain the highest average power or velocity within a set duration, are also common. Since TT tests based on a set distance most closely represent a true race environment, they may be the most appropriate for endurance performance assessment.

Previous reviews provide a comprehensive explanation of the acute and chronic responses that occur from manipulating interval training parameters [11, 12, 24, 25]. However, these reviews do not include meta-regression analyses which would provide a single effect from pooling the results of the individual studies. As a result of this deficiency, there remains a lack of consensus concerning the optimal method for structuring an interval training program for individuals who differ in age, sex and training status. The objective of this manuscript is to perform a systematic review and meta-analysis of interval training studies to determine the influence that individual characteristics and training variables have on TT performance.

2 Methods

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) was used as the protocol for the design of the review [26].

2.1 Eligibility Criteria

2.1.1 Inclusion Criteria

The following criteria were used to select studies appropriate for the review: 1. the studies were prospective in nature; 2. included individuals between the ages of 18 and 65 years; 3. included an interval training (HIIT or SIT) program at least 2 weeks in duration; 4. included a TT test that required participants to complete a set distance; 5. and programmed HIIT by power or velocity.

2.1.2 Exclusion Criteria

Studies were excluded if participants were postmenopausal, overweight or had pathology, or if the training program or outcome was inappropriate for this analysis for the following reasons: 1. training program not clearly defined; 2. training program was less than 2 weeks in duration; 3. included HIIT and SIT in the same program; 4. training mode differed from TT mode; 5. included additional exercise that was not quantified; 6. contained nutritional interventions (supplements, hydration, fed state, etc.); 7. were subject to changes in environmental conditions (heat/cold, altitude, hypoxia/hyperoxia etc.); 8. identified the inclusion of modalities (cryotherapy, compression garments, etc.); 9. included pharmacological agents; 10. TT not based on distance; 11. TT intensity not self-selected.

2.2 Information Sources

An electronic search was conducted that included all publication years (i.e. from inception to June 13, 2020). Medline with Full Text and SPORTDiscus were the two databases used to conduct a systematic literature search.

2.3 Search

2.3.1 Search String

Titles and abstracts were searched using the search string from the meta-analysis by Rosenblat et al. since that string provided an exhaustive set of results [3]. The search terms resulted from a review of previous literature as well as the use of common synonyms for interval training. The search string was as follows: "(interval training OR interval exercise OR anaerobic interval* OR aerobic interval* OR high-intensity interval* OR sprint interval* OR intermittent exercise OR intermittent training OR repeated sprint)".

2.3.2 Search Limits

To provide a more specific search, the following limits were selected: 1. English language, 2. humans, 3. journal article.

2.4 Study Selection

The lead author removed duplicates and screened the titles and abstracts of the search results. The full-text studies were retrieved if the titles and abstracts met the eligibility criteria or if there was some degree of uncertainty as to whether this was the case. Two authors independently reviewed the full-text articles for eligibility. Any disagreements as to eligibility were resolved through a discussion between the two authors. A third author was to be consulted if the first two authors could not reach agreement. The rationale for excluding articles was documented.

2.5 Data Collection Process

The Cochrane Data Extraction and Assessment Form was used as a template to create a data collection form. Two authors independently extracted the data from each of the studies. The two authors then compared their findings to check for errors. Inconsistencies were discussed and addressed by the two authors. A third author was consulted if the first two authors were unable to reach agreement.

2.6 Data Items

Information about the study methodology, participant characteristics, training characteristics and outcomes was extracted from each of the study articles included in the review. The specific variables were: participant characteristics (training status, sport specificity, sex, age, height, mass, $VO_{2max,}$ W_{peak}); W_{peak} test description (initial power/speed, stage duration, increment power/speed, number of stages); intervention description (exercise mode, interval type, training program duration, interval sessions per week, interval repetitions, interval work-bout duration, interval work-bout intensity, interval recovery mode, interval recovery duration, progressive overload performed, strength training performed; and outcome description (TT mode, distance, indoor/outdoor setting, equipment used, familiarization protocol, baseline completion time, follow-up completion time, delta time). Training status was categorized into inactive (not engaged in deliberate physical activity), active (participate in a non-structured exercise program) and trained (structured training program). The term VO_{2max} was used to represent baseline measures of maximal and peak oxygen consumption obtained from an incremental exercise test.

The authors of the included studies were contacted for relevant data that were not presented in their publications (e.g. pre-, post-test and delta values).

2.7 Risk of Bias of Individual Studies

Two reviewers used the Cochrane Collaboration Tool to assess the quality of the studies included in the review. The tool can be used to determine the level of bias in intervention studies [27]. The specific methodological components assessed include: 1. random sequence generation, 2. allocation concealment, 3. blinding of participants and researchers, 4. blind of outcome assessment, 5. incomplete data outcome, 6. selective reporting.

2.8 Summary of Measures

The primary outcome assessed in this review was the percentage change in TT performance from baseline. The moderators included the following: baseline characteristic (sex, age, training status, baseline VO_{2max}), Training characteristics (training mode, interval work-bout intensity, interval work-bout duration, interval recovery mode, interval recovery duration, interval repetitions, interval session per week, continuous training, total sessions, total weeks, total work), and outcome characteristics (TT distance). These descriptive data are available in Table 1 and in the supplemental material.

2.9 Synthesis of Results

Group data are reported as means and standard deviations (SD) with delta reported as the percentage change from baseline. Data conversions were performed to determine values for missing data as well as to standardize scores to allow for a consistent interpretation of the results. Data expressed using the standard error of the mean (SEM) were converted to a SD using the following formula: $SD = SEM\sqrt{n}$. The SD was estimated using t values derived from the p value in instances where the SEM or SD were not available using the following formula: $SD = \sqrt{n}\left(\frac{\bar{x}_1 - \bar{x}_2}{t}\right)$, where $\bar{x}_1$ is the TT mean baseline value and $\bar{x}_2$ the TT mean value at the end of the interval training. A p value expressed using an inequality (e.g. '$<$') was considered as an equality (e.g. '$=$'), providing a more conservative estimate of the SD. Delta scores were converted to percentage change using the following formula: $\%Delta = \left(\frac{Delta}{\bar{x}_1} \times 100\right)$, where Delta is the difference between $\bar{x}_2$ and $\bar{x}_1$. A negative delta score is presented in the original units indicates a faster completion time from baseline. A positive %Delta indicates that the TT mean value at the end of the interval training is higher than the TT mean baseline value.

HIIT exercise was classified as repeated bouts of exercise that occur in the severe intensity domain. SIT included exercise performed in the extreme domain. The correction factor, $Factor = 1.8596 \times Test\ Duration^{-0.242}$, used by Granata et al. [28] and based on the model proposed by Morton [29], was used to standardize exercise intensity obtained from incremental ramp testing protocols that exceeded 12-min in duration. Exercise intensity was then converted to a percentage of W_{peak} for all instances where it was expressed as an absolute power (watts) or velocity (km h^{-1}). Total session work was defined as the product of interval intensity, interval work-bout duration, and interval repetitions. Total work was defined as the product of total session work, number of sessions performed each week, and total program duration (weeks). Both measures of external work were described in arbitrary units (a.u.).

The TT %Delta scores and weighted mean difference (WMD) were pooled using the metafor package (version 2.4-0) in R (version 4.0.2) using a mixed effects model and the DerSimonian-Laird estimator. A mixed effects model was used to include covariates in the analysis to account for part of the heterogeneity of the true effects [30].

2.10 Assessment of Heterogeneity and Small Study Effects

The I^2 statistic was used to determine the percentage of the total variation in the estimated effect across 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 [31].

3 Results

The dataset used in the quantitative analysis is available in Electronic Supplementary Material Appendix S1. All figures and tables in this review include the data for studies that were in the quantitative analysis. Additional tables not provided in the results can be found in Electronic Supplementary Material Appendix S2.

3.1 Study Selection

The literature search was conducted on June 13, 2020. The databases SPORTDiscus and Medline were used to perform the search which yielded a total of 9453 results. Following the removal of 3032 duplicates, 6421 titles and abstracts were screened. A total of 51 full-text articles were screened for eligibility. Thirty-one studies met the inclusion criteria for the qualitative and 29 for the quantitative analysis (Fig. 1).

3.2 Study Characteristics

Study designs included non-controlled ($n = 7$), controlled ($n = 9$) and randomized controlled ($n = 14$) trials ranging from 2 to 10 weeks in duration (Table 1). The sample of studies for the quantitative analysis included a total of 67 separate groups. The participants included males ($n = 400$) and females ($n = 91$) with a mean group age of 25 (range 19–45) years and mean VO_{2max} of 52 (range 32–70) mL·kg^{-1}·min^{-1}. The training status of the participants comprised of inactive ($n = 75$), active ($n = 146$) and trained ($n = 258$) individuals. The different exercise modes consisted of cycling ($n = 34$ groups), running ($n = 27$ groups) and rowing ($n =$ groups) (Tables 2, 3). The TT tests included a range of distances from 1.6 to 40.0 km.

3.3 Risk of Bias Within Studies

There was a high risk of bias regarding participant, researcher and assessor blinding among the included studies. Only one of the studies included allocation concealment (Table 4).

3.4 Results of Individual Studies

Twenty-nine of the 34 HIIT intervention groups showed improvements in TT performance, with group values ranging from 0.1 up to 9.6%. Thirty-two of the 34 SIT groups

Table 1 Study characteristics

Study	Study design	Participant characteristics								Intervention			Outcome	
		Group	*n*	Age (years)		Sex	Training status	VO_{2max} (mL·kg^{-1}·min^{-1})		Weeks	Interval type	LICT	TT mode	TT distance (km)
				Mean	SD			Mean	SD					
Akca et al. [32]	RCT	1	10	21.8	2.4	M	Trained	56.1	5.5	4	HIIT	Yes	Rowing	2.0
Akca et al. [32]	RCT	2	10	21.8	2.4	M	Trained	57.0	5.7	4	SIT	Yes	Rowing	2.0
Astorino et al. [33]	CT	1	3	34.3	11.0	M	Active	40.8	2.4	3	HIIT	No	Cycling	8.0
Astorino et al. [33]	CT	2	11	24.8	6.2	F	Active	38.2	4.6	3	HIIT	No	Cycling	8.0
Capostagno et al. [34]	RCT	1	8	35.0	4.0	M	Trained	58.4	4.2	2	HIIT	Yes	Cycling	40.0
Capostagno et al. [34]	RCT	2	7	35.0	7.0	M	Trained	53.9	5.0	2	HIIT	Yes	Cycling	40.0
Denadai et al. [35]	RCT	2	8	27.4	4.4	M	Trained	60.0	6.0	4	HIIT	Yes	Running	1.5
Denadai et al. [35]	RCT	1	9	27.4	4.4	M	Trained	59.1	6.0	4	HIIT	Yes	Running	5.0
Denadai et al. [35]	RCT	2	8	27.4	4.4	M	Trained	60.0	6.0	4	HIIT	Yes	Running	5.0
Denham et al. [36]	CT	1	20	21.5	n/a	M	Inactive	49.6	4.6	4	SIT	No	Running	5.0
Dolgener et al. [37]	RCT	1	7	n/a	n/a	M	Inactive	35.5	2.4	6	SIT	No	Running	1.6
Driller et al. [38]	RCT	1	10	19.0	2.0	B	Trained	59.3	14.7	4	HIIT	Yes	Rowing	2.0
Dunham et al. [39]	RCT	1	8	20.2	2.1	B	Active	33.3	5.7	4	HIIT	No	Cycling	8.0
Esfarjani et al. [40]	CT	1	6	19.0	2.0	M	Trained	51.3	2.4	10	HIIT	Yes	Running	3.0
Esfarjani et al. [40]	CT	2	6	19.0	2.0	M	Trained	51.7	3.4	10	SIT	Yes	Running	3.0
Granata et al. [41]	RCT	1	11	20.5	1.4	M	Active	45.1	7.2	4	HIIT	No	Cycling	20.0
Granata et al. [41]	RCT	2	9	21.3	2.6	M	Active	47.1	3.8	4	SIT	No	Cycling	20.0
Gross et al. [42]	CT	1	7	21.7	3.9	M	Trained	67.0	8.4	3	HIIT	No	Cycling	5.0
Gross et al. [42]	CT	2	4	20.5	2.4	M	Trained	70.4	7.6	3	HIIT	No	Cycling	5.0
Gross et al. [42]	CT	3	2	22.5	2.1	F	Trained	44.8	1.7	3	HIIT	No	Cycling	5.0
Gross et al. [42]	CT	4	2	20.5	0.7	F	Trained	45.5	2.9	3	HIIT	No	Cycling	5.0
Hazell et al. [43]	CT	1	10	24.0	3.2	M	Active	50.4	8.0	2	SIT	No	Cycling	5.0
Hazell et al. [43]	CT	2	9	24.0	3.2	M	Active	49.0	5.1	2	SIT	No	Cycling	5.0
Hazell et al. [43]	CT	3	10	24.0	3.2	M	Active	50.7	6.0	2	SIT	No	Cycling	5.0
Hazell et al. [43]	CT	4	3	24.0	3.2	F	Active	42.5	3.5	2	SIT	No	Cycling	5.0
Hazell et al. [43]	CT	5	4	24.0	3.2	F	Active	42.2	2.3	2	SIT	No	Cycling	5.0
Hazell et al. [43]	CT	6	3	24.0	3.2	F	Active	41.7	7.4	2	SIT	No	Cycling	5.0
Inoue et al. [44]	RCT	1	7	34.0	6.7	M	Trained	63.1	4.2	6	HIIT	Yes	Cycling	40.0
Inoue et al. [44]	RCT	2	9	30.6	6.3	M	Trained	60.6	4.3	6	SIT	Yes	Cycling	40.0
Kavaliauskas et al. [45]	CT	1	8	21.0	1.0	F	Inactive	31.8	3.5	4	SIT	No	Cycling	10.0
Koral et al. [46]	NCT	1	12	21.3	3.4	M	Trained	58.1	3.9	2	SIT	No	Running	3.0
Koral et al. [46]	NCT	2	4	23.3	3.5	F	Trained	47.9	3.3	2	SIT	No	Running	3.0
Laursen et al. [47]	CT	1	8	26.5	6.9	M	Trained	65.6	6.5	4	HIIT	No	Cycling	40.0

Table 1 (continued)

Study	Study design	Participant characteristics								Intervention			Outcome	
		Group	n	Age (years)		Sex	Training status	VO_{2max} ($mL \cdot kg^{-1} \cdot min^{-1}$)		Weeks	Interval type	LICT	TT mode	TT distance (km)
				Mean	SD			Mean	SD					
Laursen et al. [47]	CT	2	9	24.6	7.0	M	Trained	66.4	4.5	4	HIIT	No	Cycling	40.0
Laursen et al. [47]	CT	3	10	25.0	5.8	M	Trained	63.7	3.8	4	SIT	No	Cycling	40.0
Lindsay et al. [48]	NCT	1	8	25.0	3.4	M	Trained	65.7	5.1	4	HIIT	Yes	Cycling	40.0
Macpherson et al. [49]	CT	1	6	24.3	3.3	M	Active	49.8	4.2	6	SIT	No	Running	2.0
Macpherson et al. [49]	CT	2	4	24.3	3.3	F	Active	42.4	2.6	6	SIT	No	Running	2.0
McKie et al. [50]	RCT	1	6	21.0	1.7	M	Active	50.1	6.8	4	SIT	No	Running	5.0
McKie et al. [50]	RCT	2	7	20.4	1.9	M	Active	51.0	4.5	4	SIT	No	Running	5.0
McKie et al. [50]	RCT	3	7	19.4	1.1	M	Active	49.4	5.1	4	SIT	No	Running	5.0
McKie et al. [50]	RCT	4	5	21.0	1.7	F	Active	39.7	4.3	4	SIT	No	Running	5.0
McKie et al. [50]	RCT	5	4	20.4	1.9	F	Active	44.3	5.7	4	SIT	No	Running	5.0
McKie et al. [50]	RCT	6	5	19.4	1.1	F	Active	39.5	3.1	4	SIT	No	Running	5.0
Ní Chéilleachair et al. [51]	RCT	1	7	21.6	4.7	M	Trained	59.5	8.1	8	HIIT	Yes	Rowing	2.0
Ní Chéilleachair et al. [51]	RCT	2	2	26.5	3.5	F	Trained	43.9	3.7	8	HIIT	Yes	Rowing	2.0
Scalzo et al. [52]	NCT	1	11	22.0	3.3	M	Active	43.6	5.5	3	HIIT	No	Cycling	40.0
Scalzo et al. [52]	NCT	2	10	23.0	3.2	F	Active	39.3	5.2	3	SIT	No	Cycling	40.0
Siahkouhian et al. [53]	NCT	1	12	19.4	1.0	M	Active	53.5	4.6	8	SIT	No	Running	3.0
Siahkouhian et al. [53]	NCT	2	12	19.1	1.0	M	Inactive	41.0	2.6	8	SIT	No	Running	3.0
Smith et al. [54]	RCT	1	9	25.2	6.8	M	Trained	60.5	4.8	4	HIIT	Yes	Running	3.0
Smith et al. [54]	RCT	1	9	25.2	6.8	M	Trained	60.5	4.8	4	HIIT	Yes	Running	5.0
Smith et al. [54]	RCT	2	9	25.2	6.8	M	Trained	60.1	1.8	4	HIIT	Yes	Running	3.0
Smith et al. [54]	RCT	2	9	25.2	6.8	M	Trained	60.1	1.8	4	HIIT	Yes	Running	5.0
Stepto et al. [55]	RCT	1	3	24.0	5.0	M	Trained	62.9	17.1	3	HIIT	Yes	Cycling	40.0
Stepto et al. [55]	RCT	2	4	28.0	1.0	M	Trained	69.9	6.8	3	HIIT	Yes	Cycling	40.0
Stepto et al. [55]	RCT	3	4	27.0	7.0	M	Trained	61.3	3.8	3	HIIT	Yes	Cycling	40.0
Stepto et al. [55]	RCT	5	4	26.0	4.0	M	Trained	60.3	5.1	3	HIIT	Yes	Cycling	40.0
Stevens et al. [56]	CT	1	8	20.0	2.0	M	Trained	61.4	7.4	4	SIT	Yes	Rowing	2.0
Swart et al. [57]	RCT	1	6	30.0	8.0	M	Trained	60.0	7.0	4	SIT	Yes	Cycling	40.0
Swart et al. [57]	RCT	2	6	30.0	5.0	M	Trained	60.0	4.0	4	HIIT	Yes	Cycling	40.0
Westgarth-Taylor et al. [58]	NCT	1	8	25.0	4.0	M	Trained	n/a	n/a	6	HIIT	Yes	Cycling	40.0
Weston et al. [59]	NCT	1	6	22.5	3.0	M	Trained	66.2	2.6	4	HIIT	No	Cycling	40.0
Willoughby et al. [60]	NCT	1	7	22.9	3.1	M	Inactive	40.5	4.8	4	HIIT	No	Running	2.0
Willoughby et al. [60]	NCT	2	5	44.7	2.7	M	Inactive	39.5	5.8	4	SIT	No	Running	2.0

Table 1 (continued)

Study	Study design	Participant characteristics								Intervention			Outcome	
		Group	*n*	Age (years)		Sex	Training status	VO_{2max} (mL·kg^{-1}·min^{-1})		Weeks	Interval type	LICT	TT mode	TT distance (km)
				Mean	SD			Mean	SD					
Willoughby et al. [60]	NCT	3	7	22.9	3.1	F	Inactive	36.2	5.2	4	SIT	No	Running	2.0
Willoughby et al. [60]	NCT	4	9	44.7	2.7	F	Inactive	32.4	4.6	4	SIT	No	Running	2.0

B both, *CT* controlled trial, *F* female , *HIIT* high-intensity interval training, *LICT* low-intensity continuous training, *M* male, VO_{2max} maximal oxygen consumption, *NCT* non-controlled trial, *n/a* not available, *RCT* randomized controlled trial, *SIT* sprint interval training, *TT* time-trial

showed improvements in TT performance with values ranging from -2.3% to 10.9% (Table 5).

3.5 Synthesis of Results

3.5.1 Baseline Characteristics

3.5.1.1 Sex There was no evidence that sex influenced the change in TT performance following HIIT (WMD = 0.1%; 95% CI − 0.9 to 1.0, p = 0.904) or SIT (WMD = 0.9%; 95% CI − 0.7 to 2.5, p = 0.270) (Fig. 2).

3.5.1.2 Training Status Training status played a substantial role in the percentage improvement in TT performance following HIIT, with active individuals demonstrating a 2.0% (95% CI 0.6–3.4, p = 0.006) greater improvement in TT performance compared to trained individuals (Fig. 3). Training status also influenced changes in TT performance with SIT. Participants classified as inactive had a 2.6% (95% CI 1.1–4.1, p = 0.001) greater improvement in TT performance compared to active individuals and a 3.4% (95% CI 1.8–4.9, $p < 0.001$) greater improvement compared to trained individuals (Fig. 4).

3.5.1.3 Age There was evidence that age influenced the change in TT performance following HIIT (β = − 0.13, 95% CI − 0.24 to − 0.03, p = 0.012). When participants were grouped by training status age was no longer a predictor of change in TT performance. There was no influence of age on change in TT performance following SIT (β = 0.11, 95% CI − 0.07 to 0.28, p = 0.247).

3.5.1.4 Baseline Maximal Oxygen Consumption The evidence suggests that baseline VO_{2max} did not influence the change in TT performance following HIIT (β = -0.04, 95% CI − 0.11 to 0.02, p = 0.157). Baseline VO_{2max} was shown to affect how individuals responded to SIT (β = -0.12, 95% CI − 0.19 to − 0.05, $p < 0.001$). However, when individuals were grouped by training status, baseline VO_{2max} no longer influenced change in TT performance.

3.5.2 Training Characteristics

3.5.2.1 Training Mode There was no evidence that training mode influenced the change in TT performance following HIIT. Training mode appeared to affect how individuals responded to SIT ($p < 0.001$). The effect of training mode following SIT was dependent on training status. There was no effect in inactive individuals (p = 0.757). In active individuals, running led to a 1.7% (95% CI 0.5–2.9, p = 0.005) greater improvement in TT performance compared to cycling. In trained individuals, cycling and running led to a significantly greater improvement in TT performance com-

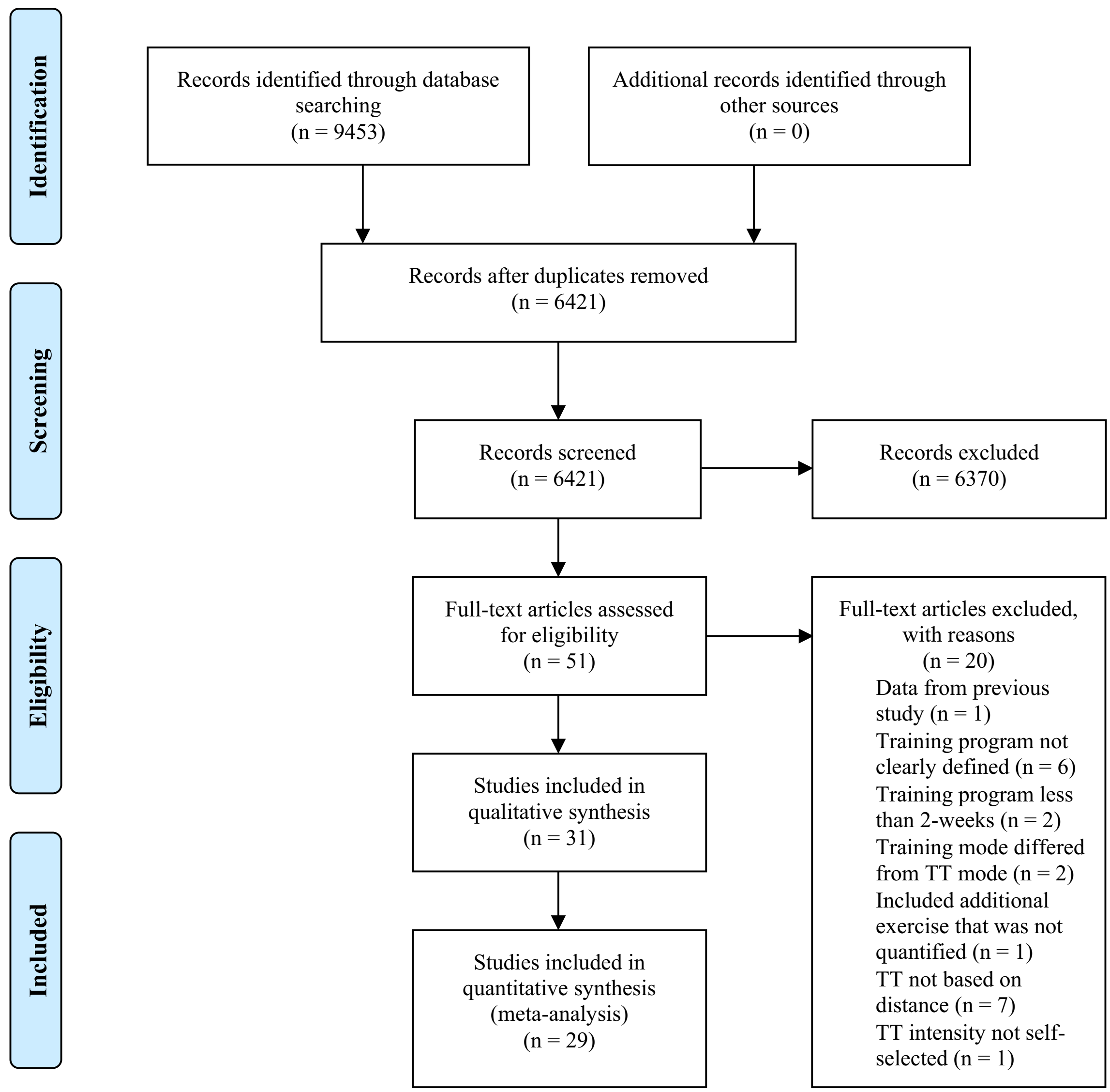

Fig. 1 PRISMA flow diagram

pared to rowing, by 2.0% ($p < 0.001$) and 3.2% ($p < 0.001$), respectively. There was a non-significant difference between running and cycling in trained individuals (1.2%, 95% CI − 0.2 to 2.6, $p = 0.094$).

3.5.2.2 Interval Work-Bout There was no effect of training intensity on change in TT performance following HIIT (Fig. 5). Since participants in the SIT groups were routinely told to exercise at their maximal or all-out effort, the power output was used to set intensity and therefore was not used as a modifier.

There was no effect of work-bout duration on change in TT performance following HIIT ($\beta = 0.16$, 95% CI − 0.23 to 0.54, $p = 0.425$) or SIT ($\beta = -1.24$, 95% CI − 5.43 to 2.95, $p = 0.561$). When HIIT studies were grouped by training status, there was a significant effect for trained participants ($\beta = 0.37$, 95% CI 0.06–0.69, $p = 0.019$) indicating that HIIT intervals of longer duration would lead to greater improvements in TT performance (Fig. 6). There was a correlation ($r = 0.53$, $p = 0.002$) between HIIT work-bout intensity and work-bout duration among the HIIT groups.

3.5.2.3 Interval Recovery-Bout There was no influence of recovery-bout mode (active versus passive) following HIIT (0.8%, 95% CI − 1.0 to 1.8, $p = 0.543$) or SIT (0.6, 95% CI − 0.7 to 2.2, $p = 0.296$). When studies were grouped by training status, SIT with passive recovery produced a 2.6% (95% CI 0.9–4.4, $p = 0.003$) greater improvement than SIT

Table 2 High-intensity interval training program description

Study	Group	Exercise mode	Sessions per week	Interval repetitions	Work-bout intensity (%W_{max} / %V_{max})	Work-bout duration (min)	Recovery-bout mode	Recovery-bout duration (min)	Total session work duration (min)	Training duration (weeks)	Total session work (a.u.)	Total sessions	Total work (a.u.)
Akca et al. [32]	1	Rowing	2	8	75	2.5	Active	3.0	20	4	1492	8	11,938
Astorino et al. [33]	1	Cycling	3	9	90	1.0	Active	1.3	9	3	809	9	7284
Astorino et al. [33]	2	Cycling	3	9	90	1.0	Active	1.3	9	3	809	9	7284
Capostagno et al. [34]	1	Cycling	2	20	96	1.0	Active	2.0	20	2	1915	4	7659
Capostagno et al. [34]	2	Cycling	2	20	97	1.0	Active	2.0	20	2	1932	4	7726
Denadai et al. [35]	2	Running	2	5	88	4.8	Active	4.8	24	4	2112	8	16,893
Denadai et al. [35]	1	Running	2	4	82	5.5	Active	2.8	22	4	1799	8	14,388
Denadai et al. [35]	2	Running	2	5	88	4.8	Active	4.8	24	4	2112	8	16,893
Driller et al. [38]	1	Rowing	2	8	75	2.5	Active	5.0	20	4	1492	7	10,446
Dunham et al. [39]	1	Cycling	3	5	90	1.0	Active	3.0	5	4	450	12	5400
Esfarjani et al. [40]	1	Running	2	7	85	3.3	Active	3.3	21	10	1814	20	36,277
Granata et al. [41]	1	Cycling	3	6	73	4.0	Active	2.0	22	4	1607	12	19,283
Gross et al. [42]	1	Cycling	3	8	100	2.5	Active	4.0	20	3	2000	9	18,000
Gross et al. [42]	2	Cycling	3	8	100	2.5	Active	4.0	20	3	2000	9	18,000
Gross et al. [42]	3	Cycling	3	8	100	2.5	Active	4.0	20	3	2000	9	18,000
Gross et al. [42]	4	Cycling	3	8	100	2.5	Active	4.0	20	3	2000	9	18,000
Inoue et al. [44]	1	Cycling	3	6	n/a	4.7	Active	4.0	30	6	n/a	17	n/a
Laursen et al. [47]	1	Cycling	2	8	100	2.4	Passive	4.8	19	4	1920	8	15,360
Laursen et al. [47]	2	Cycling	2	8	100	2.6	Passive	4.0	21	4	2080	8	16,640

Table 2 (continued)

Study	Group	Exercise mode	Sessions per week	Interval repetitions	Work-bout intensity (% W_{max} / % V_{max})	Work-bout duration (min)	Recovery-bout mode	Recovery-bout duration (min)	Total session work duration (min)	Training duration (weeks)	Total session work (a.u.)	Total sessions	Total work (a.u.)
Lindsay et al. [48]	1	Cycling	2	7	77	5.0	Active	1.0	35	4	2689	6	16,137
Ní Chéilleachair et al. [51]	1	Rowing	2	7	83	3.0	Active	5.0	22	8	1803	16	28,851
Ní Chéilleachair et al. [51]	2	Rowing	2	7	83	3.0	Active	5.0	22	8	1803	16	28,851
Smith et al. [54]	1	Running	2	6	95	2.2	Passive	4.4	13	4	1249	8	9994
Smith et al. [54]	1	Running	2	6	95	2.2	Passive	4.4	13	4	1249	8	9994
Smith et al. [54]	2	Running	2	5	93	2.6	Passive	5.2	13	4	1203	8	9621
Smith et al. [54]	2	Running	2	5	93	2.6	Passive	5.2	13	4	1203	8	9621
Stepto et al. [55]	1	Cycling	2	12	100	1.0	Active	4.0	12	3	1200	6	7200
Stepto et al. [55]	2	Cycling	2	12	85	2.0	Active	3.0	24	3	2043	6	12,259
Stepto et al. [55]	3	Cycling	2	8	85	4.0	Active	1.5	32	3	2720	6	16,320
Swart et al. [57]	1	Cycling	2	8	80	4.0	Active	1.5	32	4	2560	8	20,480
Swart et al. [57]	2	Cycling	2	8	78	4.0	Active	1.5	32	4	2496	8	19,968
Westgarth-Taylor et al. [58]	1	Cycling	2	8	85	5.0	Both	1.0	38	6	3194	12	38,324
Weston et al. [59]	1	Cycling	2	7	76	5.0	Active	1.0	35	4	2674	6	16,043

a.u. arbitrary units, V_{max} maximal velocity, W_{max} maximal wattage, *n/a* not available

Table 3 Sprint interval training program description

Study	Group	Exercise mode	Sessions per week	Interval repetitions	Work-bout intensity ($\%W_{max}/\%V_{max}$)	Work-bout duration (min)	Recovery-bout mode	Recovery-bout duration (min)	Total session work duration (min)	Total sessions	Total work duration (min)
Akca et al. [32]	2	Rowing	2	10	124	0.50	Active	4.0	5.0	8	40
Denham et al. [36]	1	Running	3	6	Maximal effort	0.50	Passive	4.0	2.8	12	33
Dolgener et al. [37]	1	Running	3	10	Maximal effort	0.50	Active	2.0	5.0	18	90
Esfarjani et al. [40]	2	Running	2	10	111	0.50	Active	4.5	4.8	20	95
Granata et al. [41]	2	Cycling	3	7	Maximal effort	0.50	Passive	4.0	3.3	12	40
Hazell et al. [43]	1	Cycling	3	5	Maximal effort	0.50	Active	4.0	2.5	6	15
Hazell et al. [43]	2	Cycling	3	5	Maximal effort	0.17	Active	4.0	0.9	6	5
Hazell et al. [43]	3	Cycling	3	5	Maximal effort	0.17	Active	2.0	0.9	6	5
Hazell et al. [43]	4	Cycling	3	5	Maximal effort	0.50	Active	4.0	2.5	6	15
Hazell et al. [43]	5	Cycling	3	5	Maximal effort	0.17	Active	4.0	0.9	6	5
Hazell et al. [43]	6	Cycling	3	5	Maximal effort	0.17	Active	2.0	0.9	6	5
Inoue et al. [44]	2	Cycling	3	8	Maximal effort	0.50	Active	4.0	3.8	17	65
Kavaliauskas et al. [45]	1	Cycling	2	4	Maximal effort	0.50	Active	4.0	2.0	8	16
Koral et al. [46]	1	Running	3	5	Maximal effort	0.50	Passive	4.0	2.7	6	16
Koral et al. [46]	2	Running	3	5	Maximal effort	0.50	Passive	4.0	2.7	6	16
Laursen et al. [47]	3	Cycling	2	12	175	0.50	Passive	4.5	6.0	8	48
Macpherson et al. [49]	1	Running	3	5	Maximal effort	0.50	Active	4.0	2.5	18	45
Macpherson et al. [49]	2	Running	3	5	Maximal effort	0.50	Active	4.0	2.5	18	45
McKie et al. [50]	1	Running	3	5	Maximal effort	0.50	Passive	4.0	2.6	12	32
McKie et al. [50]	2	Running	3	11	Maximal effort	0.25	Passive	2.0	2.6	12	32
McKie et al. [50]	3	Running	3	32	Maximal effort	0.08	Passive	0.7	2.6	12	31
McKie et al. [50]	4	Running	3	5	Maximal effort	0.50	Passive	4.0	2.6	12	32
McKie et al. [50]	5	Running	3	11	Maximal effort	0.25	Passive	2.0	2.6	12	32
McKie et al. [50]	6	Running	3	32	Maximal effort	0.08	Passive	0.7	2.6	12	31
Scalzo et al. [52]	1	Cycling	3	6	Maximal effort	0.50	Active	4.0	3.0	9	27
Scalzo et al. [52]	2	Cycling	3	6	Maximal effort	0.50	Active	4.0	3.0	9	27
Siahkouhian et al. [53]	1	Running	3	7	Maximal effort	0.50	Passive	4.0	3.7	24	88
Siahkouhian et al. [53]	2	Running	3	7	Maximal effort	0.50	Passive	4.0	3.7	24	88
Stepto et al. [55]	5	Cycling	2	12	175	0.50	Active	4.5	6.0	6	36
Stevens et al. [56]	1	Rowing	3	5	Maximal effort	1.00	Active	3.3	5.0	10	50
Willoughby et al. [60]	1	Running	3	5	Maximal effort	0.50	Active	4.0	2.7	12	32
Willoughby et al. [60]	2	Running	3	5	Maximal effort	0.50	Active	4.0	2.7	12	32
Willoughby et al. [60]	3	Running	3	5	Maximal effort	0.50	Active	4.0	2.7	12	32
Willoughby et al. [60]	4	Running	3	5	Maximal effort	0.50	Active	4.0	2.7	12	32

V_{max} maximal velocity, W_{max} maximal wattage, *n/a* not available

Table 4 Risk of bias of individual studies

	Random sequence generation	Allocation concealment	Blinding of participants and personnel	Blinding of outcome assessment	Incomplete outcome data	Selective reporting bias
Akca et al. [32]	+	?	–	–	?	–
Astorino et al. [33]	–	?	–	–	+	+
Capostagno et al. [34]	+	?	–	–	+	+
Denadai et al. [35]	+	?	–	–	+	–
Denham et al. [36]	–	?	–	–	?	–
Dolgener et al. [37]	+	?	–	–	?	–
Driller et al. [38]	+	?	–	–	+	+
Dunham et al. [39]	+	?	–	–	+	+
Esfarjani et al. [40]	–	?	–	–	+	–
Granata et al. [41]	+	?	–	–	+	+
Gross et al. [42]	–	?	–	–	+	+
Hazell et al. [43]	–	?	–	–	?	+
Innoue et al. [44]	+	+	–	–	+	+
Kavaliauskas et al. [45]	–	?	–	–	+	+
Koral et al. [46]	–	–	–	–	+	+
Laursen et al. [47]	–	?	–	–	+	+
Lindsay et al. [48]	–	–	–	–	–	–
Macpherson et al. [49]	–	?	–	–	+	+
McKie et al. [50]	+	?	–	–	+	+
Ní Chéilleachair et al. [51]	+	?	–	–	+	+
Scalzo et al. [52]	–	–	–	–	+	+
Siahkouhian et al. [53]	–	–	–	–	?	+
Smith et al. [54]	+	?	–	–	?	+
Stepto et al. [55]	+	?	–	–	+	+
Stevens et al. [56]	–	?	–	–	?	–
Swart et al. [57]	+	?	–	–	+	–
Westgarth-Taylor et al. [58]	–	–	–	–	+	–
Weston et al. [59]	–	–	–	–	+	+
Willoughby et al. [60]	–	–	–	–	+	+

High risk of bias (–), low risk of bias (+), unclear risk of bias (?)

with active recovery in trained individuals. However, 4 of the 5 groups that performed active recovery also included rowing as the training mode. Therefore, it would be difficult to determine which modifier, recovery mode or training mode, affected the results.

There was no impact of recovery duration following HIIT ($\beta = -0.08$, 95% CI -0.47 to 0.33, $p = 0.698$) or SIT ($\beta = 0.05$, 95% CI -0.83 to 0.93, $p = 0.909$. When considering training status, active individuals demonstrated a greater improvement in TT performance following longer duration recovery bouts with HIIT ($\beta = 2.30$, 95% CI 1.49–3.11, $p < 0.001$).

There was no influence of rest-to-work ratio following HIIT ($\beta = -0.29$, 95% CI -0.90 to 0.32, $p = 0.350$) or SIT ($\beta = -0.04$, 95% CI -0.26 to 0.19, $p = 0.751$). When separated by training status, recovery-bout duration influenced the training response to HIIT in trained individuals with optimal recovery duration equalling approximately 50% of the work-bout ($\beta = -0.63$, 95% CI -1.13 to -0.14, $p = 0.012$).

3.5.2.4 Interval Repetitions There was a decrement in performance by 1.0% ($\beta = -0.97$, 95% CI -1.32 to -0.62, $p < 0.001$) in active individuals and by 0.2% ($\beta = -0.14$, 95% CI -0.24 to -0.04, $p = 0.006$) in trained individuals for every additional interval repetition after the first 5 repetitions following HIIT. There was no effect of number of interval repetitions following SIT ($\beta = -0.03$, 95% CI -0.18 to 0.12, $p = 0.709$), regardless of training status (Fig. 7). There was a moderate correlation between HIIT interval repetitions and interval work-bout duration in trained individuals ($r = 0.62$, $p < 0.001$). There was no correlation between

Table 5 Time-trial results

Study	Group	*n*	Sex	Time-trial		Baseline		Follow up		Delta	
				Mode	Distance (km)	Time (s)	SD	Time (s)	SD	Time (sec)	SD
Akca et al. [32]	1	10	M	Rowing	2.0	411.60	7.50	406.60	7.00	– 5.0	4.9
Akca et al. [32]	2	10	M	Rowing	2.0	412.00	7.70	406.30	7.10	– 5.7	5.5
Astorino et al. [33]	1	3	M	Cycling	8.0	835.33	46.61	817.33	34.50	– 18.0	13.9
Astorino et al. [33]	2	11	F	Cycling	8.0	963.75	63.14	939.14	65.18	– 24.6	22.4
Capostagno et al. [34]	1	8	M	Cycling	40.0	3870.00	65.40	3865.20	30.00	– 4.8	27.0
Capostagno et al. [34]	2	7	M	Cycling	40.0	3988.80	76.80	3960.00	150.60	– 28.8	25.2
Denadai et al. [35]	2	8	M	Running	1.5	270.70	8.70	265.50	8.40	– 5.2	6.2
Denadai et al. [35]	1	9	M	Running	5.0	1001.00	61.80	986.00	56.90	– 15.0	19.5
Denadai et al. [35]	2	8	M	Running	5.0	994.70	44.80	981.00	39.60	– 13.7	16.4
Denham et al. [36]	1	20	M	Running	5.0	1464.00	298.00	1368.00	270.00	– 96.0	110.6
Dolgener et al. [37]	1	7	M	Running	1.6	382.00	15.00	355.00	14.00	– 27.0	8.6
Driller et al. [38]	1	10	B	Rowing	2.0	437.00	40.00	429.00	40.00	– 8.0	3.9
Dunham et al. [39]	1	8	B	Cycling	8.0	1089.00	136.00	1003.00	104.00	– 86.0	14.2
Esfarjani et al. [40]	1	6	M	Running	3.0	679.00	38.50	629.43	28.88	– 50.0	17.8
Esfarjani et al. [40]	2	6	M	Running	3.0	679.00	32.00	655.91	30.08	– 23.0	14.0
Granata et al. [41]	1	11	M	Cycling	20.0	2247.73	147.52	2138.09	90.73	– 109.6	72.6
Granata et al. [41]	2	9	M	Cycling	20.0	2162.33	143.12	2131.89	165.12	– 30.4	54.4
Gross et al. [42]	1	7	M	Cycling	5.0	466.01	32.78	455.77	29.40	– 10.2	8.6
Gross et al. [42]	2	4	M	Cycling	5.0	457.23	30.05	444.55	22.00	– 12.7	16.7
Gross et al. [42]	3	2	F	Cycling	5.0	545.30	4.24	534.05	0.07	– 11.3	4.2
Gross et al. [42]	4	2	F	Cycling	5.0	580.35	57.49	559.45	50.84	– 20.9	6.7
Hazell et al. [43]	1	10	M	Cycling	5.0	534.40	54.20	503.10	41.10	– 31.3	24.9
Hazell et al. [43]	2	9	M	Cycling	5.0	549.30	52.10	533.00	30.90	– 16.3	32.2
Hazell et al. [43]	3	10	M	Cycling	5.0	532.20	34.20	524.00	31.50	– 8.2	13.1
Hazell et al. [43]	4	3	F	Cycling	5.0	630.50	29.50	609.70	24.50	– 20.8	5.0
Hazell et al. [43]	5	4	F	Cycling	5.0	629.10	36.90	601.50	23.30	– 27.6	23.5
Hazell et al. [43]	6	3	F	Cycling	5.0	602.70	37.50	564.30	2.50	– 38.3	36.2
Inoue et al. [44]	1	7	M	Cycling	40.0	6091.00	478.00	5785.00	387.00	– 305.6	159.6
Inoue et al. [44]	2	9	M	Cycling	40.0	6143.00	446.00	5961.00	417.00	– 182.4	105.7
Kavaliauskas et al. [45]	1	8	F	Cycling	10.0	1055.00	129.00	997.00	110.00	– 58.0	42.2
Koral et al. [46]	1	12	M	Running	3.0	799.25	88.83	746.17	57.40	– 53.1	39.5
Koral et al. [46]	2	4	F	Running	3.0	1044.25	138.97	1002.00	144.34	– 42.3	12.1
Laursen et al. [47]	1	8	M	Cycling	40.0	3419.54	188.00	3255.90	211.23	– 163.6	95.6
Laursen et al. [47]	2	9	M	Cycling	40.0	3490.98	202.68	3299.81	167.26	– 191.2	75.2
Laursen et al. [47]	3	10	M	Cycling	40.0	3451.04	228.57	3304.31	162.53	– 146.7	111.2
Lindsay et al. [48]	1	8	M	Cycling	40.0	3384.00	216.00	3264.00	192.00	– 120.0	62.8
Macpherson et al. [49]	1	6	M	Running	2.0	530.60	54.70	504.30	69.40	– 26.3	29.4
Macpherson et al. [49]	2	4	F	Running	2.0	591.90	34.60	567.30	24.60	– 24.6	22.7
McKie et al. [50]	1	6	M	Running	5.0	1609.17	299.32	1434.33	157.40	– 174.8	189.4
McKie et al. [50]	2	7	M	Running	5.0	1428.86	138.93	1375.43	67.36	– 53.4	92.4
McKie et al. [50]	3	7	M	Running	5.0	1563.71	185.89	1494.29	175.38	– 69.4	111.4
McKie et al. [50]	4	5	F	Running	5.0	1687.60	191.94	1603.80	178.15	– 83.8	25.4
McKie et al. [50]	5	4	F	Running	5.0	1874.75	202.65	1815.25	184.64	– 56.5	81.9
McKie et al. [50]	6	5	F	Running	5.0	1741.40	239.04	1672.80	217.47	– 68.6	60.9
Ní Chéilleachair et al. [51]	1	7	M	Rowing	2.0	396.43	9.13	389.29	6.32	– 7.1	7.2
Ní Chéilleachair et al. [51]	2	2	F	Rowing	2.0	445.00	11.31	438.50	12.02	– 6.5	0.7
Scalzo et al. [52]	1	11	M	Cycling	40.0	4980.16	747.16	4660.47	280.90	– 319.7	703.7
Scalzo et al. [52]	2	10	F	Cycling	40.0	5447.26	942.66	5572.02	657.55	124.8	578.4

Table 5 (continued)

Study	Group	*n*	Sex	Time-trial		Baseline		Follow up		Delta	
				Mode	Distance (km)	Time (s)	SD	Time (s)	SD	Time (sec)	SD
Siahkouhian et al. [53]	1	12	M	Running	3.0	710.00	80.00	678.76	56.00	– 31.2	– 10.7
Siahkouhian et al. [53]	2	12	M	Running	3.0	962.50	50.50	906.68	46.46	– 55.8	– 19.0
Smith et al. [54]	1	9	M	Running	3.0	640.70	38.70	623.10	36.90	– 17.6	10.5
Smith et al. [54]	1	9	M	Running	5.0	1119.70	90.30	1094.00	67.50	– 25.7	41.4
Smith et al. [54]	2	9	M	Running	3.0	621.70	30.60	615.30	34.80	– 6.4	12.6
Smith et al. [54]	2	9	M	Running	5.0	1086.30	71.70	1082.70	64.20	– 3.6	34.8
Stepto et al. [55]	1	3	M	Cycling	40.0	3618.40	301.74	3608.20	283.03	– 10.2	25.2
Stepto et al. [55]	2	4	M	Cycling	40.0	3181.65	39.32	3138.45	105.98	– 43.2	69.5
Stepto et al. [55]	3	4	M	Cycling	40.0	3356.40	156.53	3258.75	123.88	– 97.7	49.1
Stepto et al. [55]	5	4	M	Cycling	40.0	3434.85	209.74	3354.60	165.03	– 80.3	65.9
Stevens et al. [56]	1	8	M	Rowing	2.0	414.60	18.50	410.60	17.50	– 4.0	2.1
Swart et al. [57]	1	6	M	Cycling	40.0	3914.00	151.00	3823.00	119.00	– 91.0	55.3
Swart et al. [57]	2	6	M	Cycling	40.0	3975.00	126.00	3888.00	127.00	– 87.0	52.9
Westgarth-Taylor et al. [58]	1	8	M	Cycling	40.0	3432.00	294.00	3348.00	324.00	– 84.0	100.5
Weston et al. [59]	1	6	M	Cycling	40.0	3426.00	264.00	3354.00	252.00	– 72.0	68.6
Willoughby et al. [60]	1	7	M	Running	2.0	695.70	30.39	657.40	38.44	– 32.8	19.9
Willoughby et al. [60]	2	5	M	Running	2.0	708.60	137.50	652.20	133.89	– 56.4	35.1
Willoughby et al. [60]	3	7	F	Running	2.0	806.66	194.65	746.66	163.09	– 60.0	44.6
Willoughby et al. [60]	4	9	F	Running	2.0	812.07	135.07	741.47	97.22	– 70.6	85.4

B both, *F* female , *M* male , *n/a* not available, *SD* standard deviation

A negative delta value indicates an improvement in time-trial performance and a positive delta value indicates a decrease in change in time-trial performance.

HIIT interval repetitions and total session work in trained individuals ($r = 0.07$, $p = 0.688$).

3.5.2.5 Intensity Distribution There was a 1.5% (95% CI 0.5–2.5, $p = 0.005$) greater improvement in TT performance when individuals performed three HIIT sessions per week compared to two sessions. The number of interval sessions completed per week did not influence TT performance following SIT. The individuals in the active subgroup ($n = 5$) in the HIIT studies all performed three HIIT sessions per week. This skewed the results in favour of three HIIT sessions. There were HIIT studies in the trained subgroup that included two ($n = 24$ studies) and three ($n = 9$ studies) sessions per week. The analysis of the trained subgroup indicated that there was no significant difference in TT performance when individuals completed two or three sessions (WMD = 1.0% 95% CI − 0.2 to 2.2, $p = 0.115$).

Only the trained subgroups, for both HIIT and SIT, included interventions that consisted of either interval training alone or interval training with the addition of continuous training. The results showed that there was a greater improvement in TT performance when trained individuals did not perform continuous training during the intervention period following HIIT (WMD = 1.4, 95% CI 0.3–2.4, $p = 0.009$) or SIT (WMD = 2.6%, 95% CI 0.9–4.4, $p = 0.003$). The intensity at which continuous training was performed may be relevant to this finding. However, this was not consistently reported in the included studies.

3.5.2.6 Total Work The total number of HIIT sessions had a strong influence on changes in TT performance in active ($\beta = 1.17$, 95% CI 0.55–1.79, $p < 0.001$) and trained ($\beta = 0.21$, 95% CI 0.07–0.35, $p = 0.003$) individuals. There was no relationship between the number of SIT sessions and change in TT performance ($\beta = 0.08$, 95% CI − 0.05 to 0.22, $p = 0.217$).

The number of HIIT training weeks was strongly related to improvements in TT performance in active ($\beta = 3.52$, 95% CI 1.66–5.37, $p < 0.001$) and trained ($\beta = 0.37$, 95% CI 0.67–0.01, $p = 0.014$) individuals. There was no relationship between the number of SIT training weeks and change in TT performance ($\beta = 0.11$, 95% CI − 0.27 to 0.50, $p = 0.566$). There was a strong correlation between the total number of sessions and the total number of training weeks with HIIT ($r = 0.88$, $p < 0.001$) and SIT ($r = 0.93$, $p < 0.001$).

There was no effect of total work (a.u.) on TT performance following HIIT in active individuals ($\beta = 0.03$, 95% CI − 0.46 to 0.52, $p = 0.912$). There was a positive

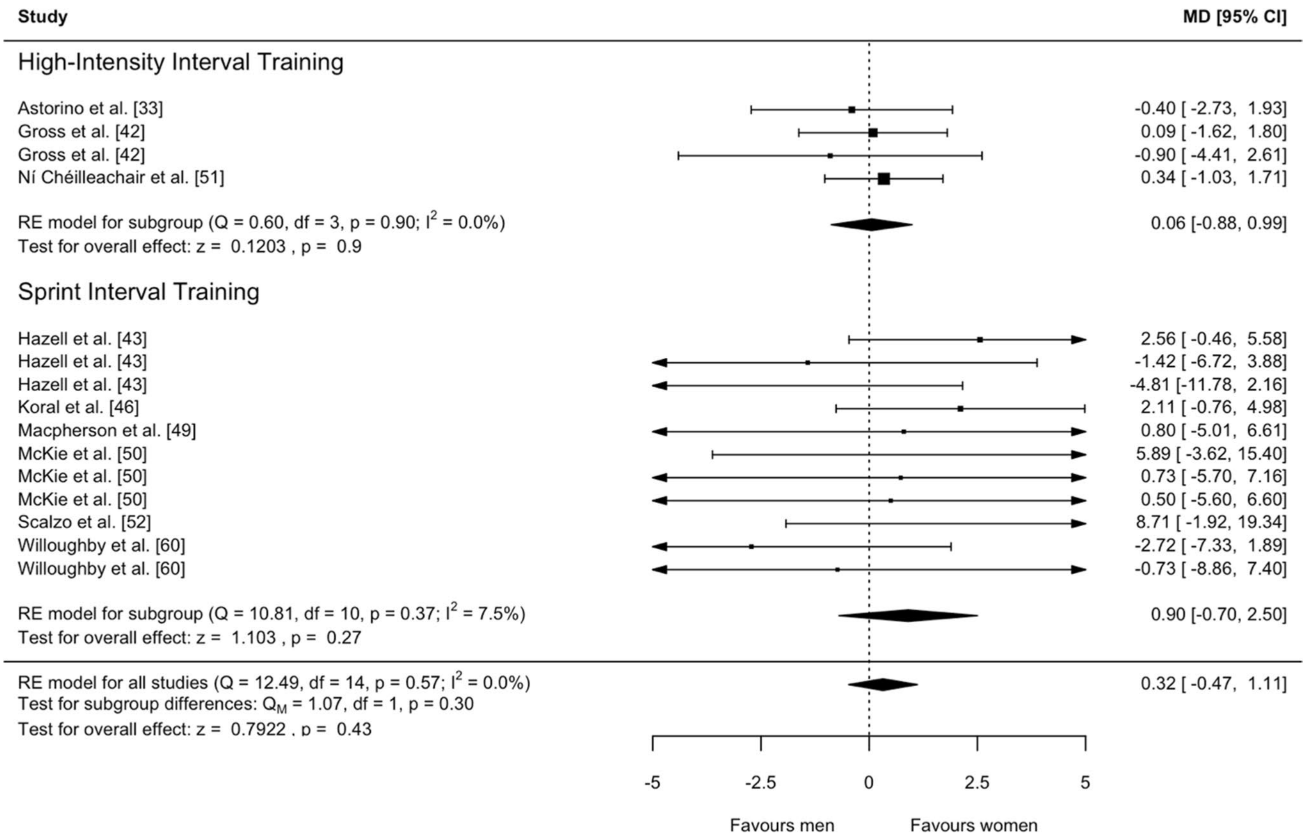

Fig. 2 Effect of sex on change in time-trial following interval training. Mean difference (MD) in percentage change in time-trial improvement between men and women. A negative effect favours men and a positive effect favours women

relationship between total work and change in TT performance in trained individuals ($\beta = 0.09$, 95% CI 0.03–0.16, $p = 0.006$). Since SIT was set to maximal perceived effort, the total work cannot be determined.

3.5.3 Time-Trial Characteristics

3.5.3.1 Distance There was no difference in TT performance, across the range of TT distances (1.5–40.0 km), following HIIT ($\beta = -0.02$, 95% CI -0.06 to 0.03, $p = 0.498$) or SIT ($\beta = -0.05$, 95% CI -0.12 to 0.02, $p = 0.144$).

3.6 Assessment of Heterogeneity and Small Study Effects

There was a high degree of heterogeneity when pooling the results from the HIIT intervention groups ($I^2 = 89.8\%$). A visual inspection of a funnel plot for the HIIT groups indicated the presence of asymmetry with the results of Egger's test suggesting the presence of small sample size bias ($p = 0.033$). When Egger's test was performed for the training status subgroups, the bias was eliminated in the active ($p = 0.174$) but not the trained ($p = 0.002$) subgroups.

There was also a high degree of statistical heterogeneity when pooling the results from the SIT interventions ($I^2 = 87.8$). There was a decrease in heterogeneity when the SIT groups were categorized by inactive ($I^2 = 0.0$), active ($I^2 = 46.0$) subgroups, but not in the trained ($I^2 = 87.5$) subgroup. The high degree of statistical heterogeneity in the trained subgroup may be explained by the presence of small sample size bias indicated by the significant results ($p < 0.001$) from Egger's test.

4 Discussion

4.1 Summary of Evidence

This systematic review and meta-analysis of interval training studies quantified the influence of individual characteristics and training variables on TT performance. Training mode (cycling, rowing, running) was shown to alter the magnitude of improvement in TT performance following an interval

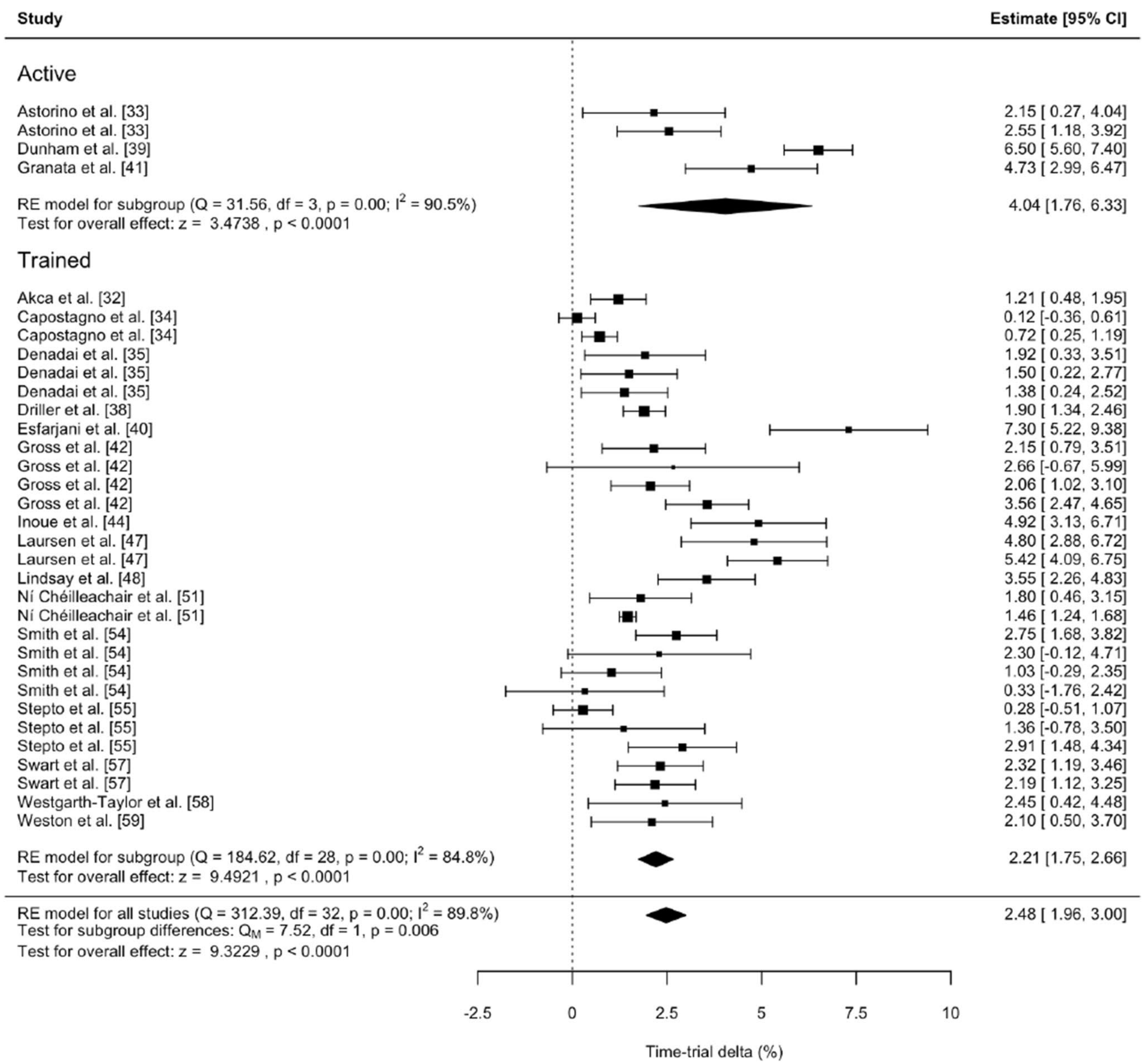

Fig. 3 Effect of training status on change in time-trial performance following high-intensity interval training. Positive change in time-trial % indicates improved performance

training program. Age, sex and baseline VO_{2max} did not influence changes in TT performance. However, a higher training status was associated with a reduced magnitude of TT change. The amount of change in TT performance with HIIT depended on the duration but not the intensity of the interval work-bout in trained individuals. There was a dose–response relationship with the number of HIIT sessions, training weeks and total work with changes in TT performance. However, there was no relationship between the number of sessions or number of weeks and change in TT performance with SIT. See Fig. 8 for a graphical representation of the key findings from the results.

4.1.1 Baseline Characteristics

4.1.1.1 Sex The pooled results of the meta-analysis showed that there are no sex-based differences in the change in TT performance (Fig. 2). These findings were consistent with the individual results of the studies included in the analysis, which found similar responses between men and women [33, 42, 43, 46, 49–51, 60, 61]. In addition to TT performance, the studies all measured change in VO_{2max} and once again there was no response difference between men and women. The similarity in responses between changes in TT performance and VO_{2max} is an important finding because it

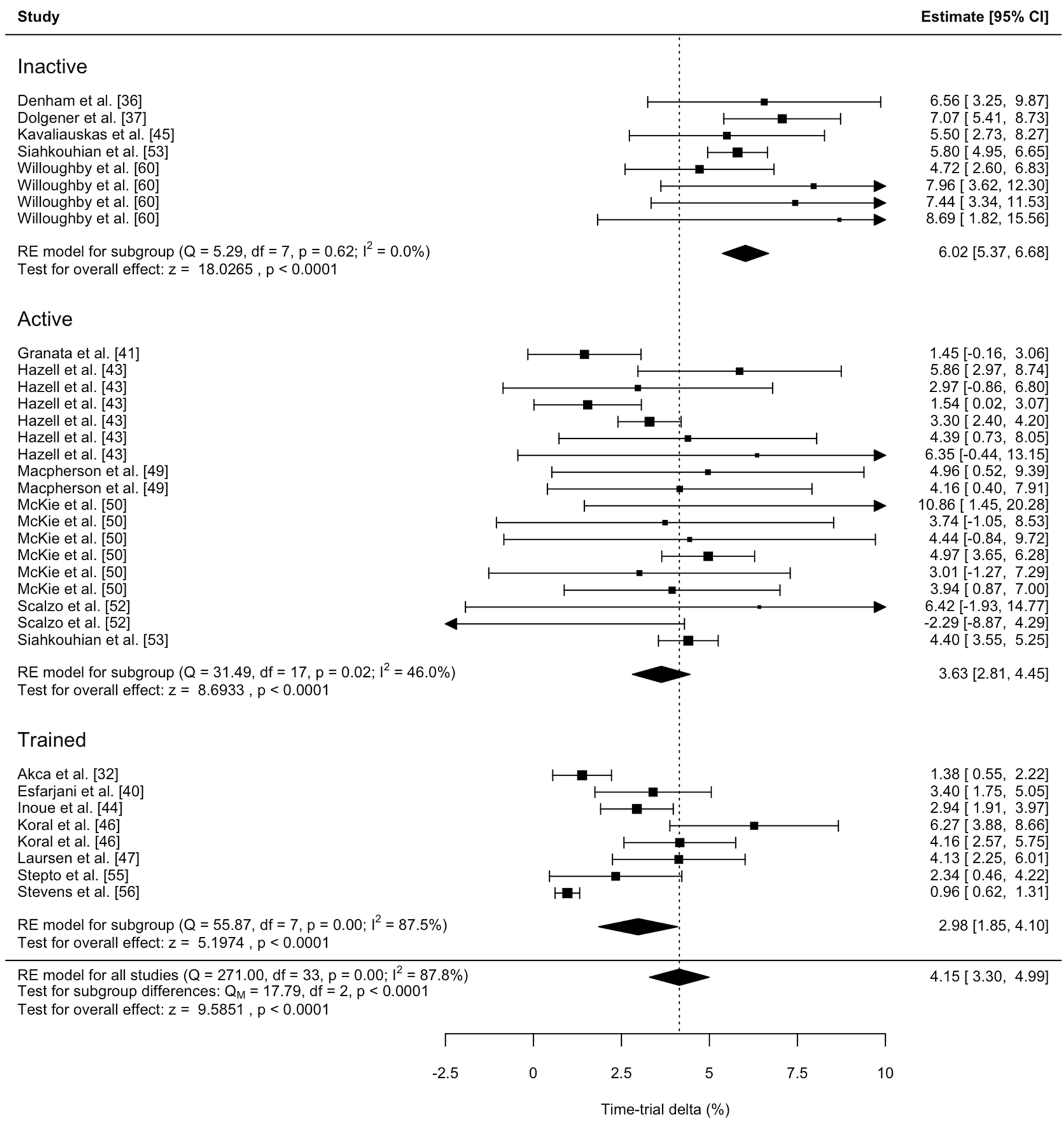

Fig. 4 Effect of training status on change in time-trial performance following sprint interval training. Positive change in time-trial % indicates improved performance

demonstrates consistency between two outcome measures that have been shown to be highly correlated [17].

While the results of the meta-analysis indicate that men and women have similar adaptive responses in TT performance, previous literature implies that there may be sex-based differences in the respective acute metabolic responses. Esbjörnsson-Liljedahl showed that women utilize as much as 42% less muscle glycogen and have lower peak lactate levels than men during SIT [62]. However, there is contradictory evidence demonstrating that peak lactate levels are similar between males and females following SIT [63]. There is also evidence of comparable responses in mitochondria biogenesis as measured by change of maximal citrate synthase activity [52]. Sex differences in acute substrate

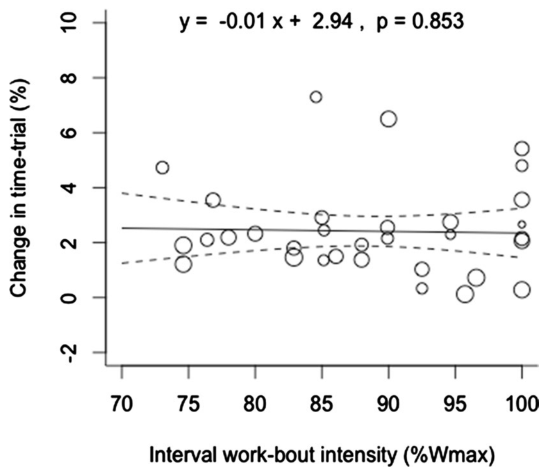

Fig. 5 Effect of high-intensity interval work-bout intensity on change in time-trial performance. Positive change in time-trial % indicates improved performance. Data points represent the individual trials included in the meta-analysis. The size of the data points is proportional to the weight that the individual trials have on the pooled effect

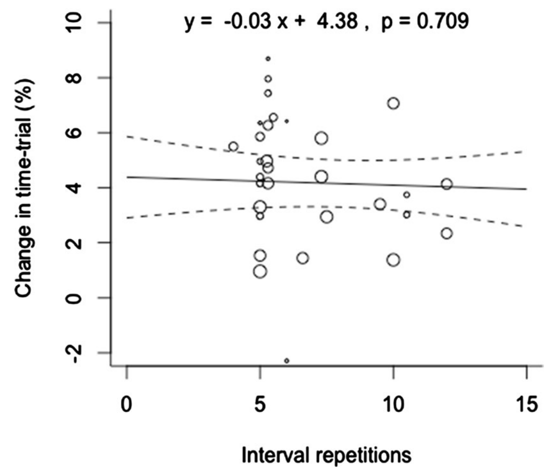

Fig. 7 Effect of sprint interval repetitions on change in time-trial performance. Positive change in time-trial % indicates improved performance. Data points represent the individual trials included in the meta-analysis. The size of the data points is proportional to the weight that the individual trials have on the pooled effect

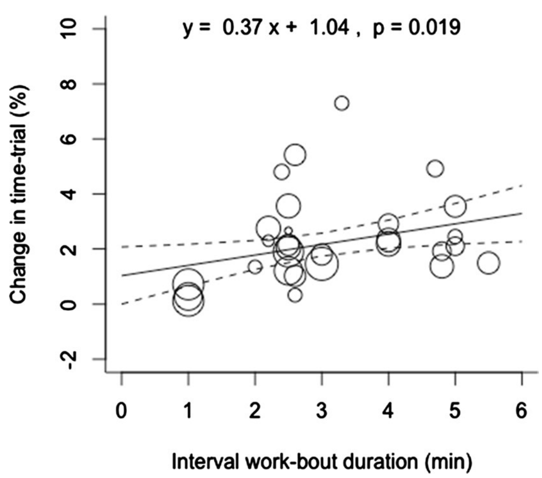

Fig. 6 Effect of high-intensity interval work-bout duration on change in time-trial performance in trained individuals. Positive change in time-trial % indicates improved performance. Data points represent the individual trials included in the meta-analysis. The size of the data points is proportional to the weight that the individual trials have on the pooled effect

utilization, specifically involving carbohydrate metabolism, may be inconsequential since the physiological and performance adaptations appear to be similar between sexes.

4.1.1.2 Training Status Training status was shown to be the only baseline characteristic that had an impact on changes in TT performance. Improvements ranged from approximately 2% in trained individuals up to 6% in inactive individuals (Figs. 3, 4). A separate meta-analysis conducted by Weston et al. found a similar trend with training status influencing change in VO_{2max} [64]. Our review and the review by Weston et al. did not include studies that performed direct comparisons of training status. The study by Støren et al., which did perform a direct comparison, determined that there was a significant correlation between training status and change in VO_{2max}. This result further supports the impact of previous training status on changes in endurance performance [65].

There are metabolic and physiological differences among individuals of different training status. Hetlelid et al. found that well-trained runners were able to oxidize fatty acids at a rate that was approximately three times greater than that found in recreationally trained runners while exercising at the same relative intensity [66]. Well-trained athletes were also shown to have higher thresholds relative to their VO_{2max} compared to recreational athletes, with VT_2 occurring at 90% versus 83%, respectively. These results suggest that well-trained athletes not only have higher thresholds, but that the thresholds may be approaching their adaptive limits. The greater improvement in TT performance in the inactive and active individuals in the current analysis may be as a result of having lower physiological starting points, leaving more room for overall improvement.

4.1.1.3 Age Age, over the observed range, did not influence the change in TT performance following HIIT or SIT. Only one study included in the meta-analysis directly compared individuals of different age ranges. Willoughby et al. examined the effects of SIT in younger (ages 20–30 years) and older (ages 30–50 years) males and observed no age difference in the change in TT performance or VO_{2max} [60].

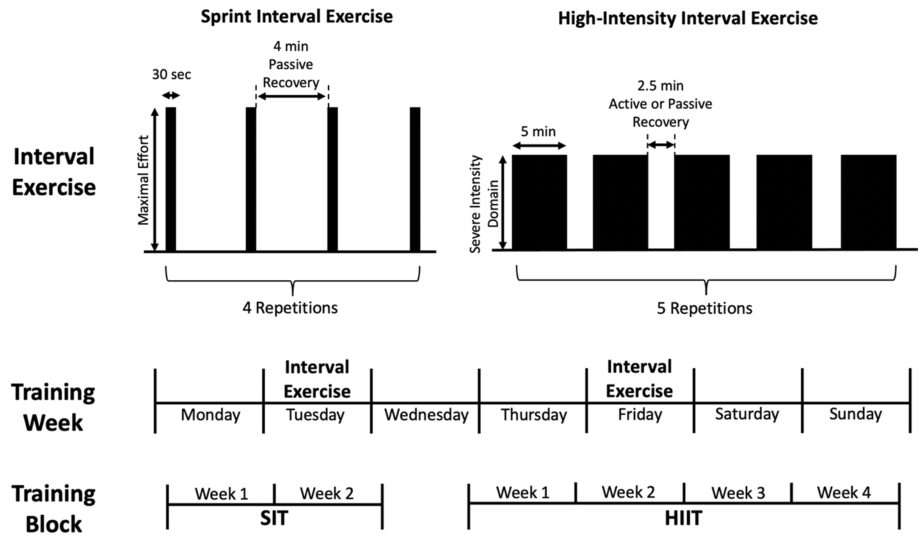

Fig. 8 Programming interval training to optimize time-trial performance in trained individuals. *HIIT* high-intensity interval training, *SIT* sprint interval training

These findings were consistent with a larger study ($n = 94$) by Støren et al. which also found no difference in the VO_{2max} adaptation following HIIT [65]. Notably, there is one study that found that when matched for baseline VO_{2max}, younger individuals can experience more than double the improvement in VO_{2max} when compared to older individuals [67]. Since there is approximately a 1% decrease in VO_{2max} every year throughout adulthood [68, 69], when older individuals are matched to younger individuals by VO_{2max}, the older adults will likely see a smaller improvement in performance because they are at a higher relative training status.

4.1.1.4 Maximal Oxygen Consumption There was no influence of baseline VO_{2max} on change in TT performance following HIIT or SIT when participants were categorized by training status. An important limitation of VO_{2max} is that it does not account for individual physiological differences in other correlates of endurance performance [70]. The highest VO_2 that can be maintained at submaximal physiological thresholds may be a better marker of endurance performance. Previous literature has shown that the lactate threshold (LT) is strongly correlated with endurance performance and has been shown to be a more reliable correlate of TT performance than VO_{2max}. Coyle et al. found that cyclists with a similar VO_{2max} but a higher relative LT were 10% faster at completing a 40-km cycling TT [19].

The study by Laursen et al. included both HIIT and SIT, and incorporated measures of VT_2 as a percentage of VO_{2max} in addition to TT performance [47, 71]. The results illustrate that there is a 15% percent increase in VT_2 following HIIT interventions and only an 8.5% improvement following SIT. These results suggest that submaximal adaptations, likely leading to improved oxidative capacity, may be greater with HIIT. Baseline VO_{2max} did influence the adaptive responses of SIT implying that TT improvements following SIT are more likely related to changes in VO_{2max} as opposed to submaximal improvements as measured by VT_2 which are critical to HIIT adaptations.

4.1.2 Training Characteristics

4.1.2.1 Training Mode Training mode was only shown to be a factor in TT adaptations following SIT. Specifically, in active individuals, running led to a 1.7% (95% CI 0.5–2.9, $p < 0.005$) greater improvement in TT performance than cycling. Changes in running economy contribute to improved performance and may play a role in the differences observed between the two exercise modes. Moore et al. found that runners develop a more efficient running gait as they become more experienced runners, which leads to improved submaximal performance [72]. In addition, sport specificity has been shown to affect exercise economy with running but not with cycling. Swinnen et al. compared running and cycling economy in a group of cyclists, runners and triathletes using submaximal cycling and running performance tests [73]. They found that runners had better running economy than cyclists, but that there was no difference in cycling economy between runners and cyclists.

Rowing led to the smallest improvement in TT performance compared to cycling and running. It is currently unclear what led to the difference in performance gains. It is possible that interval training programs do not elicit the same magnitude of change in performance as shorter duration TT tests, such as a 2000-m (~6.5 min) rowing test. However, the results of the meta-analysis indicate that distance was not a factor in changes in performance. Anecdotally, varsity-level rowers have reported that the effort for each stroke is typically performed at a maximal effort. The mean power output for a 2000-m rowing TT test from the studies included in this review is approximately 80% of the maximal power achieved from the incremental test [32, 38]. The results are in fact lower than the mean power output found in cycling TT tests of similar duration. Gross et al. found that trained cyclists performed a 5-km TT (~ 7.5 min) test at approximately 85% of the power achieved from their incremental test [42].

4.1.2.2 Interval Work-Bout Exercise intensity has been described as the most important factor influencing the adaptive responses to endurance performance [74–76]. Interval training (both HIIT and SIT) leads to greater improvements in measures of cardiovascular health and fitness compared to moderate intensity continuous training (MICT) even when performed at substantially lower volumes of work [75]. However, a higher exercise intensity within a specific intensity domain (e.g. severe domain) may not lead to greater improvements in endurance sport performance. The results of this meta-analysis show that HIIT performed at any intensity produces similar improvements in TT performance (Fig. 6). These results were consistent across the different classifications of training status. Since SIT was performed at maximal effort, exercise intensity for SIT was not addressed in the analysis.

The duration of an interval work-bout is commonly discussed as another important factor that can influence adaptations in endurance performance. However, the improvements in TT performance following HIIT and SIT were found to be independent of work-bout duration. When HIIT groups were divided by training status, the results showed that there was a significant ($p < 0.02$) relationship between work-bout duration and change in TT performance in trained individuals. For every additional minute per work-bout, there is approximately a 0.5% improvement in TT performance in trained individuals. The results of the subgroup analysis show comparable findings to previous work by Rosenblat et al. [3]. They found that when compared to SIT, longer work-bout durations of HIIT produced greater improvements in TT performance than shorter work-bouts [3]. In regard to SIT, the majority of studies included 30-s work bouts. Therefore, it is difficult to make a conclusion on the influence of work-bout duration and suggests that 30-s bouts be incorporated in a training program.

There are a number of previous studies that directly compared HIIT programs differing in work-bout duration, with some studies favouring shorter intervals [77, 78] and others favouring longer intervals [55, 79, 80]. Since it takes approximately 2 min to reach peak oxygen levels [9], longer duration intervals may allow individuals to exercise at a high percentage of their VO_{2max} for a longer continuous period of time [3]. However, the studies which found that shorter intervals were more effective also included very short recovery periods between work bouts which mitigated a decline in oxygen consumption and allowed the subsequent work bout to begin at a higher oxygen consumption [77, 78]. Therefore, during longer intervals a larger portion of total oxygen uptake is consumed during locomotion and is primarily directed toward producing mechanical work. Whereas in the shorter intervals, more oxygen is consumed during recovery intervals and used for a combination of mechanical work and restoring metabolic and substrate homeostasis [81]. The significance for endurance sport performance of whether oxygen is consumed during work or during recovery has yet to be investigated.

4.1.2.3 Interval Recovery-Bout The design of the recovery-bout between interval repetitions can greatly affect the acute physiological responses and the subsequent interval bouts in the exercise session. There are conflicting viewpoints as to which recovery mode, active versus passive, leads to optimal adaptive response because of the differences in acute responses. Active recovery has been shown to decrease plasma lactate levels at a faster rate than passive recovery [82, 83]. Time spent above 90% VO_{2max} is also higher with active recovery [82, 83]. In contrast, there is evidence to suggest that passive recovery allows for greater phosphocreatine replenishment than active recovery which permits higher power output for successive interval bouts [84, 85]. Passive recovery can also lead to a greater TTE during interval training, [84, 86, 87], allowing for a greater total amount of mechanical work to be completed.

The results of this meta-analysis indicate that recovery mode only influenced the adaptive responses to TT performance in trained individuals performing SIT, suggesting that passive recovery was more beneficial. There was a difference in the active recovery training protocols among the groups. The studies that included active recovery in the trained participants used a recovery intensity that was much greater than the protocols used in the other subgroups. It is possible that the recovery intensity was too high to allow for sufficient recovery between SIT bouts. Individual preference may be the most appropriate method of choosing recovery mode as it may improve enjoyment and adherence. However, if individuals were to perform active recovery, it should be done at an intensity below 40% of MAP/MAV to optimize performance gains.

The duration of an interval recovery-bout does not influence the acute physiological responses following an interval work-bout to the same degree as recovery mode. There is no difference in peak plasma lactate levels between shorter (1 min) and longer (4 min) recovery-bouts during HIIT exercise [88–90]. However, rating of perceived exertion during intervals with shorter recovery was found to be significantly higher compared to longer recovery [89, 90]. When performing self-paced intervals, runners have faster running speeds when recovery duration is increased from 1 to 2 min [88]. A further increase from 2 to 4 min can increase runner performance in recreationally active individuals [88], but not in trained runners [89]. These results coincide with the results of the current review, which show that longer recovery duration during HIIT can lead to greater improvements in TT performance in active but not trained individuals.

Acute studies that incorporated SIT indicate that longer recovery bouts result in lower average oxygen uptake over the course of an exercise session [91]. When self-selecting recovery times during SIT, recovery duration tends to increase leading to lower levels of total oxygen consumption. However, longer recovery bouts allow participants to maintain higher speeds during successive work-bouts [92]. Acute responses in oxygen consumption may not provide an indication of the adaptive mechanisms since measures of mitochondrial respiration improve with training regardless of rest interval during SIT [93, 94]. Furthermore, the findings from the meta-analysis suggest that recovery duration does not affect the change in TT performance with SIT.

4.1.2.4 Interval Repetitions The results suggest that an increasing number of HIIT interval repetitions can negatively impact the change in TT performance. The studies that included a greater number of repetitions primarily included interval bouts that were shorter in duration (~ 1 min) [34, 55]. There was a moderate correlation between the number of HIIT interval repetitions and interval work-bout duration in trained individuals ($r = 0.62$, $p < 0.001$). As previously discussed, longer-interval work bout has been shown to be more beneficial than shorter intervals. Therefore, when taking work-bout duration into account, the number of repetitions no longer impacts change in TT performance.

SIT repetition number did not seem to influence the adaptations in performance regardless of the work-bout duration. These results conflict with the findings from a previous meta-analysis conducted by Vollaard et al. [16]. They found that there would be a 1.2% decrement in VO_{2max} for every 2 additional repetitions [16]. One potential issue with their results is that they did not consider the relationship between the number of repetitions completed in a session and baseline VO_{2max}. Further analysis of the data in the review by Vollaard et al. [16] indicated that studies in which participants performed fewer repetitions also included participants with lower baseline VO_{2max} values than those who performed more repetitions. When the results from all studies from the review by Vollaard et al. [16] were included, the analysis did not indicate that there was a significant relationship ($p = 0.077$). However, there were two outliers, which when removed from the analysis, allowed the relationship to reach significance ($\beta = 1.4$, 95% CI 0.7 to 2.1, $p < 0.001$). The results from both the review by Vollaard et al. [16] and the current review show that individuals with a lower baseline VO_{2max} improve at a greater rate than those with a higher VO_{2max}. In addition to these results, the Vollaard et al. [16] study included participants with a variety of physiological conditions, such as diabetes and obesity, making it difficult to generalize these results due to the introduction of many covariates.

4.1.2.5 Intensity Distribution The distribution of training intensity can have a significant impact on changes in TT performance. The two common models that incorporate different training intensity distributions include a threshold training intensity model and a polarized training model. A polarized training model includes approximately 75–80% of total training in the moderate domain, 5% in the heavy domain, and 15–20% above the heavy domain [95]. A threshold training model differs from the polarized model in that a much lower percentage of total training volume is completed in the moderate domain (45–55%) with a higher percentage completed in the heavy domain (35% to 55%) [95]. A systematic review with meta-analysis conducted by Rosenblat et al. compared the effects of a polarized model with a threshold model on changes in TT performance in an athletic population [14]. The results indicated that a polarized model led to a greater improvement in TT performance (SMD = − 0.66; 95% CI − 1.17 to − 0.15, $p = 0.010$).

There was no additional improvement in TT performance when participants completed more than two interval sessions per week for HIIT or SIT. Furthermore, the results suggest that the addition of continuous training to an interval training program was detrimental to TT performance. These results conflict with the study by Stöggl et al. which found that the addition of continuous training, in a polarized model, was no different than HIIT alone for improving endurance performance [96]. However, the study by Stöggl et al. used VO_{2max} as the primary measure of endurance performance whereas the outcome of interest is TT performance. Another limitation to interpreting the findings in the current review is that it was unclear if the continuous training sessions in each of the included studies were performed in the moderate intensity or heavy intensity domains. If the continuous exercise described in the studies was performed in the heavy domain, the intensity distribution would resemble a threshold model and this may have inhibited subsequent TT improvement compared to HIIT alone.

4.1.2.6 Total Work There was a strong correlation between the total number of sessions and the total number of training weeks with HIIT ($r = 0.88$, $p < 0.001$) and SIT ($r = 0.93$, $p < 0.001$). Both variables were found to influence the changes in TT performance following HIIT. However, neither total interval sessions nor total training weeks were related to changes in TT performance following SIT. Since both HIIT and SIT led to improvements in performance, but responded differently to programming variables, it is likely that they achieve adaptations through different physiological mechanisms as previously suggested. It is important to note that the majority of HIIT studies included training protocols that ranged from 2 to 4 weeks in duration. However, the few studies that did investigate longer training interventions showed even greater improvements in TT performance [40, 44, 58]. Therefore, based on the available evidence, it may be recommended to perform HIIT training programs that are at least 4 weeks in duration.

The 'all-out' short durations of SIT exercise closely simulate heavy or explosive resistance training exercise. The primary difference between resistance training and SIT is that SIT can be performed in the same exercise mode as a TT test, making it a sport-specific form of exercise. Heavy and explosive resistance exercise has been shown to improve measures of endurance sport performance by increasing VO_{2max} as well as the rate of force development [97]. A direct comparison of SIT with resistance exercise showed no difference in the improvements in VO_{2max} or submaximal exercise performance [98]. In addition, changes in force development can occur in as few as 2 weeks [99]. This is similar to the minimal timeframe observed for changes in TT performance with SIT. An increase in measures of mitochondrial biogenesis is an important adaption that occurs following SIT [75, 100]. There are mixed results regarding the ability of resistance training to produce similar responses in mitochondrial biogenesis [101].

The findings of the study by Turnes et al. may shed some light on the mechanistic differences between HIIT and SIT [102]. They compared the effects of interval training performed at the low end and upper borders of the severe domain, consisting of 5 min and 60 s all-out work bouts, respectively. Their findings showed that there were similar improvements in TT performance between the groups. However, the higher intensity, shorter interval group showed increases in peak electromyography (EMG) activity, peak power output, and mean power output during a Wingate test following training. The lower-intensity, longer-duration-interval group showed a decrease in peak EMG activity and no change in Wingate peak or mean power output. The improvements are likely from different mechanisms; however, further studies that assess acute responses during TT trials following HIIT and SIT are necessary to determine if this is the case.

4.1.3 Time-Trial Characteristics

4.1.3.1 Time-Trial Distance The theory of specificity would suggest that SIT should lead to greater improvements in shorter distance TTs and HIIT lead to greater improvements in longer distance TTs. Previous literature shows that different duration TTs utilize different percentages of aerobic and anaerobic metabolism [103]. The results of the meta-analysis show that interval training type does not influence change in performance regardless of the distance. Both forms of interval training can produce improvements in VO_{2max}, leading to improvements in both short and long distance events [3]. Two studies included in the review directly compared the effect of interval training on multiple running TTs differing in duration [35, 54]. The results of the studies found there to be no difference in TT performance between the respective interval groups. The comparisons included relatively short events ranging from 1.5 to 5 km. Therefore, further investigations that compare changes in short (~5 km) with longer (40 km) TTs following HIIT and SIT are necessary to determine if there is a causative effect of interval type on TT distance.

4.2 Limitations

The articles selected for this review included only those that were found in the initial literature search as described in the methodology. An additional search for articles that may have been missed was not conducted to minimize selection bias and to improve the reproducibility of the article selection process. As a result, it is possible that articles that meet the inclusion criteria may have been omitted from the analysis.

Many of the studies that were included in the review contained a control group, in addition to the interval training group, as a base for comparison. The analysis performed in this review was limited to the change score of the interval training groups. This may introduce a degree of bias in the interpretation of the effectiveness of the intervention. Earlier reviews have determined that interval training is either equally or more effective at improving endurance performance as compared to other forms of endurance exercise [64]. The purpose of the current review is to determine the relationship that covariates, such as baseline and training characteristics, have with change in TT performance.

There were a number of studies ($n = 15$) that were missing data for the SD of the delta scores. For this analysis, the missing values were calculated by converting the p values for the delta scores using a *t* test, as described in the methodology. This leads to a more conservative estimate of the true deviation in scores. A conversion method was also used to standardize the measures among groups in the analysis. Specifically, the delta score for TT time (sec) was converted to a percentage difference from baseline. Correlating a change score with the baseline score can increase the potential for measurement error in the initial score as a result of regression to the mean [104]. In the case of TT tests, the greatest measurement error can occur in the initial test, but decreases following a familiarization test [105]. Thirty-three of the 77 groups included a familiarization test. Therefore, it is possible for some degree of measurement error to have occurred. In addition, using group means in a meta-analysis will increase the magnitude of the measurement error. However, this is unlikely in the current meta-analysis because the difference between the percentage change of individual scores and the percentage change of the group scores was found to be less than 0.1%. This independent analysis was performed in a sample of the studies where the raw individual datum was provided by the respective authors (158 participants from 27 groups).

The results of our meta-analysis show that training status can greatly influence the adaptive responses in performance following an interval training program. There were no studies in the analysis that examined the influence of baseline and training characteristics of HIIT in inactive participants. However, there were studies that included inactive individuals following SIT. The pooled results showed that inactive individuals have a greater response to training when compared to individuals at higher training status. It is probable that there would be a similar response in inactive individuals following HIIT. Due to the differences in physiological responses between HIIT and SIT, caution should be taken when generalizing the results between the two interval types.

Many of the studies that included both males and females did not conduct a separate analysis for sex. This type of analysis was possible once the raw data were obtained from the respective authors. In many cases, separating participants by sex produced groups with very small sample sizes and subsequent results with large standard deviations. As such, it is conceivable that the results of the analysis may be skewed since the original studies were not designed to consider sex for subgroup comparisons. In cases where individual datum was not obtained ($n = 2$), the analyses were completed using the results with males and females in the same group. Given those caveats, our results suggest men and women have a similar TT response to interval training.

There was limited information about the exercise intensity for the continuous training protocols that were included in some of the studies. A combination of interval training with continuous training performed in the heavy domain, as opposed to the moderate domain, is less effective at improving VO_{2max} and TT performance [14]. Since the information regarding exercise intensity was not available for the continuous training protocols, its inclusion as a modifier in the analysis should be interpreted cautiously.

The primary outcome in the review is TT performance as measured by a change in time. The strong validity and reliability of TT tests strengthens our interpretation of the results as indicative of endurance performance [22, 23, 105, 106]. Mean power output over the course of a cycling TT test is a more reliable measure than time-to-completion when performing outdoor tests due to variability in environmental factors [107]. However, while none of the cycling TTs were performed outdoors, a number of the running TTs were completed on outdoor tracks. Therefore, it is possible for environmental factors to have influenced the results of a small number of running TT tests. Nonetheless, change in time from baseline was used since it provided a performance measure in the same units across the different exercise modes. In addition to environmental factors, a participant's lack of experience completing a performance test can increase measurement error [22]. Familiarization tests can decrease that measurement error, but only to a certain degree [105]. Therefore, it is likely that there is some degree of measurement error in the analysis since only 33 of the 77 studies included familiarization tests.

4.3 Future Directions

The meta-analysis by Rosenblat et al. showed that longer-duration HIIT intervals (4 min to 5 min) led to greater improvements in TT performance when compared to SIT [3]. Since the results of the current review showed that both HIIT and SIT led to improvements in TT performance, it would be beneficial to investigate the effects of including both HIIT and SIT in the same intervention program. There are studies that have investigated the effects of concurrent HIIT + SIT [108] and periodization of HIIT and SIT [109]. However, those studies included interval programs that differed from the HIIT and SIT programs found in the current review to be optimal for improving TT performance. Furthermore, the studies did not include TT as one of the outcome measures to assess change in performance.

A more in depth understanding of the mechanisms that lead to performance changes following HIIT and SIT should provide further insight into the development of an interval training program. Although there are a number of similarities in the acute and chronic adaptions between SIT and resistance training, the studies that compare the two modes of training are limited. Changes in peripheral adaptations have been the focus of a majority of the recent studies on interval training [75, 100]. Due to the importance of central factors on oxygen consumption [110], it would be valuable for future training intervention studies to compare measures of central adaptations. These measures should include changes in left ventricular mass, stroke volume and cardiac output between interval types.

Active individuals engaged in a running SIT program experience a substantially greater improvement in TT performance when compared to other modes of exercise. A similar change in running TT performance was not apparent in trained runners. The results of previous studies suggest that running economy plays a larger role in performance when compared to other modes of exercise [72, 73]. Interval training studies would benefit from an investigation into whether changes in exercise economy occur to the same degree in trained runners and cyclists while each is training in the alternative mode of exercise. Furthermore, it is unclear why rowing led to the smallest improvement in TT performance when compared to other modes of exercise. Future studies could further clarify whether changes in performance are as a result of sport specific adaptations in exercise economy as opposed to changes in general measures of fitness.

Previous studies have examined the influence of different interval work-bout intensities and durations on endurance performance. The results of the meta-analysis indicate that manipulating exercise intensity within the severe intensity domain does not influence changes in TT performance. There is one study that directly compared the effect of different exercise intensities on TT performance [35, 54]. However, the study used protocols that employed only small differences in exercise intensity (~6% difference between groups). Longer work-bout durations with HIIT exercise lead to greater improvements in measures of endurance performance when compared to SIT [3]. The results of the current meta-analysis also indicate that longer interval work-bout durations lead to greater improvements in TT performance with HIIT. It would be valuable to determine the influence of interval work-bout duration on TT performance when total mechanical work is matched.

Studies that investigate the acute responses of manipulating an interval recovery-bout (i.e. active versus passive or recovery duration) have found that measures, such as lactate levels, oxygen consumption, perceived exertion and external power, are dependent on the design of the protocol. The results of the current review suggest that the differences in acute responses to a single training session may have limited impact on chronic adaptions in performance. There are no studies that directly compare the effect of interval work-bout duration consisting of identical external work on measures of endurance performance. Studies that compare a wider range of intensities and work-bout durations would provide valuable insight into interval training programming which could lead to more productive practical applications. In addition, determining the long-term adaptive responses to interval training programs based on different interval recovery-bout characteristics would enhance the body of knowledge in the field.

5 Conclusion

Optimization of interval training programs to produce TT performance improvements should be done according to training status. Non-modifiable characteristics, such as sex and age, do not influence the TT performance gains.

Our analysis suggests that increasing interval training dose beyond minimal requirements may not augment the training response. There are similar improvements in TT performance following HIIT and SIT. However, the program characteristics that lead to the changes are different for the two modes of interval exercise. For HIIT training, gains in TT performance are dependent on work-bout duration but are equivalent across training intensities from 75 to 100% of maximal power. The effect of training intensity within the extreme domain for SIT could not be assessed.

Longer program duration increased the performance benefit for HIIT but not for SIT. The evidence provided in this review suggests that in trained individuals, HIIT programs should consist of 5 repetitions of 5-min work-bouts at any intensity within the severe domain, with a 2.5-min recovery period (active or passive) between work bouts, twice a week for at least 4 weeks. Unlike HIIT, the evidence suggests that within commonly studied ranges there is no dose–response to SIT. SIT programs should consist of 4 repetitions of 30-s work bouts performed at maximal effort, with 4 min of passive recovery, twice a week for 2 weeks, for trained individuals.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s40279-021-01457-2.

Declarations

Authorship Contributions MR conceived and designed the study, performed the literature search, screening, study selection, data extraction, assessed study quality and bias, statistical analysis, and manuscript preparation. EL participated in study selection, data extraction and assessed study quality and bias. BC participated in the statistical analysis and manuscript preparation. ST participated in the study design and manuscript preparation.

Conflicts of Interest Michael Rosenblat, Edward Lin, Bruno da Costa 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 in the results section or in the supplementary material.

Funding No sources of funding were used to assist in the preparation of this article.

References

1. Bacon AP, Carter RE, Ogle EA, Joyner MJ. VO2max trainability and high intensity interval training in humans: a meta-analysis. PLoS ONE. 2013;8(9):e73182.
2. Milanović Z, Sporis G, Weston M. Effectiveness of high-intensity interval training (HIT) and continuous endurance training for VO2max improvements: a systematic review and meta-analysis of controlled trials. Sports Med. 2015;45(10):1469–81.
3. Rosenblat MA, Perrotta AS, Thomas SG. Effect of high-intensity interval training versus sprint interval training on time-trial performance: a systematic review and meta-analysis. Sports Med. 2020;50(6):1145–61.

4. Blondel N, Berthoin S, Lensel G. Relationship between run times to exhaustion at 90, 100, 120, and 140% of vVo2max and velocity expressed relatively to critical velocity and maximal velocity. Int J Sports Med. 2000;22(1):27–33.
5. Demarie S, Koralsztein JP, Billat LV. Time limit and time at VO2max during a continuous and an intermittent run. J Sports Med Phys Fitness. 2000;40(2):96–102.
6. Gaesser GA, Poole DC. The slow component of oxygen uptake kinetics in humans. Exerc Sports Sci Rev. 1996;24:35–71.
7. Keir DA, Fontana FY, Robertson TC, Murias JM, Paterson DH, Kowalchuk JM, et al. Exercise intensity thresholds: identifying the boundaries of sustainable performance. Med Sci Sports Exerc. 2015;47(9):1932–40.
8. Lucía A, Hoyos J, Pérez M, Chicharro JL. Heart rate and performance parameters in elite cyclists: a longitudinal study. Med Sci Sports Exerc. 2000;32(10):1777–82.
9. Caputo F, Denadai BS. The highest intensity and the shortest duration permitting attainment of maximal oxygen uptake during cycling: effects of different methods and aerobic fitness level. Eur J Appl Physiol. 2008;103(1):47–57.
10. Gibala MJ, Little JP, Macdonald MJ, Hawley JA. Physiological adaptations to low-volume, high-intensity interval training in health and disease. J Physiol. 2012;590(5):1077–84.
11. Buchheit M, Laursen PB. High-intensity interval training, solutions to the programming puzzle: part I: cardiopulmonary emphasis. Sports Med. 2013;43(5):313–38.
12. Buchheit M, Laursen PB. High-intensity interval training, solutions to the programming puzzle. Part II: anaerobic energy, neuromuscular load and practical applications. Sports Med. 2013;43(10):927–54.
13. Zadow EK, Gordon N, Abbiss CR, Peiffer JJ. Pacing, the missing piece of the puzzle to high-intensity interval training. Int J Sports Med. 2015;36(3):215–9.
14. Rosenblat MA, Perrotta AS, Vicenzino B. Polarized vs. threshold training intensity distribution on endurance sport performance: A systematic review and meta-analysis of randomized controlled trials. J Strength Cond Res. 2019;33(12):3491–500.
15. Schoenmakers PJ, Hettinga FJ, Reed KE. The moderating role of recovery durations in high-intensity interval-training protocols. Int J Sports Physiol Perform. 2019;14(6):859–67.
16. Vollaard NB, Metcalfe RS, Williams S. Effect of number of sprints in an SIT session on change in VO2max: a meta-analysis. Med Sci Sports Exerc. 2017;49(6):1147–56.
17. Foster C. VO2max and training indices as determinants of competitive running performance. J Sports Sci. 1983;1(1):13–22.
18. Coyle EF, Coggan AR, Hopper MK, Walters TJ. Determinants of endurance in well-trained cyclists. J Appl Physiol. 1988;64(6):2622–30.
19. Coyle EF, Feltner ME, Kautz SA, Hamilton MT, Montain SJ, Baylor AM, et al. Physiological and biomechanical factors associated with elite endurance cycling performance. Med Sci Sports Exerc. 1991;23(1):93–107.
20. Laursen PB, Francis GT, Abbiss CR, Newton MJ, Nosaka K. Reliability of time-to-exhaustion versus time-trial running tests in runners. Med Sci Sports Exerc. 2007;39(8):1374–9.
21. Hopkins WG. Measures of reliability in sports medicine and science. Sports Med. 2000;31(1):1–15.
22. Palmer GS, Dennis SC, Noakes TD, Hawley JA. Assessment of the reproducibility of performance testing on an air-braked cycle ergometer. Int J Sports Med. 1996;17(4):293–8.
23. Russell RD, Redmann SM, Ravussin E, Hunter GR, Larson-Meyer DE. Reproducibility of endurance performance on a treadmill using a preloaded time trial. Med Sci Sports Exerc. 2004;36(4):717–24.
24. Billat LV. Interval training for performance: a scientific and empirical practice. Special recommendations for middle- and long-distance running. Part II: anaerobic interval training. Sports Med. 2001;31(2):75–90.
25. Billat LV. Interval training for performance: a scientific and empirical practice. Special recommendations for middle- and long-distance running. Part I: aerobic interval training. Sports Med. 2001;31(1):13–31.
26. Liberati A, Altman DG, Tetzlaff J, Mulrow C, Gotzsche PC, Ioannidis JP, et al. The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate health care interventions: explanation and elaboration. J Clin Epidemiol. 2009;62(10):e1–34.
27. Higgins JP, Altman DG, Gotzsche PC, Juni P, Moher D, Oxman AD, et al. The Cochrane Collaboration's tool for assessing risk of bias in randomised trials. BMJ. 2011;343:d5928.
28. Granata C, Jamnick NA, Bishop DJ. Principles of exercise prescription and how they influence exercise-induced changes of transcription factors and other regulators of mitochondrial biogenesis. Sports Med. 2018;48(7):1541–59.
29. Morton RH. Why peak power is higher at the end of steeper ramps: an explanation based on the "critical power" concept. J Sports Sci. 2011;29(3):307–9.
30. Viechtbauer W. Conducting meta-analyses in R with metafor package. J Stat Soft. 2010;36(3):1–48.
31. Egger M, Davey Smith G, Schneider M, Minder C. Bias in meta-analysis detected by a simple, graphical test. BMJ. 1997;315(7109):629–34.
32. Akca F, Aras D. Comparison of rowing performance improvements following various high-intensity interval training. J Strength Cond Res. 2015;29(8):2249–54.
33. Astorino TA, deRevere J, Anderson T, Kellogg E, Holstrom P, Ring S, et al. Change in VO2max and time trial performance in response to high-intensity interval training prescribed using ventilatory threshold. Eur J Appl Physiol. 2018;118(9):1811–20.
34. Capostagno B, Lambert MI, Lamberts RP. Standardized versus customized high-intensity training: effects on cycling performance. Int J Sports Physiol Perform. 2014;9(2):292–301.
35. Denadai BS, Ortiz MJ, Greco CC, de Mello MT. Interval training at 95% and 100% of the velocity at VO2max: effects on aerobic physiological indexes and running performance. Appl Physiol Nutr Metab. 2006;31(6):737–43.
36. Denham J, Feros SA, O'Brien BJ. Four weeks of sprint interval training improves 5-km run performance. J Strength Cond Res. 2015;29(8):2137–41.
37. Dolgener FA, Brooks WB. The effects of interval and continuous training on VO2max and performance in the mile run. J Sports Med Phys Fitness. 1978;18(4):345–52.
38. Driller MW, Fell JW, Gregory JR, Shing CM, Williams AD. The effects of high-intensity interval training in well-trained rowers. Int J Sports Physiol Perform. 2009;4(1):110–21.
39. Dunham C, Harms CA. Effects of high-intensity interval training on pulmonary function. Eur J Appl Physiol. 2012;112(8):3061–8.
40. Esfarjani F, Laursen PB. Manipulating high-intensity interval training: effects on VO2max, the lactate threshold and 3000 m running performance in moderately trained males. J Sci Med Sport. 2007;10(1):27–35.
41. Granata C, Oliveira RS, Little JP, Renner K, Bishop DJ. Training intensity modulates changes in PGC-1alpha and p53 protein content and mitochondrial respiration, but not markers of mitochondrial content in human skeletal muscle. FASEB J. 2016;30(2):959–70.

42. Gross M, Swensen T, King D. Nonconsecutive- versus consecutive-day high-intensity interval training in cyclists. Med Sci Sports Exerc. 2007;39(9):1666–71.
43. Hazell TJ, Macpherson RE, Gravelle BM, Lemon PW. 10 or 30-s sprint interval training bouts enhance both aerobic and anaerobic performance. Eur J Appl Physiol. 2010;110(1):153–60.
44. Inoue A, Impellizzeri FM, Pires FO, Pompeu FA, Deslandes AC, Santos TM. Effects of sprint versus high-intensity aerobic interval training on cross-country mountain biking performance: a randomized controlled trial. PLoS ONE. 2016;11(1):e0145298.
45. Kavaliauskas M, Steer TP, Babraj JA. Cardiorespiratory fitness and aerobic performance adaptations to a 4-week sprint interval training in young healthy untrained females. Sport Sci Health. 2017;13(1):17–23.
46. Koral J, Oranchuk DJ, Herrera R, Millet GY. Six sessions of sprint interval training improves running performance in trained athletes. J Strength Cond Res. 2018;32(3):617–23.
47. Laursen PB, Shing CM, Peake JM, Coombes JS, Jenkins DG. Interval training program optimization in highly trained endurance cyclists. Med Sci Sports Exerc. 2002;34(11):1801–7.
48. Lindsay FH, Hawley JA, Myburgh KH, Schomer HH, Noakes TD. Improved athletic performance in highly trained cyclists after interval training. Med Sci Sports Exerc. 1996;28(11):1427–34.
49. Macpherson RE, Hazell TJ, Olver TD, Paterson DH, Lemon PW. Run sprint interval training improves aerobic performance but not maximal cardiac output. Med Sci Sports Exerc. 2011;43(1):115–22.
50. McKie GL, Islam H, Townsend LK, Robertson-Wilson J, Eys M, Hazell TJ. Modified sprint interval training protocols: physiological and psychological responses to four weeks of training. Appl Physiol Nutr Metab. 2018;43(6):595–601.
51. Ní Chéilleachair NJ, Harrison AJ, Warrington GD. HIIT enhances endurance performance and aerobic characteristics more than high-volume training in trained rowers. J Sports Sci. 2017;35(11):1052–8.
52. Scalzo RL, Peltonen GL, Binns SE, Shankaran M, Giordano GR, Hartley DA, et al. Greater muscle protein synthesis and mitochondrial biogenesis in males compared with females during sprint interval training. FASEB J. 2014;28(6):2705–14.
53. Siahkouhian M, Khodadadi D, Shahmoradi K. Effects of high-intensity interval training on aerobic and anaerobic indices: Comparison of physically active and inactive men. Sci Sports. 2013;28(5):e119–25.
54. Smith TP, Coombes JS, Geraghty DP. Optimising high-intensity treadmill training using the running speed at maximal O(2) uptake and the time for which this can be maintained. Eur J Appl Physiol. 2003;89(3–4):337–43.
55. Stepto NK, Hawley JA, Dennis SC, Hopkins WG. Effects of different interval-training programs on cycling time-trial performance. Med Sci Sports Exerc. 1999;31(5):736–41.
56. Stevens AW, Olver TT, Lemon PW. Incorporating sprint training with endurance training improves anaerobic capacity and 2,000-m erg performance in trained oarsmen. J Strength Cond Res. 2015;29(1):22–8.
57. Swart J, Lamberts RP, Derman W, Lambert MI. Effects of high-intensity training by heart rate or power in well-trained cyclists. J Strength Cond Res. 2009;23(2):619–25.
58. Westgarth-Taylor C, Hawley JA, Rickard S, Myburgh KH, Noakes TD, Dennis SC. Metabolic and performance adaptations to interval training in endurance-trained cyclists. Eur J Appl Physiol. 1996;75(4):298–304.
59. Weston AR, Myburgh KH, Lindsay FH, Dennis SC, Noakes TD, Hawley JA. Skeletal muscle buffering capacity and endurance performance after high-intensity interval training by well-trained cyclists. Eur J Appl Physiol. 1997;75(1):7–13.
60. Willoughby TN, Thomas MP, Schmale MS, Copeland JL, Hazell TJ. Four weeks of running sprint interval training improves cardiorespiratory fitness in young and middle-aged adults. J Sports Sci. 2016;34(13):1207–14.
61. Kavaliauskas M, Aspe RR, Babraj JA. High-intensity cycling training: the effect of work-to-rest intervals on running performance measures. J Strength Cond Res. 2015;29(8):2229–36.
62. Esbjörnsson-Liljedahl M, Sundberg CJ, Norman B, Jansson E. Metabolic response in type I and type II muscle fibers during a 30-s cycle sprint in men and women. J Appl Physiol. 1999;87(4):1326–32.
63. Schmitz B, Niehues H, Thorwesten L, Klose A, Kruger M, Brand SM. Sex differences in high-intensity interval training-are HIIT protocols interchangeable between females and males? Front Physiol. 2020;11:38.
64. Weston M, Taylor KL, Batterham AM, Hopkins WG. Effects of low-volume high-intensity interval training (HIT) on fitness in adults: a meta-analysis of controlled and non-controlled trials. Sports Med. 2014;44(7):1005–17.
65. Støren Ø, Helgerud J, Saebo M, Støa EM, Bratland-Sanda S, Unhjem RJ, et al. The effect of age on the VO2max response to high-intensity interval training. Med Sci Sports Exerc. 2017;49(1):78–85.
66. Hetlelid KJ, Plews DJ, Herold E, Laursen PB, Seiler S. Rethinking the role of fat oxidation: substrate utilisation during high-intensity interval training in well-trained and recreationally trained runners. BMJ Open Sport Exerc Med. 2015;1(1):e000047.
67. Wang E, Naess MS, Hoff J, Albert TL, Pham Q, Richardson RS, et al. Exercise-training-induced changes in metabolic capacity with age: the role of central cardiovascular plasticity. Age. 2014;36(2):665–76.
68. Fleg JL, Morrell CH, Bos AG, Brant LJ, Talbot LA, Wright JG, et al. Accelerated longitudinal decline of aerobic capacity in healthy older adults. Circulation. 2005;112(5):674–82.
69. Ekblom B, Wilson G, Åstrand PO. Central circulation during exercise after venesection and reinfusion of red blood cells. J Appl Physiol. 1976;40(3):379–83.
70. Seiler S. What is best practice for training intensity and duration distribution in endurance athletes? Int J Sports Physiol Perform. 2010;5(3):276–91.
71. Laursen PB, Shing CM, Peake JM, Coombes JS, Jenkins DG. Influence of high-intensity interval training on adaptations in well-trained cyclists. J Strength Cond Res. 2005;19(3):527–33.
72. Moore IS, Jones AM, Dixon SJ. Mechanisms for improved running economy in beginner runners. Med Sci Sports Exerc. 2012;44(9):1756–63.
73. Swinnen W, Kipp S, Kram R. Comparison of running and cycling economy in runners, cyclists, and triathletes. Eur J Appl Physiol. 2018;118(7):1331–8.
74. Londeree BR. Effect of training on lactate/ventilatory thresholds: a meta-analysis. Med Sci Sports Exerc. 1997;29(6):837–43.
75. MacInnis MJ, Gibala MJ. Physiological adaptations to interval training and the role of exercise intensity. J Physiol. 2017;595(9):2915–30.
76. Bishop DJ, Botella J, Genders AJ, Lee MJ, Saner NJ, Kuang J, et al. High-intensity exercise and mitochondrial biogenesis: current controversies and future research directions. Physiology. 2019;34(1):56–70.
77. Rønnestad BR, Hansen J, Nygaard H, Lundby C. Superior performance improvements in elite cyclists following short-interval vs effort-matched long-interval training. Scand J Med Sci Sports. 2020;30(5):849–57.
78. Rønnestad BR, Hansen J, Vegge G, Tonnessen E, Slettalokken G. Short intervals induce superior training adaptations compared

with long intervals in cyclists—an effort-matched approach. Scand J Med Sci Sports. 2015;25(2):143–51.
79. Sandbakk Ø, Sandbakk S, Ettema G, Welde B. Effects of intensity and duration in aerobic high-intensity interval training in highly trained junior cross-country skiers. J Strength Cond Res. 2013;27(7):1974–80.
80. Seiler S, Jøranson K, Olesen BV, Hetlelid KJ. Adaptations to aerobic training: interactive effects of exercise intensity and total work duration. Scand J Med Sci Sports. 2013;23(1):74–83.
81. Chidnok W, DiMenna FJ, Fulford J, Bailey SJ, Skiba PF, Vanhatalo A, et al. Muscle metabolic responses during high-intensity intermittent exercise measured by (31)P-MRS: relationship to the critical power concept. Am J Physiol Regul Integr Comp Physiol. 2013;305(9):R1085–92.
82. Ahmaidi S, Granier P, Taoutaou Z, Mercier J, Dubouchaud H, Prefaut C. Effects of active recovery on plasma lactate and anaerobic power following repeated intensive exercise. Med Sci Sports Exerc. 1996;28(4):450–6.
83. Wahl P, Mathes S, Kohler K, Achtzehn S, Bloch W, Mester J. Effects of active vs. passive recovery during Wingate-based training on the acute hormonal, metabolic and psychological response. Growth Horm IGF Res. 2013;23(6):201–8.
84. Spencer M, Bishop D, Dawson B, Goodman C, Duffield R. Metabolism and performance in repeated cycle sprints: active versus passive recovery. Med Sci Sports Exerc. 2006;38(8):1492–9.
85. Spencer M, Dawson B, Goodman C, Dascombe B, Bishop D. Performance and metabolism in repeated sprint exercise: effect of recovery intensity. Eur J Appl Physiol. 2008;103(5):545–52.
86. Dupont G, Berthoin S. Time spent at a high percentage of VO2max for short intermittent runs: active versus passive recovery. Can J Appl Physiol. 2004;29(Suppl):S3–16.
87. Dupont G, Blondel N, Berthoin S. Performance for short intermittent runs: active recovery vs. passive recovery. Eur J Appl Physiol. 2003;89(6):548–54.
88. Laurent CM, Vervaecke LS, Kutz MR, Green M. Sex-specific responses to self-paced, high-intensity interval trainign with variable recovery periods. J Strength Cond Res. 2014;28(4):920–7.
89. Seiler S, Hetlelid KJ. The impact of rest duration on work intensity and RPE during interval training. Med Sci Sports Exerc. 2005;37(9):1601–7.
90. Smilios I, Myrkos A, Zafeiridis A, Toubekis AG, Spassis A, Tokmakidis SP. The effects of recovery duration during high-intensity interval exercise on time spent at high rates of oxygen consumption, oxygen kinetics, and blood lactate. J Strength Cond Res. 2018;32(9):2183–9.
91. Glaister M, Stone MH, Stewart AM, Hughes M, Moir GL. The influence of recovery duration on multiple sprint cycling performance. J Strength Cond Res. 2005;19(4):831–7.
92. Gosselin LE, Kozlowski KF, DeVinney-Boymel L, Hambridge C. Metabolic response of difference high-intensity aerobic interval exercise protocols. J Strength Cond Res. 2012;26(10):2866–71.
93. Raleigh JP, Giles MD, Islam H, Nelms M, Bentley RF, Jones JH, et al. Contribution of central and peripheral adaptations to changes in maximal oxygen uptake following 4 weeks of sprint interval training. Appl Physiol Nutr Metab. 2018;43(10):1059–68.
94. Cochran AJ, Percival ME, Tricarico S, Little JP, Cermak N, Gillen JB, et al. Intermittent and continuous high-intensity exercise training induce similar acute but different chronic muscle adaptations. Exp Physiol. 2014;99(5):782–91.
95. Seiler S, Kjerland GO. Quantifying training intensity distribution in elite endurance athletes: is there evidence for an "optimal" distribution? Scand J Med Sci Sports. 2006;16(1):49–56.
96. Stöggl TL, Sperlich B. Polarized training has greater impact on key endurance variables than threshold, high intensity, or high volume training. Front Physiol. 2014;5:33.
97. Rønnestad BR, Mujika I. Optimizing strength training for running and cycling endurance performance: a review. Scand J Med Sci Sports. 2014;24(4):603–12.
98. Kristoffersen M, Sandbakk O, Ronnestad BR, Gundersen H. Comparison of short-sprint and heavy strength training on cycling performance. Front Physiol. 2019;10:1132.
99. Kamen G, Knight CA. Training-related adaptations in motor unit discharge rate in young and older adults. J Gerontol A Biol Sci Med Sci. 2004;59(12):1334–8.
100. Granata C, Jamnick NA, Bishop DJ. Training-induced changes in mitochondrial content and respiratory function in human skeletal muscle. Sports Med. 2018;48(8):1809–28.
101. Parry HA, Roberts MD, Kavazis AN. Human skeletal muscle mitochondrial adaptations following resistance exercise training. Int J Sports Med. 2020;41(6):349–59.
102. Turnes T, de Aguiar RA, de Oliveira Cruz RS, Pereira K, Salvador AF, Caputo F. High-intensity interval training in the boundaries of the severe domain: effects of sprint and endurance performance. Int J Sports Med. 2016;37(12):944–51.
103. Borszcz FK, Tramontin AF, de Souza KM, Carminatti LJ, Costa VP. Physiological correlations with short, medium, and long cycling time-trial performance. Res Q Exerc Sport. 2018;89(1):120–5.
104. Tu YK, Gilthorpe MS. Revisiting the relation between change and initial value: a review and evaluation. Stat Med. 2007;26(2):443–57.
105. Laursen PB, Shing CM, Jenkins DG. Reproducibility of a laboratory-based 40-km cycle time-trial on a stationary wind-trainer in highly trained cyclists. Int J Sports Med. 2003;24(7):481–5.
106. Laursen PB, Shing CM, Jenkins DG. Reproducibility of the cycling time to exhaustion at VO2peak in highly trained cyclists. Can J Appl Physiol. 2003;28(4):605–15.
107. Balmer J, Davison RC, Bird SR. Peak power predicts performance power during outdoor 16.1-km cycling time trial. Med Sci Sports Exerc. 2000;32(8):1485–90.
108. Hebisz P, Hebisz R, Zaton M, Ochmann B, Mielnik N. Concomitant application of sprint and high-intensity interval training on maximal oxygen uptake and work output in well-trained cyclists. Eur J Appl Physiol. 2016;116(8):1495–502.
109. Astorino TA, Edmunds RM, Clark A, King L, Gallant RA, Namm S, et al. High-intensity interval training increases cardiac output and VO2max. Med Sci Sports Exerc. 2017;49(2):265–73.
110. Montero D, Diaz-Canestro C, Lundby C. Endurance training and VO2max: role of maximal cardiac output and oxygen extraction. Med Sci Sports Exerc. 2015;47(10):2024–33.

Authors and Affiliations

Michael A. Rosenblat[1,2] · Edward Lin[1,3] · Bruno R. da Costa[4,5,6] · Scott G. Thomas[1]

[1] Department of Exercise Science, Faculty of Kinesiology and Physical Education, University of Toronto, Toronto, ON, Canada

[2] Present Address: Department of Biomedical Physiology and Kinesiology, Faculty of Science, Simon Fraser University, Burnaby, BC, Canada

[3] Schulich School of Medicine and Dentistry, Western University, London, ON, Canada

[4] Institute of Health Policy, Management, and Evaluation, Dalla Lana School of Public Health, University of Toronto, Toronto, ON, Canada

[5] Applied Health Research Center (AHRC), Li Ka Shing Knowledge Institute, St Michael's Hospital, Toronto, ON, Canada

[6] Institute of Primary Health Care (BIHAM), University of Bern, Bern, Switzerland