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Physiological Adaptations and Performance Improvements to Interval Training in Endurance-Trained Cyclists: An Exploratory Systematic Review and Meta-Analysis

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ABSTRACT

Background: In endurance cycling, both high-intensity interval training (HIIT) and sprint interval training (SIT) have become popular training modalities due to their ability to elicit improvements in performance. Studies have attempted to ascertain which form of interval training might be more beneficial for maximising cycling performance as well as a range of physiological parameters, but an amalgamation of results which explores the influence of different interval training programming variables in trained cyclists has not yet been conducted.
Objective: The aims of this study were to: (1) systematically review training interventions to determine which training modality, HIIT, SIT or low- to moderate-intensity continuous training (LIT/MICT), leads to greater physiological adaptations and performance improvements in trained cyclists; and (2) determine the moderating effects of intervention length on the effectiveness of the HIIT/SIT programme.
Data Sources: Electronic database searches were conducted using SPORTDiscus and PubMed.
Study Selection: Inclusion criteria were: (1) at least recreationally-trained cyclists aged 18–49 years (maximum/peak oxygen uptake [$\dot{V}O_{2max}$/$\dot{V}O_{2peak}$] ≥45 $mL \cdot kg^{-1} \cdot min^{-1}$); (2) training interventions that included a HIIT or SIT group and a control group (or two interval training groups for direct comparisons); (3) minimum intervention length of 2 weeks; (4) interventions that consisted of 2–3 weekly interval training sessions.
Results: Interval training leads to small improvements in all outcome measures combined (overall main effects model, SMD: 0.33 [95%CI = 0.06 to 0.60]) when compared to LIT/MICT in trained cyclists. At the individual outcome level, point estimates favouring HIIT/SIT were negligible in the Wingate model (0.01 [95%CI = -3.56 to 3.57]) and trivial for relative $\dot{V}O_{2max}$/$\dot{V}O_{2peak}$ (0.10 [95%CI = -0.34 to 0.54]). There were small improvements in absolute $\dot{V}O_{2max}$/$\dot{V}O_{2peak}$ (0.28 [95%CI = 0.15 to 0.40]), absolute maximum aerobic power/peak power output (0.38 [95%CI = 0.15 to 0.61]), relative maximum aerobic power/peak power output (0.43 [95%CI = -0.09 to 0.95]) and physiological thresholds (0.46 [95%CI = -0.24 to 1.17]) in HIIT/SIT compared to LIT/MICT. Finally, the time-trial/time-to-exhaustion model (0.96 [95%CI = -0.81 to 2.73]) evidenced large improvements in

performance variables following HIIT/SIT compared to controls. However, interval estimates were very imprecise for most outcomes. In addition, intervention length did not contribute significantly to the improvements in outcome measures in this population, as the effect estimate was only trivial ($\beta_{Duration}$: 0.04 [95%CI = -0.07 to 0.15]). Finally, the network meta-analysis did not reveal a clear superior effect of any HIIT/SIT types when directly comparing interval training differing in interval work-bout duration.

Conclusion: The results of the meta-analysis indicate that both HIIT and SIT are effective training modalities to elicit physiological adaptations and performance improvements in trained cyclists. Our analyses highlight that the optimisation of interval training prescription in trained cyclists cannot be solely explained by interval type or interval work-bout duration and an individualised approach that takes into account the training/competitive needs of the athlete is warranted.

Keywords: cycling, exercise prescription, maximal oxygen consumption, high-intensity, intervention, programme optimisation

INTRODUCTION

Over recent decades, optimisation of endurance training has attracted considerable attention in the literature, in an attempt to provide a more scientific basis to endurance performance through 'evidence-informed' coaching practice. In this sense, training strategies which seek to optimise physiological adaptations have been widely investigated, with a particular emphasis on training intensity distribution [e.g., 1–3], exercise modalities [e.g., 4–9] and the manipulation of training variables [e.g., 10–12]. Ensuring an integrated approach to periodisation which covers all aspects of performance is considered important for continuously eliciting adaptations, managing fatigue/recovery, and avoiding stagnation during an athlete's competitive season [13–16].

Exercise intensity is an important training variable that influences physiological adaptations and performance [17]. Indeed, in athletes with already high volumes of training, it would appear that appropriate manipulation of training intensity influences the extent to which further performance gains are made [18]. As such, an appropriate blend of high-volume and high-intensity training is required to induce the physiological and metabolic adaptations that ultimately drive performance enhancements [19]. Nonetheless, there remains equivocal evidence regarding the comparative effects of high-intensity training sessions with other approaches and the most appropriate ways to prescribe high-intensity training sessions to endurance athletes.

High-intensity interval training (HIIT) is recognised as a viable training modality for eliciting physiological adaptations. By its traditional definition, HIIT consists of submaximal or near maximal efforts (often at 85–95% maximum heart rate and ≥80% maximal power output from a graded exercise test [W_{max}/PPO]), performed above the lactate turnpoint (LTP) or critical power (CP) or second ventilatory threshold (VT2), interspersed by periods of rest or low-intensity exercise [17, 20]. HIIT protocols usually incorporate work intervals lasting 2–8 min, with longer intervals (up to ~16 min) being described as "aerobic" interval training (AIT) [21]. Recovery intervals in HIIT are usually prescribed using a fixed work:recovery ratio (e.g., 2:1, 1:1, 1:4) or self-selected recovery durations [22–24]. Different variations of HIIT which are shorter in duration (usually 20–30 s) have also emerged, referred to as sprint interval training (SIT) [4]. SIT is performed in the extreme exercise intensity domain at power outputs or velocities above those associated with maximal/peak oxygen consumption ($\dot{V}O_{2max}$/$\dot{V}O_{2peak}$), often with fixed recovery periods of 1.5–4 min [25–28]. Implementing HIIT/SIT has been shown to induce cardiovascular [e.g., 29–32], metabolic [e.g., 33–35], neuromuscular [36, 37], molecular [25, 38, 39] and performance [e.g., 40–42] adaptations, which are at least comparable to the physiological adaptations observed in traditional (moderate intensity) endurance training despite a substantially lower training volume and/or session duration [31, 43–47].

Prescribing HIIT/SIT can be challenging due to the large number of training variables which may influence the exercise stimulus, including the duration and intensity of individual work intervals and recovery (relief) intervals, the total number of individual work intervals (i.e., repetitions) and the number of series/sets (i.e., groups of work intervals separated by longer recoveries), and the duration and intensity of the between-series recovery periods [4]. The differences in the application of interval training between HIIT and SIT lie primarily in the duration and intensity of the exercise bouts, reflecting distinct acute metabolic processes that, consequently, may lead to different chronic adaptations to training [48]. The moderating effects of recovery durations should also be weighed, and likely contribute to the overall physiological stimulus of a training session in distinct ways depending on the interval training modality [21, 49]. Moreover, other programming variables (e.g., session frequency, weekly volume, training intensity distribution, the inclusion of resistance training or other forms of exercise, and period of the season) [50–54] and population characteristics (e.g., training history, sex, age, baseline physiological measures, phenotype) [55, 56] also influence the magnitude of training responses/ adaptations and, in turn, the potential of a given training intervention to elicit performance improvements.

Despite the lack of standardisation enabling our understanding of different periodisation models and exercise protocols using HIIT and SIT [57], the evidence has consistently shown that both interval training modalities produce beneficial physiological adaptations that enhance endurance performance. In cycling, high-intensity training programmes lead to performance gains in participants ranging from recreationally-trained [58] to elite-level cyclists [59]. Improvements in $\dot{V}O_{2max}$ [26, 60, 61], CP [62], power output at different blood lactate markers [58, 60, 61] and ventilatory thresholds (VT_1/VT_2) [63, 64] have been reported following HIIT/SIT training regimens lasting up to 10–12 weeks, with 2 weeks being the minimum intervention length required to elicit adaptations even in highly trained cyclists [63]. Other performance measures such as time-trials (TT) [59, 60, 65, 66] and time-to-exhaustion (TTE) [58] are also improved, which could be partly explained by an increased ability to tolerate higher blood lactate concentrations [64] after a period of HIIT/SIT. Importantly, physiological adaptations are dictated by the aforementioned programming variables and population characteristics. Given the complexity of endurance training, the mechanisms driving improvements in performance are likely multifactorial and warrant further investigation to optimise HIIT/SIT prescription.

Previous reviews have shown that interval training (HIIT/SIT) may lead to greater improvements in $\dot{V}O_{2max}$ [67, 68] and fat oxidation in overweight/ obese individuals [69] than moderate-intensity continuous training (MICT), whilst others [70–74] revealed no clear superior benefits in a range of physiological and body composition measures. The effectiveness of HIIT/SIT interventions has been systematically investigated in overweight/obese adults [74], trained athletes in a range of sports [75], healthy/sedentary adults [67, 70, 73], mixed populations [68, 71, 72], and young athletes [76], but not solely in trained cyclists. The aforementioned systematic reviews compare interval training with MICT in health and disease, which albeit important for public health guidance and disease prevention/ amelioration, provides very little information with regard to endurance training optimisation in athletes with already high-volume training backgrounds. To our knowledge, only two systematic reviews have focused on chronic adaptations to cycling training in trained cyclists [53, 77], with a particular focus on cycling cadence [77] and periodisation models [53] rather than specific exercise prescription. In addition, although it is undeniable that both HIIT and SIT improve physiological adaptations in various populations, the number of reviews directly comparing both interval training modalities is sparse [78–80]. Therefore, the purpose of the present review was to systematically investigate the effects of different HIIT/SIT interventions in comparison to low-intensity training (LIT) or MICT on physiological adaptations and performance in trained cyclists. To address the lack of reviews discriminating between HIIT and SIT, the secondary aims of this investigation were: (1) to examine the potential effects of HIIT differing in interval work-bout duration on performance outcomes; (2) to determine whether traditional HIIT modality is superior in inducing performance adaptations in comparison with SIT (or vice-versa); and (3) to investigate the moderating effects of intervention length in relation to overarching training adaptations.

METHODS

The review was conducted in accordance with the guidelines recommended in the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement [81]. This review was not pre-registered as it was conducted as part of an undergraduate dissertation and thus is considered exploratory.

Literature Search Strategy

Electronic database searches were performed using SPORTDiscus and PubMed. All available records published from inception to 3 July 2023 were considered for initial analysis. Articles were retrieved from each database using the following search criteria in the search query box: (High-intensity interval training OR HIIT OR HIT OR High-intensity training OR Sprint interval training OR Repeated sprint training) AND (cycling performance). Additional articles were identified through reference lists of potentially eligible papers.

Search Limits

During the initial search, the following search limits were selected to optimise the search strategy: (1) Abstract available, (2) Journal articles, (3) Humans, and (4) English language.

Eligibility Criteria

Inclusion and exclusion criteria were used according to the PICO criteria (i.e., participants, intervention, comparators, outcome) to guide the study selection process.

Type of Study

The systematic review included randomised and matched controlled trials.

Type of Participants

Healthy recreationally–highly trained cyclists aged 18–49 years with a minimum relative $\dot{V}O_{2max}$/$\dot{V}O_{2peak}$ of 45 mL·kg^{-1}·min^{-1} were considered. The inclusion of males and females aged 49 years or under was based on a previous study which demonstrated that physiological adaptations to endurance training are not impacted by sex in this age group [82]. Training categorisation of cyclists followed the guidelines of Quesada et al. [83] regarding training volume and frequency, and that of De Pauw et al. [84] based on the need for physiological information as a means of classifying subject groups. It is important to note that not all included studies reported metabolic 'threshold' data (Table 1). Nevertheless, we believe cyclists in all included studies were at least recreationally-trained as per De Pauw et al., [84] and indeed physiological data suggest a sufficient training level was met. Finally, studies performed on participants with underlying health conditions, and acute or chronic diseases (e.g., diabetes, heart problems) were excluded from this review.

Type of Interventions

Training interventions were required to last a minimum duration of 2 weeks (with at least two interval training sessions per week), which has been shown to be sufficient to induce positive physiological adaptations in highly trained cyclists [63]. Participants had to be allocated to an interval training group (HIIT/SIT) or a matched comparator group that performed either LIT or MICT (or both) referred to as the control group (CON). Studies that did not have a control group but included multiple interval training groups were considered for analyses involving direct comparisons of both interval training modalities, and between HIIT differing in work-bout duration. In contrast, studies comparing an interval training group solely with a no-exercise CON were excluded from the review. Articles which incorporated both HIIT and SIT (i.e., 'combined' HIIT/SIT) in the same training intervention were considered for analysis as long as the abovementioned criteria were met (i.e., the study allowed for comparisons against other interval training groups and/or CON performing LIT/MICT). Studies reporting the effects of HIIT interventions consisting of intense overloading strategies (e.g., block periodisation) were excluded. Performing two to three weekly HIIT sessions is sufficient to signal physiological adaptations and further increases may induce symptoms of overreaching/overtraining [1]. In this sense, training interventions consisting of more than 3 weekly interval training sessions were not considered. Studies in which participants were under supplement administration were excluded from this review due to potential performance enhancements [85] and, thus, lead to confusion in ascertaining the true effects of HIIT/SIT. For the same reason, studies that manipulated environmental conditions or combined cycling training with strength training were also excluded, similar to that of other systematic reviews in this area [67, 74]. For the purpose of this review, HIIT was defined as near maximal exercise at 85–95% maximum heart rate and ≥80% W_{max}/PPO, lasting anywhere from ~1–8 min. HIIT incorporating longer submaximal work intervals (up to 16 min) was described as AIT, despite work intensities being undeniably high. SIT was defined as 'all-out' or 'supramaximal' exercise lasting 20–30 s, interspersed by fixed recovery periods.

Outcome Measures

Studies comparing measures of cycling performance between two or more interval training groups (or with CON) as the primary or secondary aim of the study were included. In order to be included in the systematic review, each study had to include at least one of the following physiological and performance variables typically measured in endurance training studies: (1) $\dot{V}O_{2max}$/$\dot{V}O_{2peak}$; (2) Lactate Threshold (LT)/LTP; (3) VT_1/VT_2; (4) OBLA; (5) MLSS; (6) TT performance; (7) Power output associated with $\dot{V}O_{2max}$/$\dot{V}O_{2peak}$ (in individual studies, referred to as "Maximum Aerobic Power" [MAP] or W_{max}/PPO); (10) TTE; (11) CP; (12) Work capacity above CP (*W′*) (13) Anaerobic capacity (e.g. Wingate test variables); (14) Gross Efficiency (GE); (15) Cycling economy.

Study Selection

All potential articles identified at the search phase were exported to an external citation management software (EndNote20, Clarivate, Philadelphia, PA), where all the duplicates were removed. The lead author (BN) independently screened titles, followed by abstracts, and full-text articles. In instances where the inclusion or exclusion of studies could not be ascertained through titles/abstracts only, these studies progressed to the next stage of the screening process and full-text articles were assessed. The study selection process was reviewed by one author (JS) and possible disagreements were resolved by consulting a third author (JW). Studies that did not meet the inclusion and exclusion criteria listed above were excluded from this review.

Data Extraction

The following characteristics were extracted from each included study by one author (BN) and checked by two other authors (JW and JS): article title and author(s), participant information (age, sex, stature, body mass, training level/status, baseline physiological measures), method (intervention length, research design), description of the intervention protocol (HIIT modality, interval intensity, duration and frequency) and study outcomes (relevant findings based on the parameters measured). Data on physiological and performance parameters were extracted in the form of pre- and post-training intervention Means and Standard Deviations (SD) (Mean ± SD) or 95% Confidence Intervals (CI) (Mean ± 95% CI), p values and relationships between performance variables (if appropriate). We asked the corresponding authors of one article [86] to provide additional data but the authors no longer had access to it. Despite this, we managed to retrieve relevant baseline and post-intervention data ($\dot{V}O_{2max}$/$\dot{V}O_{2peak}$, MAP/PPO, Wingate, TT/TTE performance outcomes) from this study which had been reported in another meta-analysis [78] for all but one group that performed 8-min intervals and did not feature in the analysis of this investigation. One study [65] did not present mean ± SD in tabular format nor in-text (only reported percentage improvements from baseline); therefore, we used WebPlotDigitizer to retrieve relevant data for all outcomes from the Figures in the paper.

Risk of Bias and Quality of Evidence

The Cochrane risk of bias tool for randomized trials (RoB 2) was used to assess the risk of bias for each included outcome in the meta-analysis [87]. RoB 2 comprises five domains and a series of signalling questions concerning: 1) the randomisation process, 2) deviations from intended interventions, 3) missing outcome data, 4) measurement of the outcome and 5) selection of the reported results. Judgements for each domain are expressed as “low”, “high” or “some concerns”. The least favourable assessment across all the domains in each study corresponded to the overall bias judgement for that study [87]. Bias assessments were made independently by one author (BN), with outcome data being double-checked by the other authors (JS and JW).

The quality of evidence for each outcome was rated using the Grading of Recommendation, Assessment, Development, and Evaluation (GRADE) approach [88]. GRADE has four levels of evidence (“very low”, “low”, “moderate” and “high”), and the certainty evidence is downgraded for each outcome based on the following factors: 1) risk of bias, 2) inconsistency of results, 3) indirectness of evidence, 4) imprecision of results and 5) publication bias [89]. The evidence was downgraded by one level if we judged that there was a *serious limitation* or by two levels if we judged there to be a *very serious limitation*, and an overall GRADE quality rating was generated for each outcome.

Meta-Analysis

Summary of Measures

The primary outcome measure was cycling performance and respective physiological attributes typically associated with cycling performance, assessed via absolute and relative $\dot{V}O_{2max}$/$\dot{V}O_{2peak}$, absolute and relative MAP/PPO, physiological thresholds, Wingate parameters and TT/TTE for comparisons between interval training groups and CON. Secondly, intervention length was fitted as a continuous moderator (meta-regression) to determine its impact on physiological adaptations and performance changes. Thirdly, the effects of different HIIT prescriptions (i.e., SIT, long-duration HIIT, short-duration HIIT, combined HIIT/SIT) were examined as a multilevel network meta-analysis for direct comparisons between specific interval training types, and against CON.

Statistical Analysis

After careful inspection of the included articles, it became evident that the outcomes of two training interventions had been split into different studies in two occasions [62, 64, 91, 92]. Therefore, the data extrapolated from different articles was considered as one single training intervention and any identical outcomes that may have been reported across different studies were not repeated for the purpose of the analyses.

Quantitative synthesis of data was performed with the 'metafor' [93] package in R (v 4.0.2; R Core Team, https://www.r-project.org/). All analysis code and data are openly available in the supplementary materials (https://osf.io/k97th/).

Included studies followed pre-post between group comparison designs which was accounted for in the calculation of standardised effects (Hedges' *g*) using the escalc function in metafor. For within-group effects, pre-post correlations for measures are often not reported in original studies, thus we selected a conservative value of r = 0.7 though explored the sensitivity of conclusions to other correlations (r = 0.5 and 0.9). We used the pooled group baseline standard deviation as the numerator as per Morris [94]. Standardised effect sizes were interpreted as per Cohen's [32]thresholds: trivial (<0.2), small (0.2 to <0.5), moderate (0.5 to <0.8), and large (≥0.8). Standardised effects were calculated in such a manner that a positive effect size value favours the IT conditions.

To perform a sub-group analysis, interventions were divided into interval training groups that differed in work-bout duration and/or interval training modality. Long-duration HIIT ('long-HIIT') and AIT were grouped together under 'long-HIIT', defined as interval bouts of at least 4 min in duration (ranged between 4–16 min in the included studies). Conversely, short-duration HIIT ('short-HIIT') was defined as interval bouts of less than 4 min in duration. Previous reviews [68, 78] have classified HIIT into smaller subgroups, particularly in the short-duration range (e.g., <2 min and 2–4 min), which may be an appropriate approach based on known oxygen uptake kinetics, as $\dot{V}O_{2max}$ during high-intensity exercise in trained cyclists can be reached in as little as 117 s [95] and would justify the ~2 min 'cut-off'. However, given the low number of interventions employing short-duration HIIT protocols in our review, we did not attempt to further categorise training groups based on interval work-bout duration. Furthermore, accurately quantifying the emphasis of anaerobic metabolism during a given HIIT session can be challenging [5]. Since individually determined oxygen uptake kinetics is not available in the reviewed studies, we chose a more simplistic HIIT classification (i.e., fixed time points) to clearly differentiate between short (<4 min) and long (≥4 min) intervals.

Because there was a nested structure to the effect sizes calculated from the studies included (i.e., multiple effects nested within groups and nested within studies), multilevel mixed-effects meta-analyses with both study and intra-study groups included as random effects in the model were performed. Cluster robust point estimates and precision of those estimates using 95% compatibility (confidence) intervals (CIs) along with 95% prediction intervals were produced, weighted by the inverse sampling variance to account for the within- and between-study variance (τ^2). Restricted maximal likelihood estimation was used in all models. A main model was produced that combined all performance outcomes including all standardised effect sizes to provide a general estimate of the comparative treatment effects. We also fitted a separate model for each outcome grouping individually to explore outcome-specific effects and explored the impact of intervention length in weeks as a continuous moderator. Lastly, an exploratory multilevel network meta-analysis model of all outcomes was performed to compare the general efficacy of different types of HIIT interventions (i.e., SIT, long-duration HIIT, short-duration HIIT, combined HIIT/SIT, and CON). A network meta-analysis relies on the assumption of exchangeability (i.e., that the treatment effect estimated for comparing one intervention to another is exchangeable between trials and each trial is assumed to be a random independent draw from an overarching distribution of effects). Homogenous study characteristics such as those used as inclusion criteria here (e.g., population, interventions etc.) help to ensure this assumption is met. Thus, our interpretations of the network model are necessarily cautious, particularly given the relative lack of direct comparisons for many intervention types.

For all models, we avoided dichotomizing the existence of an effect for the main results and therefore did not employ traditional null hypothesis significance testing, which has been extensively critiqued [96, 97]. Instead, we considered the implications of all results compatible with these data, from the lower limit to the upper limit of the interval estimates, with the greatest interpretive emphasis placed on the point estimate. We also present 95% prediction intervals to supplement the exploration of heterogeneity across study/group effects. Given the large number of included studies and effects, the main model of all outcomes is visualized here using an ordered caterpillar plot to aid interpretation as opposed to traditional forest plots containing study characteristics. Traditional forest plots are, however, provided for sub-grouped outcome types.

The risk of small study bias was examined visually through contour-enhanced funnel plots. Q and I^2 statistics also were produced and reported [98]. A significant Q statistic is typically considered indicative of effects likely not being drawn from a common population. I^2 values indicate the relative degree of heterogeneity in the effects that are not due to sampling variance and are qualitatively interpreted as: 0-40% not important, 30-60% moderate heterogeneity, 50-90% substantial heterogeneity, and 75-100% considerable heterogeneity [99].

RESULTS

Included Studies

The search strategy identified a total of 2368 potentially eligible articles from PubMed (*n* = 1485) and SPORTDiscus (*n* = 883) electronic databases, and 10 additional records were retrieved from reference lists of the potential manuscripts. Following the removal of duplicates (*n* = 102), 2266 articles were initially screened via title and/or abstract, and a further 51 articles were selected for full-text analysis. After full-text reviews, a total of 14 articles met the inclusion criteria and were included in this systematic review addressing the effects of different HIIT interventions on cycling performance parameters in trained cyclists (see Figure 1).

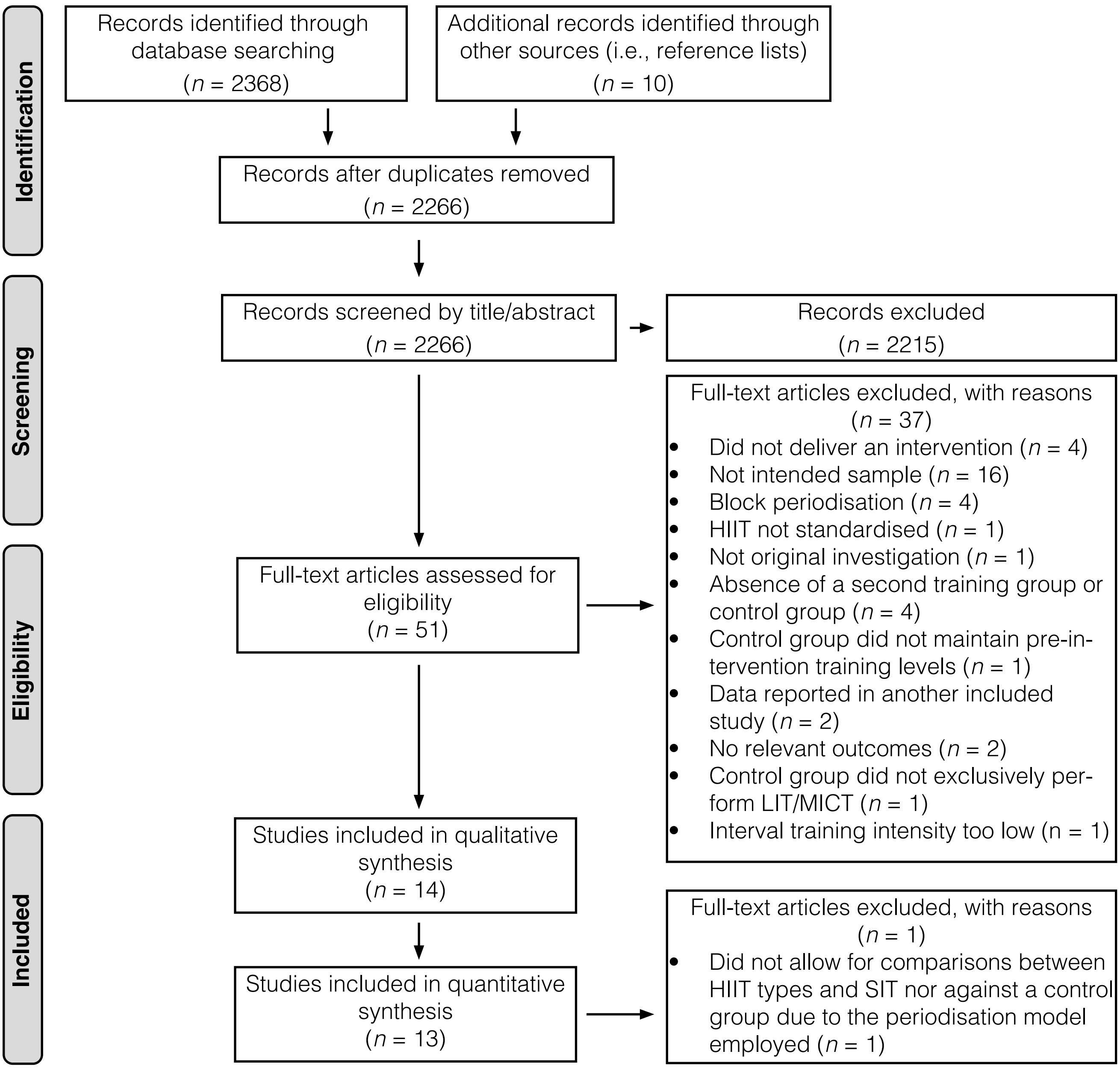

Figure 1. Flow diagram of the study selection process

Study Characteristics

We collated data from all individual studies' baseline values corresponding to a physiological and/or performance parameter that approximated the boundary between heavy and severe exercise intensity domains (e.g., CP, LTP, VT_2, Onset of Blood Lactate Accumulation [OBLA], or Maximal Lactate Steady State [MLSS]) (Table 1). Mean power outputs at the boundary between heavy and severe exercise ranged between 220–361 W (Table 1) in the studies which reported this outcome (i.e., CP, OBLA, MLSS, LTP, VT_2).

The studies included 302 cyclists with a mean age range of 21–43 years and a mean relative $\dot{V}O_{2max}$/ $\dot{V}O_{2peak}$ range of 47.0–73.3 mL·kg^{-1}·min^{-1}. Based on the training categorisation of cyclists by De Pauw et al. [84], this review included 4 studies with recreationally-trained [58, 62, 90, 92], 4 studies with trained [26, 61, 66, 86], 5 studies with well-trained [60, 63, 64, 65, 91] and 1 study with national level/ professional cyclists [59]. The full details of the participants' characteristics can be found in Table 1.

Seven studies included CON, where cyclists were not engaged in interval training and performed LIT/MICT [26, 58, 63, 64, 66, 90, 91]. One study [61] included a no-exercise CON and for that reason, the endurance training group (performing MICT) was used as CON. Five studies included HIIT and SIT groups [59, 64, 65, 86, 91], one study had training groups where cyclists performed SIT and HIIT concomitantly [26] and another [60] alternated between different HIIT work-bout durations throughout the intervention period. Seven of the 14 studies included more than one HIIT group [58, 62, 64, 66, 86, 91, 92]. Of the 14 studies included in the systematic review, 8 allowed for comparisons between interval training groups and CON [26, 61, 58, 63, 64, 66, 90, 91], and HIIT versus SIT comparisons was possible in 5 studies only [59, 64, 65, 86, 91]. Overall, there were 10 short-HIIT interval groups, 6 groups comprised of long-HIIT and 6 studies that included training groups consisting of SIT (Table 1). Comparisons between training modes (i.e., interval training versus LIT/MICT) and interval training modalities (i.e., short-HIIT versus long-HIIT, and HIIT versus SIT) were not possible with one study [60] and had to be excluded from the meta-analysis. Interventions were conducted for 5.8 ± 3.1 weeks (range 2–12 weeks) and cyclists performed interval training for 2.3 ± 0.5 days·week^{-1}.

Results of Individual Studies

$\dot{V}O_{2max}$ improved significantly following SIT (mean range: 2.6–8.7%, *n* = 5), short-HIIT (3.1–8.0%, n = 4), long-HIIT (3.3–10.4%, *n* = 3) and mixed-HIIT (3.8–10.6%, *n* = 5) between pre- and post-intervention in different training groups ($p < 0.05$). Similarly, MAP/PPO increased in all training groups consisting of SIT (3.1–10.4%) and short-HIIT, except for one group (Short-$HIIT_1$) in Stepto et al. [86]. Long-HIIT resulted in significant MAP/PPO improvements (3.1–10.1%) in two studies [58, 62], whereas no significant changes were found in three long-HIIT groups [59, 65, 86]. All short-HIIT groups (*n* = 3) improved parameters related to performance at thresholds (6.0–54.8%) [58, 62–64]. VT_1 [64], MLSS [61], OBLA [65] and VT_2 [64] improved significantly by approximately 16.8%, 9.6%, 12.0% and 8.6% (all $p < 0.01$) following SIT, respectively; however, changes in OBLA and fractional utilisation of $\dot{V}O_{2max}$ at OBLA were nonsignificant after SIT in the study by Ronnestad et al. [59] with national level/professional cyclists. There were significant improvements in TT performance in all SIT [59, 65, 86, 91] and short-HIIT [66, 86, 91, 92] groups, apart from short-$HIIT_1$ in Stepto et al. [86]. With respect to sprint performance variables, SIT induced significant improvements in the PPO (6%), MPO (6%) and total work (6%) during the Wingate test [90], but did not elicit any changes in PPO in a 15-s sprint in a different study [61]. Similarly, short-HIIT significantly increased the PPO (5.7%), MPO (3.7%) and Fatigue Index (FI; 3.9%) in the Wingate test after 4 weeks of training in recreationally-trained cyclists, whereas long-HIIT resulted in a significant reduction in FI (−4.5%) with no changes in PPO and MPO [92]. Three studies measured TTE, but only one [58] observed increases between pre- and post-intervention (62.3–91.1% in all HIIT groups, $p < 0.05$). Cycling economy did not improve as a result of the interventions [59, 65] and gross efficiency decreased by 1.4–2.6% in mixed-HIIT groups [60], but not in long-HIIT or SIT [59]. Intervention results are summarised in Table 2.

Table 1. Baseline physiological measures (VO_{2max}/VO_{2peak}, MAP/Wmax/PPO, Metabolic Thresholds) reported in each included study (data are presented as Mean ± SD unless otherwise stated).

Study authors	Group	Measured Units	VO_{2max}/VO_{2peak}	MAP/W_{max}/PPO (W)	Upper Metabolic 'Threshold' (W, unless stated otherwise) – Parameter
Creer et al. [90]	SIT	L·min-1	3.9 ± 0.3	NR	NR
	Control		4.1 ± 0.5		
Hebisz et al. [26]	SIT+HIIT$_1$	mL·kg-1·min-1	57.4 ± 3.4	370 ± 43	
	SIT+HIIT$_2$		58.6 ± 5.9	349 ± 27	
	Control		55.4 ± 7.2	346 ± 44	
Hommel et al. [61]	SIT	mL·kg-1·min-1	62.6 ± 8.8	NR	259.7 ± 67.6 (MLSS)
	Control		61.0 ± 4.8		269.1 ± 52.0 (MLSS)
Laursen et al. [91] and Laursen et al. [64] [a]	Short HIIT$_1$	mL·kg-1·min-1	66.5 ± 6.2	439 ± 29	3.83 ± 0.40 (VT_2) [b]
	Short HIIT$_2$		63.7 ± 4.1	431 ± 32	3.82 ± 0.42 (VT_2) [b]
	SIT		62.6 ± 4.1	425 ± 32	3.82 ± 0.44 (VT_2) [b]
	Control		65.2 ± 5.9	422 ± 29	3.91 ± 0.31 (VT_2) [b]
Laursen, Blanchard and Jenkins [63]	Short HIIT	mL·kg-1·min-1	68.7 ± 3.6	469 ± 38	340 ± 35 (VT_2)
	Control		66.3 ± 3.7	490 ± 47	361 ± 17 (VT_2)
Rønnestad et al. [65] [c]	Long HIIT	mL·min-1	5015.8 ± 665.5	409.0 ± 42.9	272.9 ± 35.5 (OBLA)
	SIT		5021.3 ± 455.3	398.6 ± 31.1	243.3 ± 34.0 (OBLA)
Rønnestad et al. [59]	Long HIIT	mL·kg-1·min-1	72.7 ± 4.9	469 ± 35	329 ± 41 (OBLA)
	SIT		73.3 ± 3.6	460 ± 26	334 ± 37 (OBLA)
Seiler et al. [58]	Long HIIT$_1$	mL·kg-1·min-1	52.8 ± 4.8	378 ± 52	241 ± 41 (OBLA)
	Long HIIT$_2$		51.1 ± 5.8	361 ± 51	228 ± 51 (OBLA)
	Short HIIT		50.4 ± 5.8	343 ± 68	220 ± 49 (OBLA)
	Control		52.7 ± 8.0	349 ± 44	222 ± 42 (OBLA)
Stepto et al. [86]	Short HIIT$_1$	L·min-1	4.52 ± 0.14	350 ± 95	NR
	Short HIIT$_2$		5.19 ± 0.50	403 ± 20	
	Short HIIT$_3$		4.90 ± 0.25	390 ± 25	
	SIT		4.70 ± 0.38	372 ± 29	
Swart et al. [66]	Short HIIT$_1$	mL·kg-1·min-1	59.9 ± 7	372 ± 34	NR
	Short HIIT$_2$		60.3 ± 4	370 ± 26	
	Control		54.4 ± 7	369 ± 46	
Sylta et al. [60] [d]	HIIT - INC	mL·kg-1·min-1	61.8 (59.5–64.1)	376 (361–390)	276 (265–287, OBLA)
	HIIT - DEC		60.6 (58.7–62.5)	372 (355–388)	283 (273–292, OBLA)
	HIIT - MIX		61.6 (59.8–63.4)	369 (348–390)	286 (272–300, OBLA)
Turnes et al. [62] and Turnes et al. [92] [a]	Long HIIT	mL·kg-1·min-1	47.0 ± 5.4	265 ± 45	208 ± 37 (CP)
	Short HIIT		48.5 ± 5.4	269 ± 37	212 ± 41 (CP)

Note: Interval training groups of identical HIIT types but distinct interval work-bout durations were differentiated using numbers (e.g., 'Short-HIIT$_1$', 'Short-HIIT$_2$', etc.). HIIT = High-intensity interval training; SIT = Sprint interval training; HIIT - INC = Training group performed the interval work bouts in an increasing intensity order; HIIT - DEC = Training group performed the interval work bouts in a decreasing intensity order; HIIT - MIX = Training group performed the interval training sessions in an alternating (mixed) order compared to the other training groups; VO_{2max}/VO_{2peak} = Maximum/peak oxygen uptake; MAP = Maximum aerobic power; PPO = Peak power output; Wmax = Power output at the end of an incremental (step/ramp) protocol test; MLSS = Maximal lactate steady state; VT_2 = Second ventilatory threshold; OBLA = Onset of blood lactate accumulation; CP = Critical power.

[a] *The outcomes of this intervention were divided into two separate studies, but the intervention/sample was the same.*

[b] *Data reported in L·min-1.*

[c] *Data was extrapolated with WebPlotDigitizer, as the authors in this study only reported percentage improvements.*

[d] *Data reported as Mean (95% CI).*

Table 2. Study Characteristics

Study authors	Participant characteristics (mean ± SD) - age (years), sex, body mass (kg), stature (cm), groups (n), training level	Study Design	Intervention		Outcomes and Results
Creer et al. [90]	17 recreationally-trained cyclists with ≥2 years of cycling training experience. SIT (age: 25.1 ± 2.3 years; stature: 178.5 ± 7.0 cm; mass: 69.0 ± 5.2 kg) CON (age: 24.5 ± 0.5 years; stature: 178.3 ± 7.5 cm; mass: 68.9 ± 5.9 kg)	Randomised controlled trial (4 weeks)	SIT (*n* = 10)	SIT group performed two controlled sessions per week of 4 x 30-s all-out sprints, each separated by 4 min at 50 W (≤75 rev·min^{-1}). Two additional intervals were added each week (a total of 10 sprints per training session by week 4). Cyclists performed a total of 28 min of sprint training over the intervention.	↑ $\dot{V}O_{2max}$ (4.0 ± 0.4 to 4.2 ± 0.4 L·min^{-1}) in both groups SIT: ↑ PPO (6%) and MPO (6%) in the Wingate test, and plasma lactate concentrations (18.2 ± 2.4 to 19.4 ± 3.1 mmol·l^{-1}). CON: ↑ PPO (4%) and MPO (3%) output in the Wingate test. ↑ Total training volume in CON (8.0 ± 1.7 h·week^{-1}) than in SIT (5.0 ± 1.1 h·week^{-1}) during the intervention
			CON (*n* = 7)	Cyclists were only required to maintain pre-intervention endurance levels. Each subject was given a training log to record weekly training volume.	
Hebisz et al. [26]	24 trained MTB cyclists, with ≥2 years of competitive experience. SIT+HIIT$_1$ (age: 21.7 ± 6.6 years, stature: 179.5 ± 6.0 cm; mass: 70.2 ± 9.9 kg) SIT+HIIT$_2$ (age: 21.2 ± 4.8 years; stature: 176.4 ± 5.2 cm; mass: 67.4 ± 8.6 kg) CON (age: 20.2 ± 4.3 years; stature: 176.5 ± 5.8 cm; mass: 68.4 ± 9.1 kg)	Matched controlled trial (8 weeks). Participants were matched for the amount of training volume/intensity in the 3 months leading up to the intervention.	SIT+HIIT$_1$ (*n* = 10)	Cyclists in this group had a high-volume training background at moderate intensities (14–16 h·week^{-1}). They performed HIIT (once a week), SIT (twice a week) and MICT concomitantly (twice a week). HIIT sessions involved 5–7 repetitions of 5 min at an intensity of 85–95% MAP, with 10-15 min of recovery between intervals at 45-50% MAP. SIT sessions consisted of 3–4 sets of 4 x 30-s all-out repetitions with 90-s recovery ≤30 W between repetitions. Recovery between sets lasted 25 min at ≤50% MAP. MICT sessions lasted 120–180 min, performed at 70–80% HR_{max}. Weekly training volume was 11–13 hours, apart from every fourth week in which volume was decreased by ~50%.	SIT+HIIT$_1$: ↑ Total amount of work (kJ) in each SIT repetition (216.2 ± 24.6 vs. 220.9 ± 12.4 kJ, *p*<0.01), ↑ MAP (369.5 ± 42.5 to 393.9 ± 39 W) and ↑ $\dot{V}O_2$max (57.4 ± 3.4 to 63.5 ± 6.1 mL·kg·min^{-1}). SIT+HIIT$_2$: ↑ $\dot{V}O_{2max}$ (58.6 ± 5.9 to 63.6 ± 3.9 mL·kg·min^{-1}); MAP did not significantly improve from pre- to post- (349.3 ± 26.5 to 365.0 ± 35.4 W, *p* = 0.09). No significant changes in CON.
			SIT+HIIT$_2$ (*n* = 7)	Cyclists in this group had a low-volume, high-intensity training background (7–9 h·week^{-1}). The 8-week intervention followed exactly the same structure and volume as SIT+HIIT$_1$.	
			CON (*n* = 7)	The training background of this group consisted of high-volume cycling at moderate intensities (14–16 h·week^{-1}). Cyclists performed both varied-intensity training and MICT. Varied-intensity training sessions were held twice a week and followed a sequence of several minutes at 65–70%, followed by 80-85% and then 70–80% HR_{max} repeated multiple times for 120–180 min. MICT sessions were identical to SIT+HIIT$_1$ and SIT+HIIT$_2$ but were held three times a week. Training volume was identical to pre-intervention, with a ~50% reduction every fourth week.	
Hommel et al. [61]	20 recreationally-trained amateur cyclists. SIT (age: 27.9 ± 1.8 years; mass: 73.43 ± 4.84 kg; stature: 181.4 ± 4.3 cm) CON (age: 26.7 ± 2.2 years; mass: 75.52 ± 11.66; stature: 180.6 ± 6.6 cm)	Randomised controlled trial (6 weeks). Physiological measures were taken every 2 weeks.	SIT (*n* = 10)	Cyclists trained three times per week. During weeks 1–2, interval sessions consisted of 4 x 30-s all-out efforts, interspersed with a fixed recovery period (30 W with cadence <50 rev·min^{-1}) of 4.5 min. The number of Wingate tests in each interval session progressively increased during the intervention (5 all-out efforts in weeks 3–4; and 6 in weeks 5–6).	SIT: ↑ $\dot{V}O_{2max}$ (62.6 ± 8.8 to 65.2 ± 7.9 mL·kg^{-1}·min^{-1}) and ↑ Power at MLSS (259.7 ± 67.6 to 284.7 ± 58.7 W) after 6 weeks. CON: ↑ $\dot{V}O_{2max}$ (61.0 ± 4.8 to 66.7 ± 4.8 mL·kg^{-1}·min^{-1}) and ↑ Power at MLSS (269.1 ± 52 to 300.8 ± 58.4 W). Differences in $\dot{V}O_{2max}$ and power at MLSS between SIT and CON were not statistically significant post-intervention.
			CON (*n* = 10)	Cyclists trained three days per week throughout the intervention. Each session consisted of 60 min of cycling at a blood lactate of 1.5–2.5 mmol·L^{-1}, performed throughout the study period.	

Study authors	Participant characteristics (mean ± SD) - age (years), sex, body mass (kg), stature (cm), groups (n), training level	Study Design	Intervention		Outcomes and Results
Laursen et al. [91], Laursen et al. [64]	41 trained male cyclists (12 triathletes, 3 duathletes), with ≥3 years of training experience (age: 25 ± 6 years; stature: 180 ± 5 cm; mass: 75 ± 7 kg). During the intervention, the weekly training distance was 285 ± 95 km·week-1, and it was similar to the pre-intervention volume. Data from 3 participants were excluded from the analysis due to illness/failure to comply with the training regimen.	Matched, controlled trial (4 weeks). Participants were assigned to groups based on (1) TT performance and (2) $\dot{V}O_{2peak}$. Participants were tested at baseline, and after 2 and 4 weeks of training.	Short $HIIT_1$ (n = 8)	Cyclists trained twice per week. Each interval session consisted of 8 bouts at MAP, for a work duration of 60% of the time to exhaustion at MAP, with a 1:2 recovery ratio (120% of the time to exhaustion at MAP).	Short $HIIT_1$: ↑ $\dot{V}O_{2peak}$ (5.00 ± 0.52 to 5.26 ± 0.47 L·min-1), ↑ PPO (439 ± 29 to 460 ± 37 W), ↑ TT-40 km speed (42.2 ± 2.4 to 44.4 ± 2.8 km·h^{-1}), ↑ VT_1 (3.25 ± 0.22 to 3.74 ± 0.28 L·min^{-1}), ↑ VT_2 (3.83 ± 0.40 to 4.43 ± 0.22 L·min^{-1}) Short $HIIT_2$: ↑ $\dot{V}O_{2peak}$ (4.89 ± 0.38 to 5.28 ± 0.35 L·min^{-1}), ↑PPO (431 ± 32 to 457 ± 26 W), ↑ TT-40 km speed (41.4 ± 2.5 to 43.7 ± 2.4 km·h^{-1}), ↑ VT_1 (2.99 ± 0.38 to 3.63 ± 0.26 L·min^{-1}), ↑ VT_2 (3.82 ± 0.42 to 4.41 ± 0.45 L·min^{-1}) SIT: ↑ $\dot{V}O_{2peak}$ (4.91 ± 0.37 to 5.06 ± 0.46 L·min^{-1}), ↑ PPO (425 ± 32 to 438 ± 36 W), ↑ TT-40 km speed (41.9 ± 2.6 to 43.7 ± 2.1 km·h^{-1}), ↑ VT_1 (3.16 ± 0.59 to 3.69 ± 0.52 L·min^{-1}), ↑ VT_2 (3.82 ± 0.44 to 4.15 ± 0.57 L·min^{-1}) Changes in $\dot{V}O_{2peak}$ and PPO in short-$HIIT_2$ were ↑ than in SIT.
			Short $HIIT_2$ (n = 9)	Cyclists trained twice per week. The intervention in this group was the same as Short-HIIT1, except that recovery duration was dependent on heart rate returning to 65% HR_{max}.	
			SIT (n = 10)	Cyclists trained twice per week. SIT performed 12 intervals of 30 s efforts at 175% PPO, with 4.5 min of recovery between bouts.	
			CON (n = 11)	Participants were asked to continue with their LIT/MICT training programme.	
Laursen, Blanchard and Jenkins [63]	14 well-trained cyclists with ≥3 years training and competitive experience (age: 23.5 ± 3.5 years; stature: 179.1 ± 2.6 cm; mass: 71.6 ± 5.8 kg). In the 2 months leading up to the intervention (base period), training was predominantly low-intensity (289 ± 42 km·week^{-1}).	Controlled trial (2 weeks).	Short HIIT (n = 7)	Cyclists performed four HIIT sessions over a 2-week period.. Each HIIT session consisted of 20 x 1 min bouts at MAP/PPO, with 2 min recovery between efforts at 50 W. After the twentieth bout and an additional 2 min recovery, cyclists were required to perform a final effort at the same intensity until volitional exhaustion in each session.	Short HIIT: ↑ PPO (4 ± 3%), ↑ VT_1 and VT_2 (23 ± 8% and 15 ± 8%, respectively), ↑ Power at VT_1 and VT_2 (6 ± 3% and 7 ± 3%, respectively). CON: No changes in PPO and VT_1/VT_2 (W and L·min^{-1}). $\dot{V}O_{2peak}$ did not change significantly in either group. Changes in VT_2 were strongly correlated with changes in PPO (r = 0.83, p < 0.05) in the short-HIIT group.
			CON (n = 7)	Cyclists were required to maintain their normal training during the intervention.	
Ronnestad et al. [65]	20 well-trained cyclists (age: 33 ± 10 years; stature: 182 ± 4 cm; mass: 76 ± 6 kg). Training volume of the cyclists during the 4 weeks prior to the intervention period was 8 ± 5 and 10 ± 5 h·week^{-1} for SIT and HIIT groups, respectively, performed predominantly at lower intensities (0.3 ± 0.2 and 0.4 ± 0.3 h·week^{-1} of high-intensity training for SIT and HIIT, respectively). 4 cyclists did not complete the study due to illness/withdrawal without justification.	Randomised controlled trial, matched (10 weeks). Participants were randomly assigned to one of the groups following stratification by $\dot{V}O_{2max}$.	SIT (n = 9)	Cyclists performed two weekly SIT sessions. Each session consisted of 30-s work intervals, interspersed by 15-s recovery periods, performed continuously for 9.5 min. Each set was separated by 3 min recovery. Cyclists performed 3 sets per session, equating to a total of 19.5 min of SIT work. Cyclists performed each interval at their maximal sustainable intensity. The intensity of recovery bouts between intervals and sets corresponded to 50% mean power output achieved during intervals.	SIT: ↑ $\dot{V}O_{2max}$ (8.7 ± 5.0%), ↑ MAP (8.5 ± 5.2%), ↑ Power at OBLA (12 ± 9%), ↑ TT-5 min MPO (8 ± 7%), ↑ TT-40 min MPO (12 ± 10%), ↑ 30-s Wingate (5 ± 3%). Long HIIT: ↑ TT-40 min MPO (4 ± 4%), non-significant improvements in power at OBLA (5 ± 6%, p = 0.08), no significant changes in $\dot{V}O_{2max}$, MAP, TT-5 min and 30-s Wingate. No within or between-group changes in cycling economy and GE during the intervention period.
			Long HIIT (n = 7)	Cyclists performed two weekly HIIT sessions. HIIT group performed 4 x 5 min intervals at their maximal sustainable intensity in each repetition, separated by 2.5 min recovery bouts at 50% of the power output achieved during intervals.	
Ronnestad et al. [59]	18 national-level road and MTB cyclists. SIT (age: 24 ± 6 years; stature: 181 ± 4 cm; mass: 75.2 ± 3.6 kg). Long HIIT (age: 25 ± 6 years, stature: 183 ± 4 cm, mass: 74.9 ± 6.1 kg). The intervention was conducted during the preparatory period. All cyclists had been involved in high volume low-intensity training in the 3 weeks prior to the intervention.	Matched, controlled trial (3 weeks). Participants were matched based on $\dot{V}O_{2max}$.	SIT (n = 9)	Cyclists in this group performed SIT 3 times a week. Each session consisted of 3 sets of 30 s work intervals separated by 15 s recovery periods performed continuously for 9.5 min. Recovery between each set was 3 min. Participants were instructed to perform the intervals at their maximal sustainable intensity. Recovery between sets and repetitions was set to an intensity of 50% of the power output achieved during the intervals.	SIT: ↑ $\dot{V}O_{2max}$ (2.6 ± 2.7%), ↑ MAP (3.7 ± 4.3%), ↑ TT-20 min MPO (4.7 ± 4.4%). Long HIIT: no changes in $\dot{V}O_{2max}$, MAP and TT-20 min between baseline and post-intervention. The cycling economy and power output at OBLA did not change in any of the training groups.
			Long HIIT (n = 9)	Cyclists performed 3 weekly HIIT sessions of 4 x 5 min intervals at their maximal sustainable work intensity for each interval, interspersed with 2.5 min recovery bouts at 50% of power output used during work intervals.	

Study authors	Participant characteristics (mean ± SD) - age (years), sex, body mass (kg), stature (cm), groups (n), training level	Study Design	Intervention		Outcomes and Results
Seiler et al. [58]	37 recreationally-trained cyclists, with 4-10 h·week^{-1} of training at the inclusion stage. CON (age: 40 ± 6 years; mass: 80.4 ± 12.5 kg). Short HIIT (age: 43 ± 7 years; mass: 79.9 ± 13.3 kg). Long HIIT1 (age: 39 ± 8 years; mass: 89.7 ± 11.3 kg). Long HIIT2 (age: 43 ± 4 years; mass: 83.8 ± 10.8 kg). One participant withdrew from the study, and another was excluded based on training status misrepresentation. The intervention was conducted during the early preparatory period of the cyclists (January to March).	Randomised controlled trial, matched (7 weeks). Training groups were initially matched for (1) weekly training volume and (2) weekly interval sessions.	Short HIIT (n = 9)	Two weekly sessions of 4 x 4 min intervals with 2 min recovery between bouts. Cyclists were instructed to perform each interval session at their maximal sustainable intensity, and the 2–3 additional weekly sessions exclusively at a low intensity.	Short HIIT: ↑ MAP (343 ± 68 to 361 ± 72 W), ↑ power at OBLA (220 ± 49 to 238 ± 55 W), ↑ TTE at 80% $\dot{V}O_{2max}$ (9.7 ± 2.8 to 15.84 ± 7.1 min). Long HIIT$_1$: ↑ $\dot{V}O_{2max}$ (52.8 ± 4.8 to 58.3 ± 5.8 mL·kg^{-1}·min^{-1}), ↑ MAP (378 ± 52 to 410 ± 27 W), ↑ power at OBLA (241 ± 41 to 280 ± 33 W), ↑ TTE at 80% $\dot{V}O_{2max}$ (11.88 ± 4.1 to 22.7 ± 12 min). Long HIIT$_2$: ↑ $\dot{V}O_{2max}$ (51.1 ± 5.8 to 54.4 ± 5.2 mL·kg^{-1}·min^{-1}), ↑ MAP (361 ± 51 to 372 ± 50 W), ↑ power at OBLA (228 ± 51 to 249 ± 45 W), ↑ TTE at 80% $\dot{V}O_{2max}$ (8.52 ± 1.8 to 13.83 ± 4 min). CON: ↑ power at OBLA (222 ± 42 to 239 ± 38 W). Improvements in TTE at 80% power at $\dot{V}O_{2max}$ in all three interval training groups were significantly correlated with the change in power at 4 mmol·L^{-1} (r = 0.66, p < 0.001).
			Long HIIT$_1$ (n = 9)	Two weekly sessions of 4 x 8 min intervals with 2 min recovery between bouts. Cyclists were instructed to perform each interval session at their maximal sustainable intensity, and the 2–3 additional weekly sessions exclusively at a low intensity.	
			Long HIIT$_2$ (n = 9)	Two weekly sessions of 4 x 16 min intervals with 2 min recovery between bouts. Cyclists were instructed to perform each interval session at their maximal sustainable intensity, and the 2–3 additional weekly sessions exclusively at a low intensity.	
			CON (n = 8)	Cyclists performed LIT to MICT during the intervention, 4–6 times per week. Participants were advised to increase weekly training volume by 20–30% during the intervention	
Stepto et al. [86]	19 male trained cyclists, who had not been engaged in interval training in the 3-4 months preceding the intervention. SIT (age: 26 ± 4 years; mass: 78 ± 15 kg) Short HIIT1 (age 24 ± 5 min; mass: 70 ± 20 kg) Short HIIT2 (age: 28 ± 1 years; mass: 73 ± 4 kg) Short HIIT3 (age: 27 ± 7 years; mass: 80 ± 8 kg) Long HIIT (age: 26 ± 6 years; mass: 78 ± 8 kg)	Randomised controlled trial (3 weeks). Each cyclist performed a total of six interval training sessions.	SIT (n = 4)	Each session consisted of 12 x 30 s intervals at 175% MAP, with 4.5 min of recovery between bouts at 100 W.	SIT, Short HIIT$_2$ and Short HIIT$_3$ improved time-trial performance and MAP; however, the cubic trend predicted the greatest enhancements in performance in the SIT (2.4%, 4.0–0.7%) and Short HIIT$_3$ (2.8%, 4.3–1.3%) groups. Intervals in the Short HIIT1 and Long HIIT groups did not result in greater performance improvements.
			Short HIIT$_1$ (n = 3)	Cyclists performed 12 x 1 min intervals at 100% MAP, with a 4 min of recovery between bouts at 100 W.	
			Short HIIT$_2$ (n = 4)	Cyclists performed 12 x 2 min intervals at 90% MAP, with 3 min of recovery between bouts at 100 W.	
			Short HIIT$_3$ (n = 4)	Cyclists performed 8 x 4 min intervals at 85% MAP, with 1.5 min of recovery between work bouts at 100 W.	
			Long HIIT (n = 4)	Cyclists performed 4 x 8 min intervals at 80% MAP, with 1 min of recovery between work bouts at 100 W.	
Swart et al. [66]	21 well-trained cyclists, with ≥3 years of competitive experience (age: 31 ± 6 years; stature: 182 ± 7 cm; mass: 74.9 ± 8.8 kg). Participants had a training volume of ≥6 h·week^{-1} in the 6 weeks prior to the intervention. Four subjects were excluded from the analysis due to illness, injury and training level.	Randomised, controlled trial (4 weeks).	Short HIIT$_1$ (n = 6)	Cyclists performed 2 weekly HIIT sessions. Each session consisted of 8 x 4 min intervals at 80% of power output at MAP, interspersed by 90 s recovery periods at self-selected intensity.	Short HIIT$_1$: ↑ MAP (3.5%) (5.1 ± 0.6 to 5.3 ± 0.6 W·kg^{-1}) and ↑ TT-40 km (2.3%) (65:14 ± 2:31 to 63:43 ± 1:59 min:s) compared to CON. Short HIIT$_2$: ↑ MAP (5%) (5.3 ± 0.3 to 5.5 ± 0.4 W·kg^{-1}) and ↑ TT-40 km (2.1%) (66:15 ± 2:06 to 64:48 ± 2:07 min:s) compared to CON. No significant differences in $\dot{V}O_{2max}$ between baseline and post-intervention in either group. Changes in MAP were significantly correlated with the percentage change in 40-km TT for all groups (r = 0.70).
			Short HIIT$_2$ (n = 6)	Cyclists performed the same intervals as Short HIIT1 but performed their intervals at the heart rate coinciding with 80% of MAP. Due to heart rate lag, cyclists were asked to achieve the target heart rate within the first 3 min in interval 1, 2 min in interval 2, and 1 min in intervals 3–8.	
			CON (n = 5)	CON performed a 40 km TT twice a week at <70% MAP. Cyclists were also required to complete the same training as the HIIT groups outside of the laboratory environment (LIT to MICT).	

Study authors	Participant characteristics (mean ± SD) - age (years), sex, body mass (kg), stature (cm), groups (n), training level	Study Design	Intervention		Outcomes and Results
Sylta et al. [60] *	69 male well-trained cyclists, with >3 years of cycling experience and competing regularly (age: 38 ± 8 years). 6 subjects were excluded from the analysis due to failure to comply with at least 70% of prescribed interval sessions and/or absence from post-intervention testing. The intervention was performed in the early preparatory period (January–March).	Randomised controlled trial (12 weeks). Training groups were matched based on (1) age, (2) cycling experience, and (3) $\dot{V}O_{2peak}$.	Increasing HIIT intensity (INC) (*n* = 23)	The intervention consisted of three 4-week mesocycles. INC group performed 8 interval sessions in mesocycle 1 (weeks 1–4, 4 x 16 min intervals), 8 interval sessions in mesocycle 2 (weeks 5–8, 4 x 8 min intervals) and 8 interval sessions in mesocycle 3 (weeks 9–12, 4 x 4 min intervals). Intervals were prescribed at maximal sustainable intensity, aiming to achieve even or progressive power from the first to the fourth interval. Recovery between work bouts was 2 min in all interval sessions.	INC: ↑ TT-40 min (8%, 5.3–10.6%), ↑ PPO (7.1%, 4.7–9.5%), ↑ Power at OBLA (5.8%, 2.7–8.9%), ↑ $\dot{V}O_{2peak}$ (5.8%, 3.7–8.0%), ↓ GE (-2.6%, -4.4 to -0.9%)
			Decreasing HIIT intensity (DEC) (*n* = 20)	DEC group followed the same three 4-week mesocycle structure as INC. DEC performed the interval sessions in the opposite mesocycle order as INC (weeks 1–4, 4 x 4 min intervals; weeks 5–8, 4 x 8 min; weeks 9–12, 4 x 16 min). The intensity of work bouts and recovery between intervals was the same as INC.	DEC: ↑ TT-40 min (7.4%, 4.4–10.4%), ↑ PPO (6.0%, 3.4–8.6%), ↑ Anaerobic power output (2.7%, 0.7–4.7%), ↑ Power at OBLA (5.9%, 2.6–9.2%), ↑ $\dot{V}O_{2peak}$ (4.5%, 2.3–6.8%), ↑ % $\dot{V}O2peak$ at OBLA (3.7%, 1.2–6.3%), ↓ GE (-2.0%, -3.8 to -0.2%)
			Mixed HIIT intensity (MIX) (*n* = 20)	MIX group followed the same mesocycle structure as the two previous training groups. MIX performed the 24 interval sessions in alternating order (session 1: 4 x 16 min; session 2: 4 x 8 min; session 3: 4 x 4 min; session 4: 4 x 16 min; etc.). The intensity at which intervals were performed and duration of recovery bouts was identical to INC and DEC.	MIX: ↑ TT-40 min (4.9%, 1.8–8.0%), ↑ PPO (6.5%, 3.9–9.2), ↑ Anaerobic power output (2.4%, 0.3–4.4), ↑ $\dot{V}O_{2peak}$ (3.8%, 1.5–6.0%)
Turnes et al. [62], Turnes et al. [92]	21 recreationally-trained cyclists (19 males, 2 females). Long HIIT (age: 22 ± 2 years; mass: 76 ± 6 kg; stature: 175 ± 6 cm). Short HIIT (age: 23 ± 3 years; mass: 78 ± 8 kg; stature: 174 ± 7 cm).	Matched, controlled trial (4 weeks).	Long HIIT (*n* = 11)	Cyclists performed 3 sessions per week for a 4-week period. Participants completed a single series of 4 x 5 min intervals at 105% CP, corresponding to 218 ± 39 W, with 1 min of passive recovery between bouts, during each interval training session. An additional interval was added to each interval series per session per week.	Long HIIT: ↑ $\dot{V}O_{2max}$ (3.3 ± 1.8%), ↑ LT (27.9 ± 11.3%), ↑ MAP (10.1 ± 2.5%), ↑ CP (11.6 ± 5.0%), ↑ I_{HIGH} (7.3 ± 3.1%), ↓ FI (45.6 ± 8.3 to 42.3 ± 8.3%), ↑ 250-kJ TT (9.2%) (1148 ± 217 to 1040 ± 188 s), ↑ 250-kJ TT MPO (226 ± 47 to 248 ± 47 W)
			Short HIIT (*n* = 10)	Cyclists trained 3 times per week during the intervention. In each interval session, this group performed two series of four intervals at the highest intensity at which $\dot{V}O2max$ was attained (355 ± 60 W; IHIGH) for a duration equal to 60% of the lowest exercise duration at which $\dot{V}O2max$ was attained (TLOW; 100% TLOW: 131 ± 27 s), with a 1:2 recovery ratio between intervals at 80% of LT. Between series, the cyclists recovered for 10 min (5 min of passive and active recovery each). Training was progressively increased by including a single extra interval in each series per week.	Short HIIT: ↑ $\dot{V}O_{2max}$ (6.3 ± 1.9%), ↑ LT (54.8 ± 11.8%), ↑ MAP (10.4 ± 2.6%), ↑ CP (12.1 ± 5.2%), ↑ I_{HIGH} (6.0 ± 3.3%), ↑ PPO in the Wingate test (5.7 ± 2.3%), ↑ MPO in the Wingate test (3.7 ± 2.0%), ↑ FI (41.4 ± 8.8 to 45.3 ± 9.0%), ↑ 250-kJ TT (8.7%) (1137 ± 199 to 1014 ± 208 s), ↑ 250-kJ TT MPO (227 ± 45 to 252 ± 40 W) Improvements in $\dot{V}O_{2max}$ and LT were ↑ in Short HIIT compared to Long HIIT after the intervention. No significant changes in *W′* and TLOW in either group.

Note: *↑ = Significant improvement between baseline and post-intervention (p < 0.05); ↓ = Significant decrease between baseline and post-intervention (p < 0.05); HIIT = High-Intensity Interval Training; SIT = Sprint Interval Training; LIT = Low-Intensity Training; MICT = Moderate Intensity Continuous Training; HRmax = Maximum Heart Rate; VO2max/VO2peak = Maximal/Peak Oxygen Uptake; MAP = Maximal Aerobic Power; PPO = Peak Power Output; LT = Lactate Threshold; CP = Critical Power; W′ = Work capacity above Critical Power; MLSS = Maximal Lactate Steady State; OBLA = Onset of Blood Lactate Accumulation; TT = Time-Trial Performance; TTE = Time-to-Exhaustion; GE = Gross Efficiency; FI = Fatigue Index (%); IHIGH = The highest exercise intensity at which VO2max was attained; TLOW = The lowest exercise duration at which VO2max was attained. Data presented as Mean ± SD or Mean ± 95% CI (*).*

Risk of Bias and Quality of Evidence

We assessed the risk of bias for all outcomes across all studies included in this review. An overall risk of bias assessment is presented for all outcomes combined (Figure 2) based on the individual outcomes which raised the greatest concerns in the bias assessments. Individual risk of bias assessments for each outcome included in the meta-analysis are available in the supplementary material, although these did not vary considerably between outcomes. Eleven trials were judged to raise some concerns overall, and one trial was deemed to have a high overall risk of bias. Common concerns were bias in the domains concerning the outcome measurement and the selection of the reported result.

GRADE assessments showed that the quality of evidence was low for absolute and relative $\dot{V}O_{2max}$/ $\dot{V}O_{2peak}$ and absolute and relative MAP/PPO, very low for Wingate and TT/TTE outcomes, and moderate for performance at thresholds outcomes. This was mainly due to the risk of bias judgements within individual studies and low precision of estimates (i.e., wide interval estimates in forest plots and/ or small sample size for each of the outcomes). A summary table with GRADE quality ratings can be found in Table 3.

Synthesis of Results

Overall Model of Main Effects

The main model for all outcomes (84 across 13 groups in 7 studies [median = 7, range = 4–36 effects) revealed a small standardised point estimate favouring interval training over LIT/MICT that was relatively imprecise with interval estimates ranging from trivial to moderate (0.33 [95% CI = 0.06 to 0.60]), with relatively low heterogeneity ($Q_{(83)}$ = 97.4, p = 0.13, I^2 = 29.43%). Figure 3 presents all standardised effects across studies in an ordered caterpillar plot. Figure 4 shows the contour enhanced funnel plot for all effects from these studies, the inspection of which did not reveal any obvious small

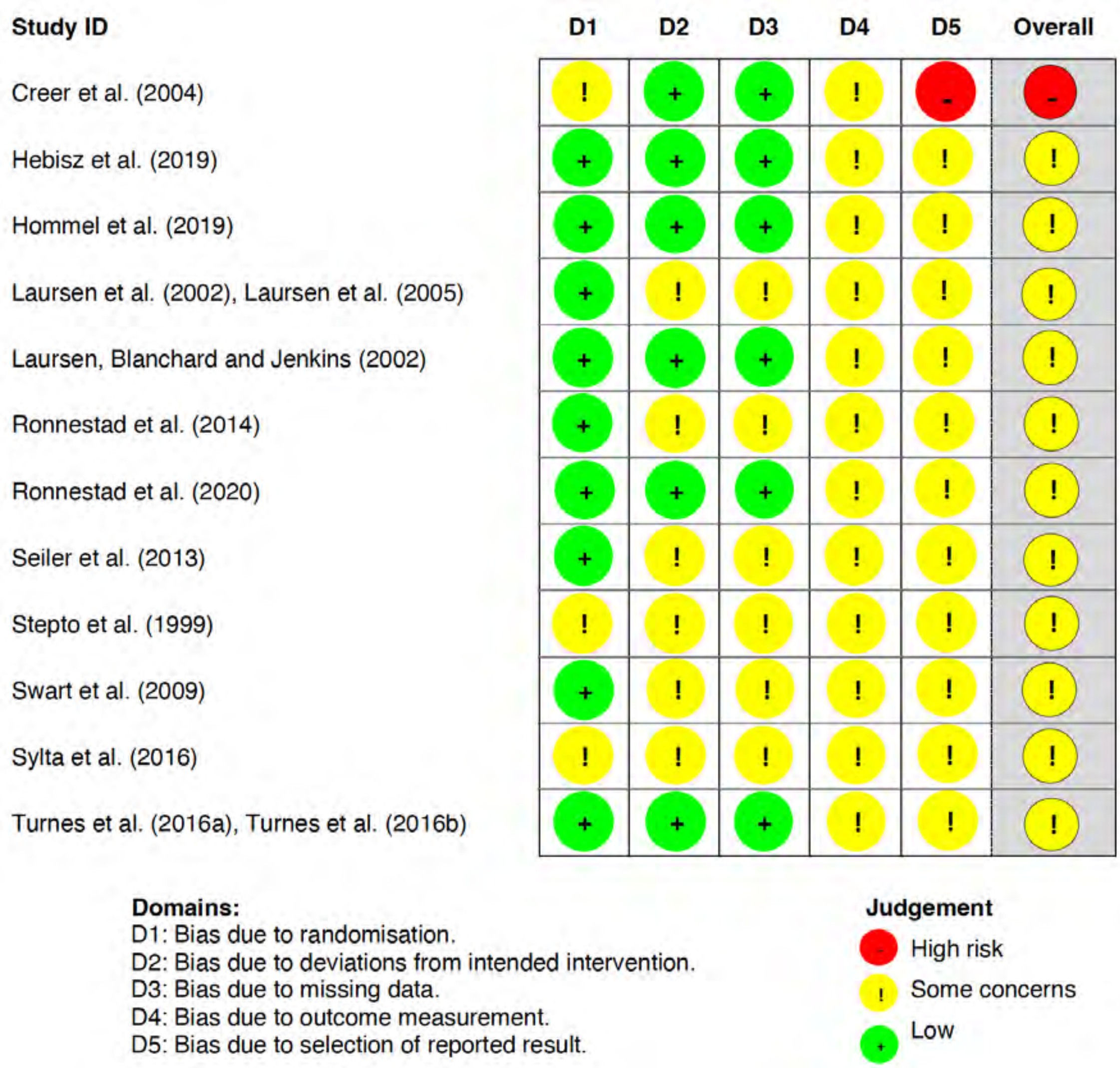

Figure 2. Risk of bias judgements for overall interventions in each included study, using the revised Cochrane risk of bias tool for randomised trials (RoB 2).

Table 3. Summary of findings and GRADE evidence profile

Summary of findings				Quality assessment					
Outcome	**No. of participants (interventions)**	**Pooled Hedges' g (95% CI)**	**I^2**	**Risk of bias**	**Inconsistency**	**Indirectness**	**Imprecision**	**Publication bias**	**Quality rating**
Absolute $\dot{V}O_{2max}/\dot{V}O_{2peak}$	104 (4)	0.28 (0.15 to 0.40)	0.00%	Serious limitations [a]	No serious inconsistency	No serious indirectness	Serious imprecision	Undetected	Low
Relative $\dot{V}O_{2max}/\dot{V}O_{2peak}$	120 (5)	0.10 (-0.34 to 0.54)	21.94%	Serious limitations [a]	No serious inconsistency	No serious indirectness	Serious imprecision	Undetected	Low
Absolute MAP/PPO	111 (4)	0.38 (0.15 to 0.61)	0.00%	Serious limitations [a]	No serious inconsistency	No serious indirectness	Serious imprecision	Undetected	Low
Relative MAP/PPO	52 (2)	0.43 (-0.09 to 0.95)	0.00%	Serious limitations [a]	No serious inconsistency	No serious indirectness	Serious imprecision	Undetected	Low
Wingate test parameters	47 (2)	0.01 (-3.56 to 3.57)	43.48%	Serious limitations [a]	Serious inconsistency [c]	No serious indirectness	Very serious imprecision	Undetected	Very Low
Performance at thresholds	117 (4)	0.46 (-0.24 to 1.17)	48.40%	No serious limitations [b]	No serious inconsistency	No serious indirectness	Serious imprecision	Undetected	Moderate
TT/TTE	90 (3)	0.96 (-0.81 to 2.73)	71.70%	Serious limitations [a]	Serious inconsistency [c]	No serious indirectness	Very serious imprecision	Undetected	Very Low

Note: GRADE = Grading of Recommendation, Assessment, Development, and Evaluation approach. $\dot{V}O_{2max}/\dot{V}O_{2peak}$ = Maximum/peak oxygen uptake; MAP/PPO = Maximum aerobic power/peak power output; TT = Time-trial performance; TTE = Time-to-exhaustion.

[a] *At least 50% of studies were judged to have some concerns in three or more domains in the Cochrane risk of bias tool for randomized trials (RoB 2).*

[b] *At least 50% of studies were judged to have a low risk of bias in three or more domains in the Cochrane risk of bias tool for randomized trials (RoB 2).*

[c] *Quality of evidence was downgraded on the basis of differences in direction of point estimates in individual studies, the width of the 95% CIs in the forest plots (range of interval estimates effects), and heterogeneity.*

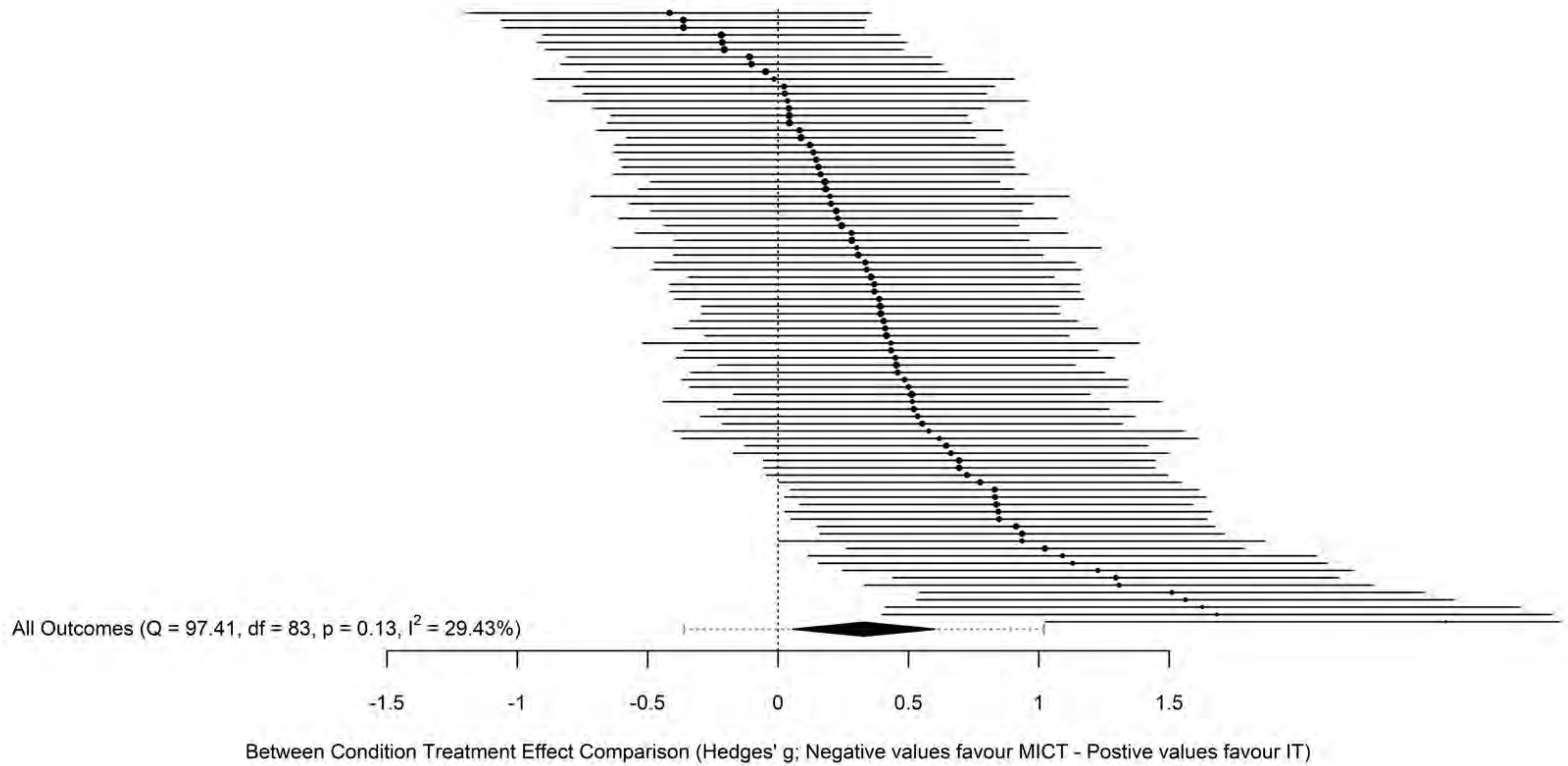

Figure 3. Standardised effects and interval estimates (note, dotted line on summary estimate are 95% prediction intervals) for all outcomes across all studies in an ordered caterpillar plot.

study bias.

Absolute/Relative Maximum/Peak Oxygen Uptake

The model for absolute $\dot{V}O_{2max}/\dot{V}O_{2peak}$ (11 across 4 studies [median = 2, range = 1–6 effects) revealed a small standardised point estimate favouring HIIT/SIT compared to LIT/MICT that was relatively imprecise with interval estimates ranging from trivial to small (0.28 [95% CI = 0.15 to 0.40]), with negligible heterogeneity ($Q_{(10)} = 3.19$, $p = 0.98$, $I^2 \approx 0\%$). Figure 5 presents the forest plot for absolute $\dot{V}O_{2max}/\dot{V}O_{2peak}$.

In contrast, the model for relative $\dot{V}O_{2max}/\dot{V}O_{2peak}$ (11 across 5 studies [median = 2, range = 1–3 effects) revealed only a trivial standardised point estimate favouring HIIT/SIT compared to LIT/MICT that was very imprecise with interval estimates ranging from small effects favouring CON to moderate effects favouring HIIT/SIT (0.10 [95% CI = -0.34 to 0.54]), with relatively low heterogeneity ($Q_{(10)} = 6.77$, $p = 0.75$, $I^2 = 21.94\%$). Figure 6 presents the forest plot for relative $\dot{V}O_{2max}/\dot{V}O_{2peak}$.

Maximal Aerobic Power/ Peak Aerobic Power

The model for absolute MAP/PPO (12 across 4 studies [median = 2.5, range = 1–6 effects) revealed a small standardised point estimate favouring HIIT/SIT compared to LIT/MICT that was relatively imprecise with interval estimates ranging from trivial to moderate effects favouring HIIT/SIT (0.38 [95% CI = 0.15 to 0.61]), with negligible heterogeneity ($Q_{(11)} = 3.38$, $p = 0.98$, $I^2 = 0\%$). Figure 7 presents the forest plot for absolute MAP/PPO.

The model for relative MAP/PPO (5 across 2 studies [median = 2.5, range = 2–3 effects) revealed a small standardised point estimate favouring HIIT/SIT over LIT/MICT that was relatively imprecise with interval estimates ranging from trivial effects favouring CON to large effects favouring HIIT/SIT (0.43 [95% CI = -0.09 to 0.95]), with negligible heterogeneity ($Q_{(4)} = 0.42$, $p = 0.98$, $I^2 = 0\%$). Figure 8 presents the forest plot for relative MAP/PPO.

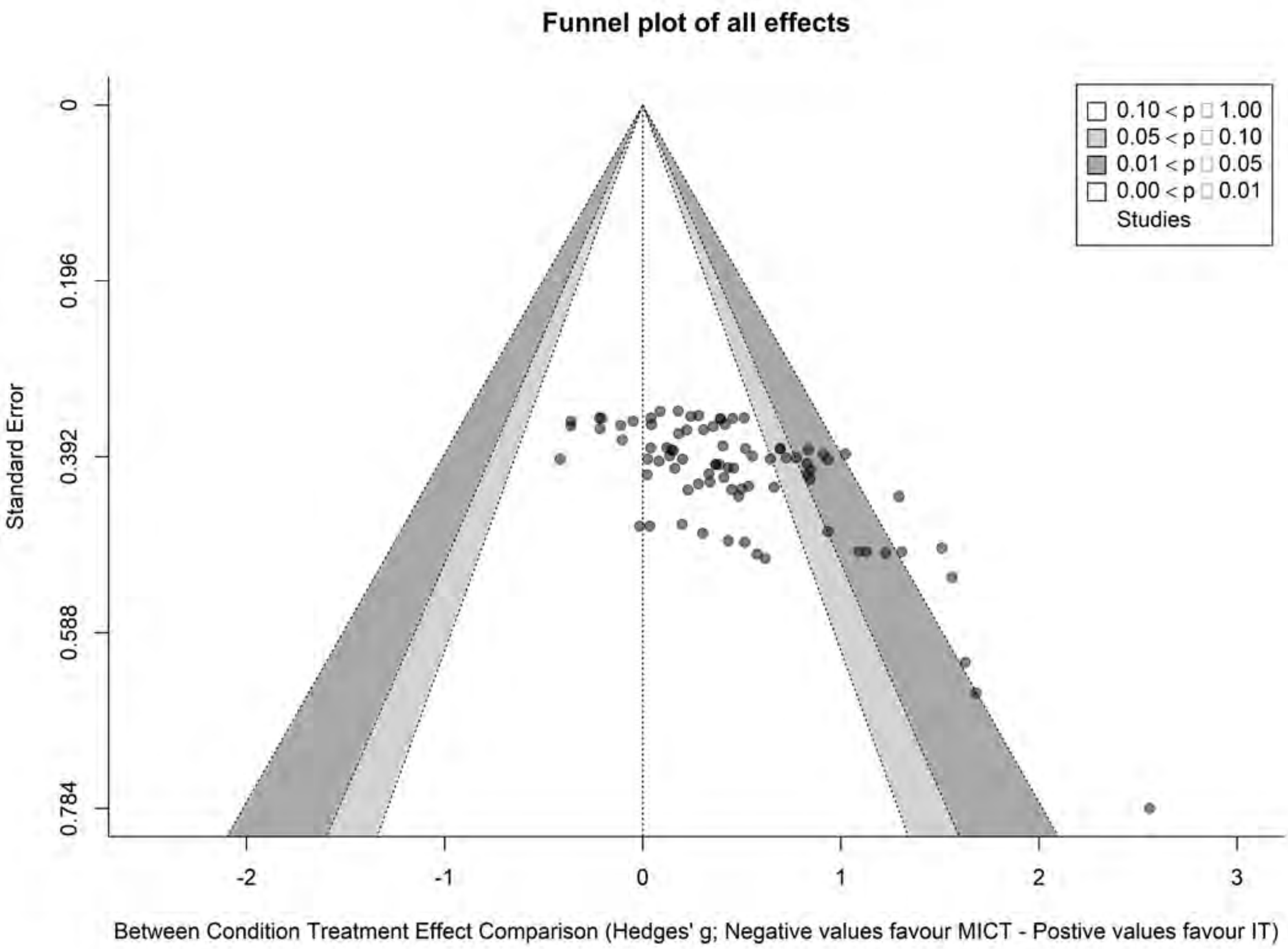

Figure 4. Contour enhanced funnel plot for all effects from the included studies.

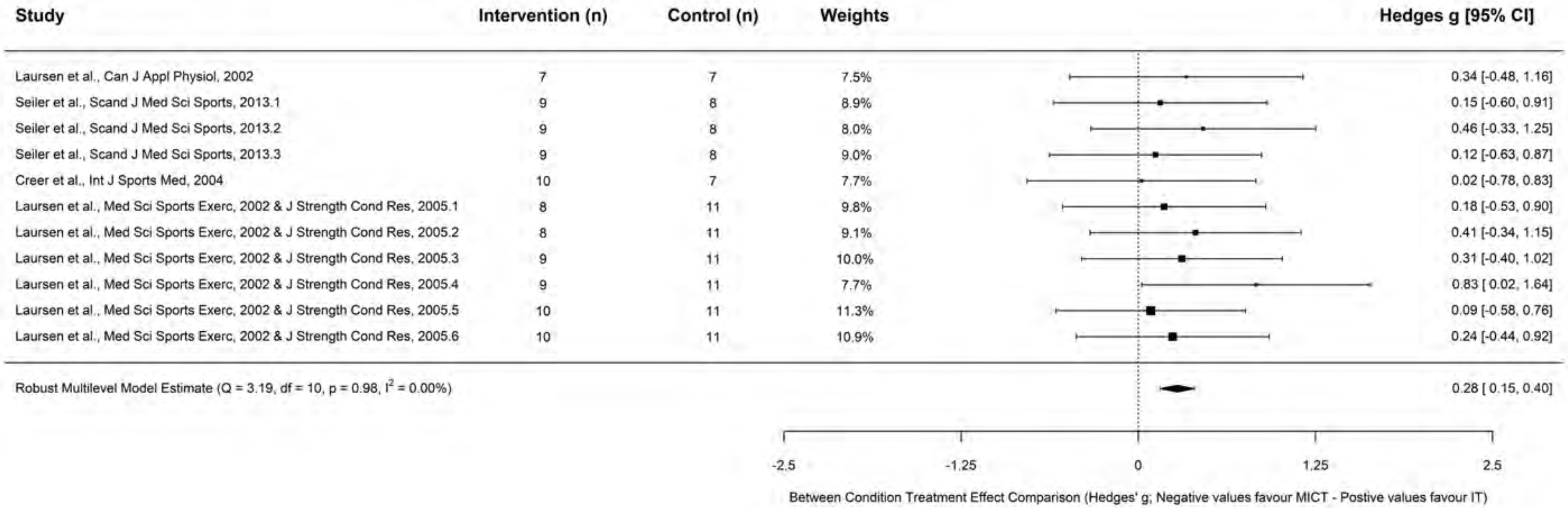

Figure 5. Standardised effects and interval estimates (note, dotted line on the summary estimate are 95% prediction intervals) for all absolute maximum/ peak oxygen uptake outcomes across all studies in the forest plot.

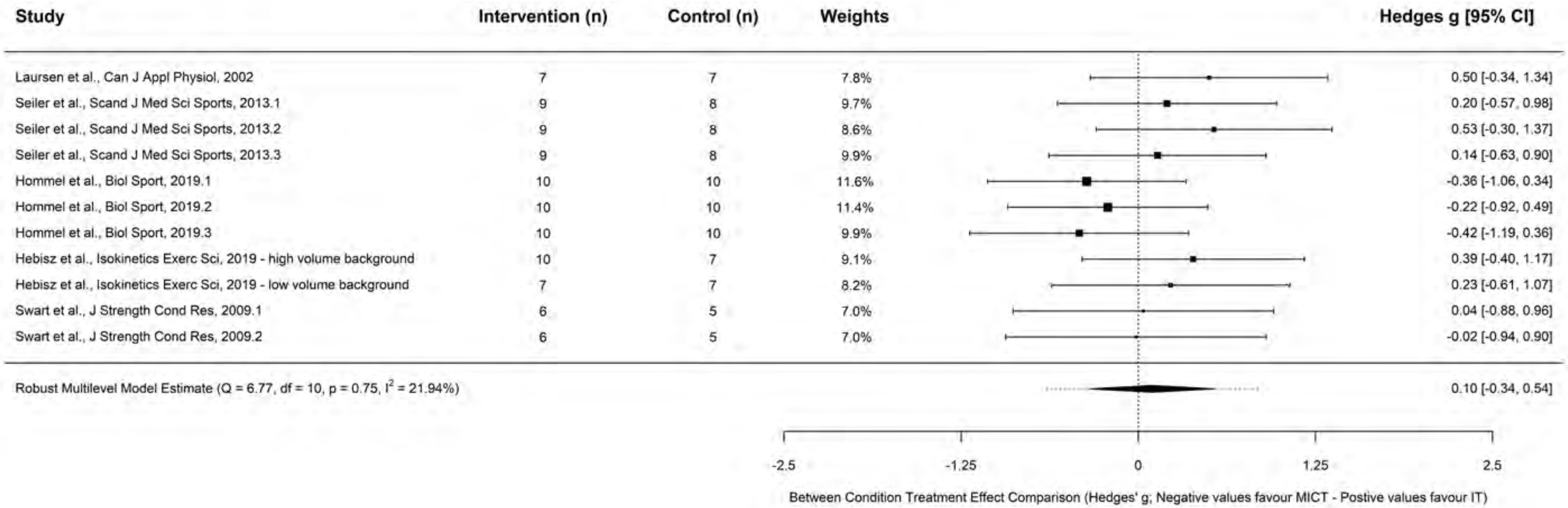

Figure 6. Standardised effects and interval estimates (note, dotted line on the summary estimate are 95% prediction intervals) for all relative maximum/ peak oxygen uptake outcomes across all studies in the forest plot.

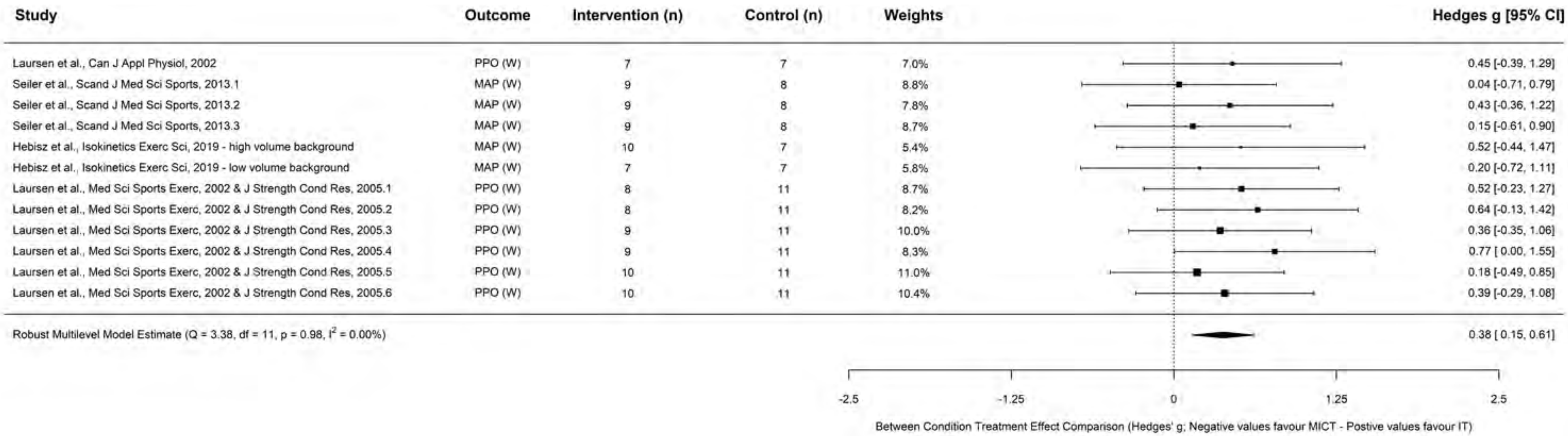

Figure 7. Standardised effects and interval estimates (note, dotted line on the summary estimate are 95% prediction intervals) for all absolute maximum aerobic power/peak power output outcomes across all studies in the forest plot.

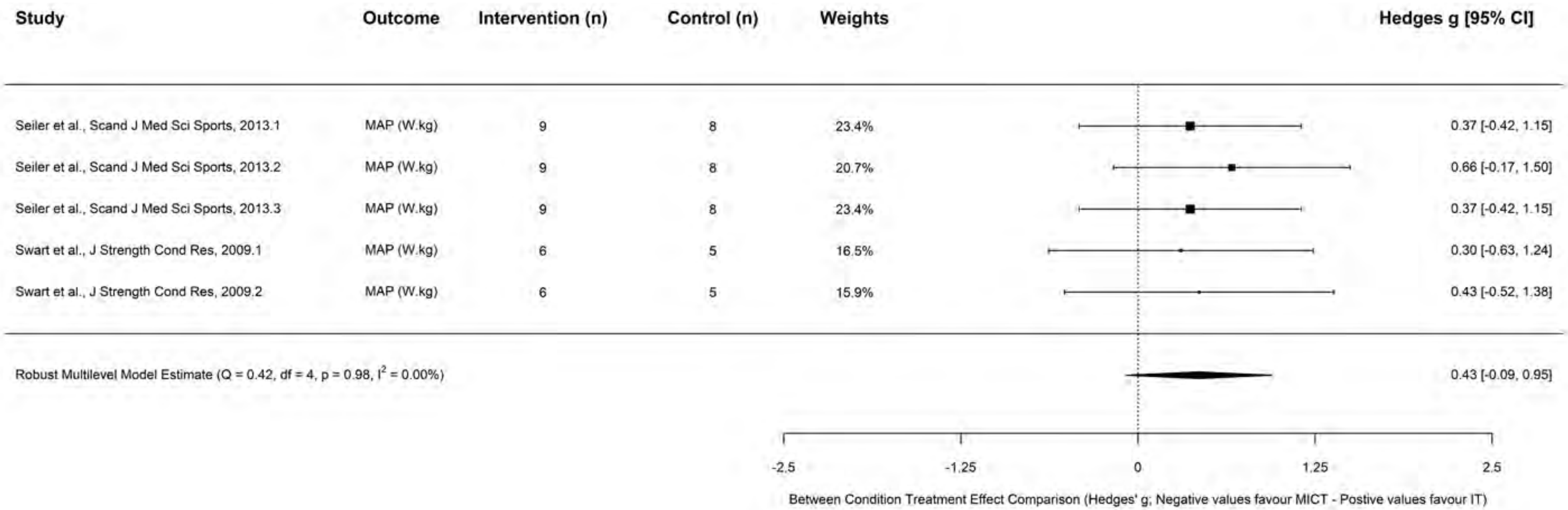

Figure 8. Standardised effects and interval estimates (note, dotted line on the summary estimate are 95% prediction intervals) for all relative maximum aerobic power/peak power output outcomes across all studies in the forest plot.

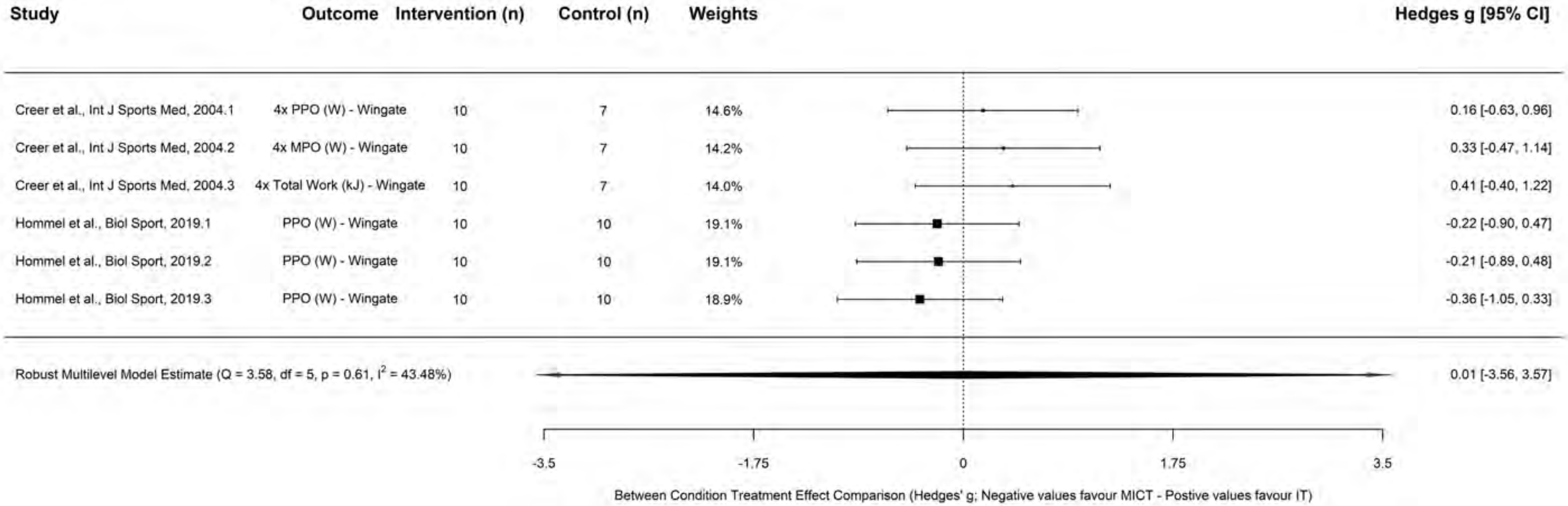

Figure 9. Standardised effects and interval estimates (note, dotted line on the summary estimate are 95% prediction intervals) for all Wingate outcomes across all studies in the forest plot.

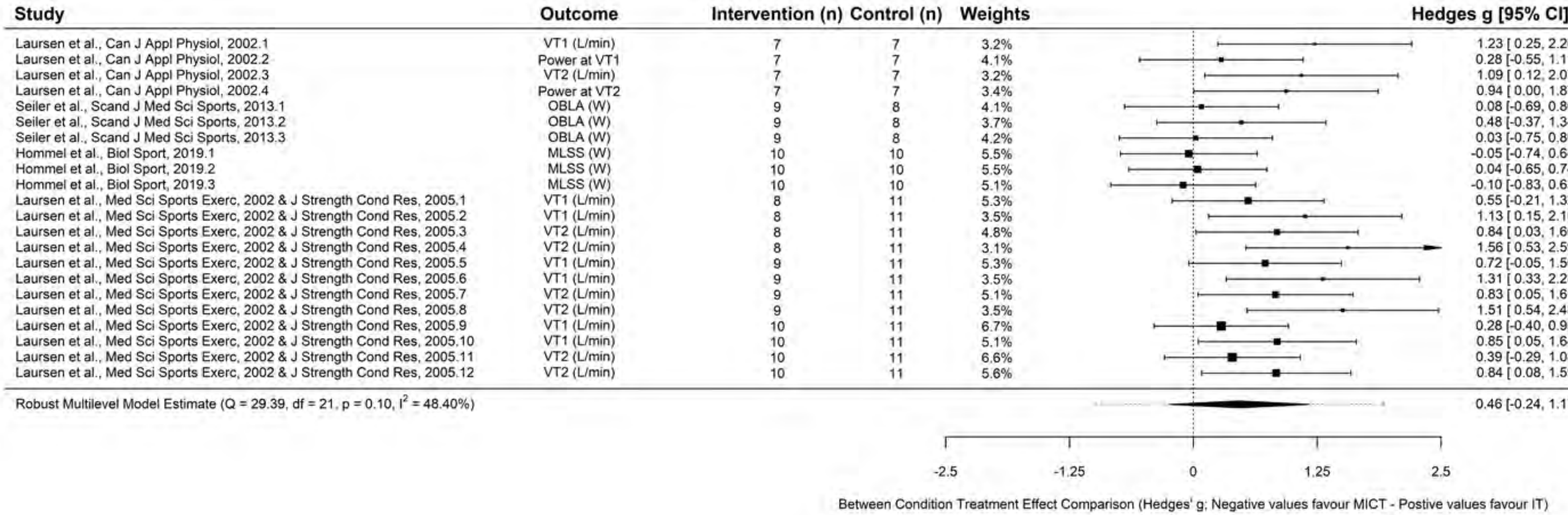

Figure 10. Standardised effects and interval estimates (note, dotted line on the summary estimate are 95% prediction intervals) for all performance at thresholds outcomes across all studies in the forest plot.

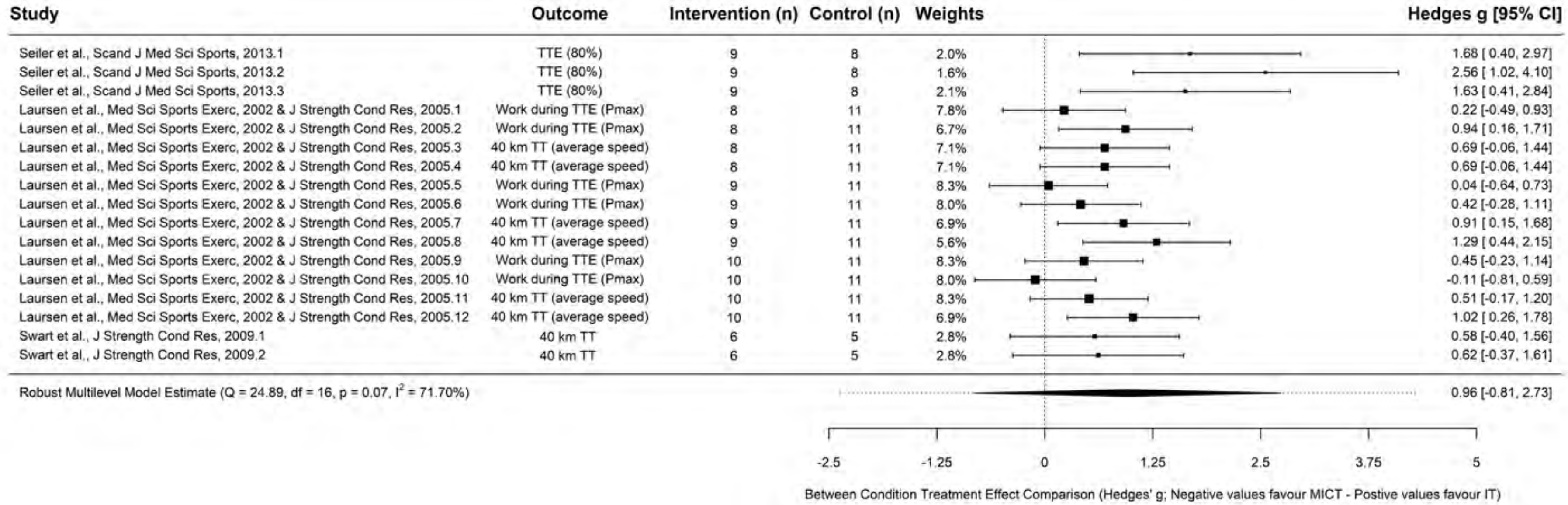

Figure 11. Standardised effects and interval estimates (note, dotted line on the summary estimate are 95% prediction intervals) for all Wingate outcomes across all studies in the forest plot.

Power Output/Total Work in Wingate Test

The model for Wingate-derived parameters (6 across 2 studies [3 effects per cluster]) revealed a negligible standardised point estimate for the difference between conditions and was highly imprecise with interval estimates ranging from large negative to positive effects favouring HIIT/SIT when directly compared to LIT/MICT (0.01 [95% CI = -3.56 to 3.57]), with moderate heterogeneity ($Q_{(5)}$ = 3.58, p = 0.61, I^2 = 43.48%). Figure 9 presents the forest plot for all reported parameters of the Wingate test.

Performance at Thresholds

The model for performance at thresholds (22 across 4 studies [median = 4, range = 3–12 effects) revealed a small standardised point estimate favouring HIIT/SIT over LIT/MICT that was relatively imprecise with interval estimates ranging from small effects favouring CON to moderate effects favouring HIIT (0.46 [95% CI = -0.24 to 1.17]), with moderate heterogeneity ($Q^{(16)}$ = 29.39, p = 0.10, I^2 = 48.40%). Figure 10 presents the forest plot for performance at thresholds.

Time-Trial and Time-to-Exhaustion

The model for TT/TTE outcomes (17 across 3 studies [median = 3, range = 2–12 effects) revealed a large standardised point estimate favouring HIIT/SIT compared to LIT/MICT that was very imprecise with interval estimates ranging from large effects favouring CON to large effects favouring HIIT/SIT (0.96 [95% CI = -0.81 to 2.73]), with relatively substantial heterogeneity ($Q_{(16)}$ = 24.89, p = 0.07, I^2 = 71.70%). Figure 11 presents the forest plot for TT/TTE outcomes.

Effect of Intervention Length

The meta-regression model of intervention length in weeks (84 outcomes across 7 studies [median = 7, range 4–36 effects]) revealed only a trivial effect and relatively precise effect estimate (β = 0.04 [95%CI = -0.07 to 0.15]). Figure 12 presents the meta-analytic scatterplot for the effects of intervention length.

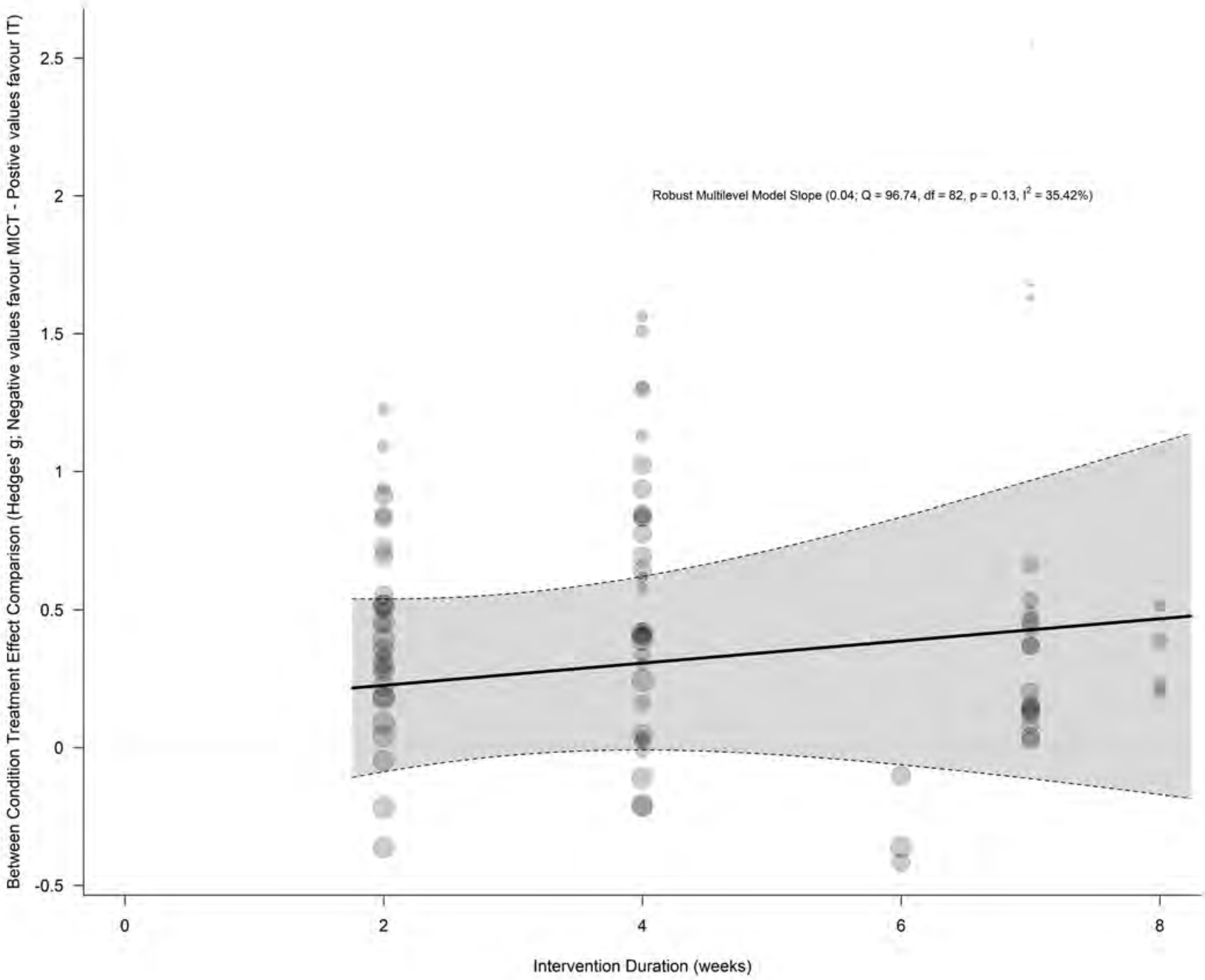

Figure 12. Standardised effects of intervention length (note, dot size reflects weighting by inverse variance) for all outcomes across all studies in the meta-analytic scatterplot.

Network Model of HIIT Types

The exploratory multilevel network meta-analysis model of all outcomes was performed to compare the general efficacy of different types of HIIT interventions (i.e., SIT, long-duration HIIT, short-duration HIIT, combined HIIT/SIT, and CON). Results showed little difference between different HIIT types, with most contrast effect point estimates being trivial to small and very imprecise (see Figure 13).

DISCUSSION

Summary of Evidence

The aims of the present review were: (1) to investigate the effectiveness of different interval training interventions when compared to LIT/MICT, and (2) to examine the modifying effects of interval work-bout duration and intervention length in driving performance improvements in trained cyclists. To our knowledge, this is the first systematic review and meta-analysis to measure physiological adaptations and changes in performance following HIIT differing in interval work-bout duration and SIT in trained cyclists alone. Furthermore, this study provides a quantitative evaluation of the effects of HIIT, SIT and endurance training on $\dot{V}O_{2max}$, MAP/PPO, physiological thresholds, Wingate, and TT/TTE performance, whereas most meta-analyses on interval training have focused solely on $\dot{V}O_{2max}$ trainability [67, 73, 100, 101]. The influence of $\dot{V}O_{2max}$ on endurance performance is well-established and should not be ignored; however, focusing solely on this variable may neglect the individual physiological adaptations that occur at submaximal levels during training [102]. Examining other physiological variables, in conjunction with $\dot{V}O_{2max}$, allows for a more comprehensive understanding of the factors driving the changes in performance seen in these studies [78].

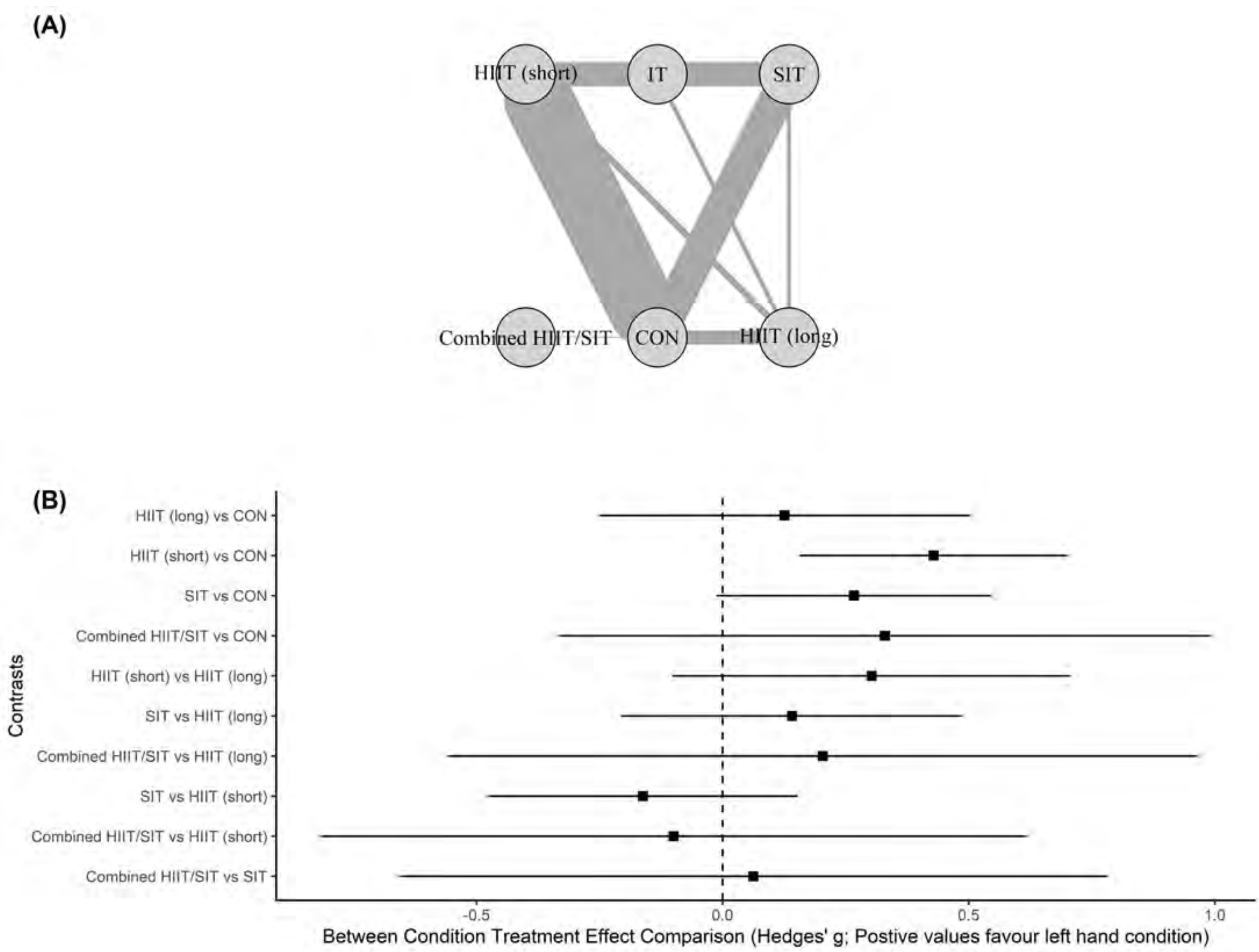

Figure 13. (A) Network graph model depicting the direct contrasts available across studies (note, the thickness of lines depicts the relative number of contrasts available). (B) Standardised effects for all pairwise contrasts between HIIT types from network model for all outcomes across all studies (note, the direction of contrast effects is such that effects favouring the left-hand condition are positive).

The results of this meta-analysis revealed that, firstly, performing interval training leads to small improvements in all outcome measures combined (overall main effects model, Hedges' g = 0.33) when compared to LIT/MICT in trained cyclists. At the individual level, HIIT/SIT induced negligible (Wingate model), trivial (relative $\dot{V}O_{2max}$/$\dot{V}O_{2peak}$), small (absolute $\dot{V}O_{2max}$/$\dot{V}O_{2peak}$, absolute MAP/PPO, relative MAP/PPO, performance at thresholds), and large (TT/TTE) improvements in physiological/performance variables compared to controls, with relatively to very imprecise interval estimates for most outcomes. Existing reviews on $\dot{V}O_{2max}$ have found either an unclear [72], a possibly small (67) or a possibly moderate [72, 103] favourable effect of HIIT compared to MICT in mixed populations. Other meta-analyses have reported an unclear [73] benefit of SIT compared to MICT control groups, and a moderate effect of SIT on $\dot{V}O_{2max}$ [104] when compared to healthy adults or overweight/obese adults. With the exception of $\dot{V}O_{2max}$, there is a paucity of meta-analytic data that compare different modes of interval training and LIT/MICT for physiological outcomes and markers of endurance performance in trained populations.

The network meta-analysis did not reveal a clear superior effect of any HIIT/SIT types when directly comparing interval training differing in interval work-bout duration (Figure 13). Contrastingly, long-HIIT (≥4 min) has been shown to lead to ~2% and ~4% greater improvements in TT performance and maximum aerobic power/velocity, respectively, compared to SIT in a different study of endurance-trained athletes [78]. It is worth noting that in our network meta-analysis we grouped together all physiological and performance variables assessed in each study (including outcome measures not reported in the

HIIT/SIT versus LIT/MICT comparisons such as cycling economy, GE, among others) to perform the subgroup comparisons (Figure 13B), which may explain to some extent the lack of differences between HIIT/SIT types. However, subgroup comparisons reported separately would have yielded one or two data points for some outcome measures and, therefore, not resulted in an accurate representation of the appropriateness of short-HIIT, long-HIIT, SIT and combined HIIT/SIT in driving physiological adaptations in this population. A recent meta-analysis [105] showed that improvements in TT performance depended on the duration but not the intensity of the HIIT work-bouts, with intervals of longer duration leading to greater increases in TT performance among trained individuals. Of the included studies in our review, we cannot draw any conclusions about the suitability of HIIT/SIT of distinct interval work-bout durations for ameliorating specific physiological or performance measures, as all HIIT/SIT types led to a variety of improvements across different variables. SIT appears to be particularly effective at improving physiological variables across different regions of a cyclist's power profile, including $\dot{V}O_{2max}$/$\dot{V}O_{2peak}$ [59, 61, 64, 65, 90, 91], MAP/PPO [58, 59, 64, 65, 86, 91], TT performance [59, 64, 65, 86, 91], threshold parameters [58, 61, 64, 65, 91], TTE [58] and Wingate outcomes [65, 90]. Likewise, short-HIIT produced beneficial effects in $\dot{V}O_{2max}$/$\dot{V}O_{2peak}$ [62, 64, 91, 92], MAP/PPO [62, 63, 64, 66, 86, 91, 92], TT performance [62, 64, 66, 86, 91, 92], threshold parameters [62, 63, 64, 91, 92] and Wingate outcomes [62, 92]. The training effects following long-HIIT were also favourable for a range of outcomes such as $\dot{V}O_{2max}$/$\dot{V}O_{2peak}$ [58, 62, 92], MAP/PPO [58], TT performance [62, 65, 92], TTE [58, 62, 92] and threshold parameters [58, 62, 92], but not in all studies [59, 65, 86]. If a specificity effect (whereby greater improvements are observed in variables which closely resemble how interval training sessions were prescribed) does exist, this could not be ascertained with the present dataset of trained cyclists.

Absolute (Hedges' g = 0.28) and relative (Hedges' g = 0.10) $\dot{V}O_{2max}$/$\dot{V}O_{2peak}$ did not improve to a greater extent following interval training compared to LIT/MICT. The size of this effect is similar to that reported by Gist et al. [73], who found a nonsignificant effect of SIT (Cohen's *d* = 0.04) when compared to endurance training control groups. Participants in this study had not been engaged in regular training prior to the intervention, which possibly explains the improvements made following both approaches (SIT and LIT/MICT). In our review, two studies [61, 90] significantly improved $\dot{V}O_{2max}$ in both SIT and MICT groups between pre- and post-intervention, and an additional two studies [26, 58] found nonsignificant increases in $\dot{V}O_{2max}$ in control groups at the end of the training period (+6.3% and +3.4%, respectively). This is perhaps due to the fact that cyclists in the MICT group had a significantly greater weekly training volume than cyclists in HIIT groups [58, 90], or the nature of the training itself [26, 61], which consisted of varied-intensity endurance training and MICT (or a combination of both). These findings corroborate the conclusions of previous studies [106, 107] which have shown that performing MICT can elicit improvements in $\dot{V}O_{2max}$, albeit to a smaller extent when compared to the effects of HIIT. There was one study, however, in which cyclists in the MICT group improved $\dot{V}O_{2max}$ to a larger extent than those in SIT [61]. A possible explanation for a greater increase in $\dot{V}O_{2max}$ in the endurance training group is that cyclists in this study were physical education students who were recreationally active in the sport but not specifically trained for endurance cycling, despite possessing a $\dot{V}O_{2max}$ (61.45 ± 7.55 $mL \cdot kg^{-1} \cdot min^{-1}$) that would class them as trained cyclists [84]. It may be that, when individuals are not highly trained, incorporating low- to moderate-intensity training with minimal emphasis on high-intensity training is likely sufficient for signalling positive physiological adaptations and performance gains [73]. Notwithstanding the performance improvements that can occur from intensification of training, it may still be important to place a large emphasis on LIT/MICT regardless of training status, as evidenced by the peripheral adaptations seen in capillary density and mitochondrial content [17]. These peripheral adaptations appear to continue to respond to large volumes of LIT/MICT even when cyclists are regarded as elite [108]. Indeed, establishing an endurance base built over time from high volumes of LIT/MICT may be needed for tolerating higher dosages of HIIT during the competitive season [1]. Nonetheless, HIIT/SIT tends to induce greater increases in mitochondrial content and $\dot{V}O_{2max}$ than LIT/MICT for a given weekly training volume [17].

When compared to endurance training controls, the network meta-analysis revealed that short-HIIT elicited significant improvements in outcome measures (Figure 13, B), whereas no significant differences were found between long-HIIT and SIT subgroups versus LIT/MICT. This is consistent with findings from a meta-analysis by Bacon et al. [101], who found greater increases in $\dot{V}O_{2max}$ when studies used intervals of 3–5 min, which is of similar length to the intervals prescribed by studies in the short-HIIT subgroup (~2 to 4 min). In studies with healthy individuals, but not trained athletes, it has been suggested that longer interventions (~10 weeks) generate the biggest improvements in $\dot{V}O_{2max}$ [67, 101]. This conclusion cannot be corroborated by the results of this study, as interventions in the short-HIIT subgroup ranged from 2–7 weeks. Regardless, differences in participants' training status (trained cyclists herein versus sedentary–recreationally active individuals in the above studies) likely dictate the extent of $\dot{V}O_{2max}$ enhancements after prolonged interventions. Despite this, two studies [58, 65] included in this review had interventions lasting a minimum of 10 weeks and both reported some of the greatest improvements in $\dot{V}O_{2max}$ (3.8–8.7%) among the included studies, which may still indicate that it is possible to generate significant $\dot{V}O_{2max}$ improvements with longer interventions, but this will likely vary depending on initial training status (e.g., highly-trained versus recreationally-trained cyclists) and interval training history in the months leading up to the intervention. Further research is needed to confirm these findings, particularly with trained athletes.

Evidence concerning the impact of SIT on physiological and performance parameters in trained cyclists is lacking. Due to the low number of studies examining the effects of SIT interventions, the results of this meta-analysis are inconclusive, particularly in direct comparisons with HIIT. Five studies investigated the effects of SIT versus HIIT on physiological and/or performance adaptations [59, 64, 65, 86, 91], but with clear differences in interval training prescription. Two studies [59, 65] employed a SIT protocol consisting of 30-s work periods interspersed with 15-s recovery periods performed continuously for 9.5 min. Applying a 2:1 work-to-recovery ratio has been shown to increase the total time spent above 90% $\dot{V}O_{2max}$ during 30-s intervals, thus increasing the total training stimulus of the session [77, 109]. Alongside increased cardiovascular stress, performing this type of SIT prescription exposes cyclists to higher blood lactate concentrations and may result in increased muscular adaptations, metabolite tolerance and buffering capacity [64, 65]. This possibly explains why SIT was particularly effective in inducing physiological adaptations across different power output regions in the power-duration curve in cyclists of different ability levels (well-trained and recreationally-trained cyclists) [59, 65]. In contrast, HIIT groups in these studies improved only one measure of performance [65] or did not improve at all [59]. The lack of improvements in the HIIT group in the study by Ronnestad et al. [65] is surprising, given that cyclists were only recreationally trained and the intervention lasted 10 weeks; however, cyclists had been engaged in structured interval training for ≥4 weeks prior to the start of the intervention, which may have hindered the possibility for improvements. Nonetheless, cyclists in the SIT group had also performed HIIT leading up to the intervention and still improved performance in all physiological parameters. Similarly, 3 weeks of SIT resulted in significant increases in $\dot{V}O_{2max}$, MAP/PPO and 20-min TT performance in elite cyclists, whereas no improvements were made following long-HIIT, despite minimal training volume consisting of HIIT prior to the intervention [59]. Every other study in this review with SIT groups prescribed SIT with recovery periods of either 1.5 min [26] or 4.0–4.5 min [61, 64, 86, 90, 91], two of which [61, 90] were compared against CON only. It can be argued that implementing SIT interventions with a reduced recovery period (e.g., 0.5–1.5 min) between work-bouts might provide a greater training stimulus and leads to enhanced physiological adaptations in cyclists of different ability levels [59]. Whether continued exposure to SIT is sustainable for prolonged periods of time and capable of inducing further performance gains than those already observed in HIIT interventions remains unknown [73]. Given its nature (i.e., performed at supramaximal intensities), one could question whether this type of training would be more suited for periods in the season where athletes significantly reduce training volume and maintain/increase training intensity (e.g., tapering), as well as its possible relevance for time-crunched cyclists. Additional research is needed to determine whether performance improvements following SIT are still evident with longer interventions, or if training adaptations cease to occur after a given training block consisting of SIT.

The majority of training studies did not disclose the training period in which the HIIT/SIT intervention was performed, with only three studies providing information that their training programme took place in the base period/early preparatory period [58, 60, 63]. Similarly, information on pre-intervention interval training frequency was not available in several studies [26, 61, 62, 63, 64, 66, 90, 91, 92]. Of the studies that reported pre-intervention training data, most interventions appear to have been performed following a period of predominantly low-intensity training [58, 59, 63, 64, 65, 86, 91]. Despite this, interval training (~1-2 times/week) was not entirely absent from the cyclists' training regimens in three studies before the intervention period [58, 60, 65]. Nonetheless, the fact that the HIIT/SIT stimulus was introduced after a somewhat prolonged period of non-existent or minimal high-intensity training (i.e., 'novel' stimulus) does not dissipate questions that may exist about the performance-enhancing potential of this training strategy when endurance athletes are already incorporating high-intensity work during the competitive season. In the 'real-world', there is always a combination of different training approaches (e.g., HIIT/SIT, 'threshold'-based training, interval training performed in a fatigued or 'semi-fatigued' state, neuromuscular or anaerobic work, etc.) which makes cycling performance a much more complex 'puzzle' that cannot be solved by an oversimplistic (and often incomplete) comparison between HIIT/SIT and LIT/MICT.

Limitations

There is some degree of variation between interval training groups in the studies included in this meta-analysis. Specifically, only two studies [64, 91] compared HIIT and SIT with a control group performing LIT/MOD, three studies [59, 65, 86] compared HIIT with SIT interventions (no CON included), and the remaining studies compared interval training programmes of either HIIT or SIT (or both performed concomitantly) with CON performing LIT/MICT. Because the studies reporting the greatest improvements in performance following SIT did not include control groups [59, 65], subgroup analysis did not capture the entire spectrum of SIT interventions for SIT versus LIT/MICT comparisons. Likewise, two studies [61, 90] which included both CON and SIT groups did not include a HIIT group, thereby not allowing for SIT versus HIIT comparisons in the network meta-analysis. Conversely, three studies with HIIT protocols of different work-bout durations did not include SIT groups [58, 63, 66], resulting in a limited number of subgroup pairwise comparisons in the network meta-analysis, which were not independently discriminated based on each outcome for this reason. This limits the potential for interpreting the findings, as a relatively low number of studies may skew the results. For the majority of outcomes, the number of studies/effects was too small to yield sufficiently precise point estimates which would allow for more firm conclusions.

Practical Applications

When cyclists have already been exposed to periods of high training volumes, strategically incorporating HIIT/SIT into a cyclist's training programme may elicit further performance enhancements than LIT/MICT. The results of the network model suggest that neither HIIT modality ('traditional' HIIT or SIT) nor interval work-bout duration contributed to greater physiological/performance improvements in trained cyclists when directly comparing interval training interventions. This means that short-HIIT, long-HIIT and SIT (or a combination of the three) may all have a similar role to play in an athlete's periodisation strategy in order to achieve specific outcomes at different time points in a season. It is the interplay between training history, training phase, race specificity and competitive goals that, ultimately, influence the decision-making of coaches in the applied field with regard to the best interval training strategies to use in order to optimise performance. Endurance coaches are often confronted by their athletes with questions regarding the most appropriate type of intervals to be performing at any given time. The answer to this question is likely to vary depending on the aforementioned factors. Given the absence of meaningful differences in physiological adaptations between HIIT differing in interval work-bout duration and SIT reported herein, employing an individualised rather than a 'one-size-fits-all' approach may reign supreme if athletes are to maximise their true physiological potential.

Future Directions

Further research directly comparing SIT with shorter and longer HIIT intervals is advised, particularly if investigated over a prolonged period of time with regular testing at different time points during the intervention (e.g., after 4 weeks and at post-intervention), and for a wider range of outcomes relevant to performance. Similarly, it may be beneficial to investigate the potential for performance adaptations using different interval training prescriptions over the course of the cycling season. Two studies [58, 86] included interval work-bouts of longer durations (≥8 min) which appear to have been performed closer to the boundary between heavy and severe intensity exercise, but the vast majority of studies examined HIIT/SIT prescriptions that seem to be aligned with the severe and extreme exercise intensity domains, with little to no emphasis on the heavy domain. As already alluded to, HIIT and SIT are not the only forms of interval training, and more attention should be placed on training optimisation strategies in the heavy intensity domain. Future studies should try to include multiple interval training groups of HIIT/SIT/threshold-based interval training, in addition to a control group following regular training (LIT/MICT), in order to facilitate comparisons between protocols differing in work-bout duration.

CONCLUSION

Both HIIT and SIT are effective interval training strategies to improve performance in trained cyclists. When compared to endurance training control groups, interval training elicited a potentially large effect on TT/TTE performance outcomes, though with relatively large imprecision making it unclear as to its exact effects, and with negligible to small improvements in the remaining models (absolute and relative $\dot{V}O_{2max}/\dot{V}O_{2peak}$, absolute and relative MAP/PPO, Wingate parameters, physiological thresholds, and intervention length). Furthermore, HIIT did not show a clear superiority in increasing physiological and performance variables compared to SIT. Overall, differences in performance improvements between HIIT and SIT interventions were trivial. Given that both interval training modalities may elicit improvements in performance in comparison to traditional LIT/MICT, additional research is needed to enable more precise estimates. Investigating the effects of HIIT which differ in intensity and interval work-bout duration at different phases during the season would provide further insights into the manipulation of HIIT dose in order to achieve optimal stimulus for adaptation.

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