Effect of number of sprints in a SIT session on change in VO_2max: a meta-analysis

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ABSTRACT

Purpose: Recent meta-analyses indicate that sprint interval training (SIT) improves cardiorespiratory fitness ($\dot{V}O_2$max), but the effects of various training parameters on the magnitude of the improvement remain unknown. The present meta-analysis examined the modifying effect of the number of sprint repetitions in a SIT session on improvements in $\dot{V}O_2$max.

Methods: The databases PubMed and Web of Science were searched for original studies that have examined pre- and post-training $\dot{V}O_2$max in adults following ≥2 weeks of training consisting of repeated (≥2) Wingate-type cycle sprints, published up to 1 May 2016. Articles were excluded if they were not in English, involved patients, athletes, or participants with a mean baseline $\dot{V}O_2$max of >55 $mL \cdot kg^{-1} \cdot min^{-1}$ or a mean age <18 years, and if a SIT trial was combined with another intervention or used intervals shorter than 10 s. A total of 38 SIT trials from 34 studies were included in the meta-analysis. Probabilistic magnitude-based inferences were made to interpret the outcome of the analysis.

Results: The meta-analysis revealed a likely large effect of a typical SIT intervention on $\dot{V}O_2$max (mean ± 90 CL %: 7.8% ± 4.0%) with a possibly small modifying effect of the maximum number of sprint repetitions in a training session (-1.2 ± 0.8% decrease per 2 additional sprint repetitions). Apart from possibly small effects of baseline $\dot{V}O_2$max and age, all other modifying effects were unclear or trivial.

Conclusion: We conclude that the improvement in $\dot{V}O_2$max with SIT is not attenuated with fewer sprint repetitions, and possibly even enhanced. This means that SIT protocols can be made more time-efficient, which may help SIT to be developed into a viable strategy to impact public health.

Key words: systematic review; cardiorespiratory fitness; aerobic capacity; sprint interval training

1 INTRODUCTION

The global increase in prevalence of noncommunicable diseases over the past decades (33) can be attributed, at least in part, to the low levels of physical activity undertaken by the majority of the general population (16). In light of this, a key aim of public health organisations is to increase population physical activity levels (20). Of the health markers that can be improved by physical activity, maximal aerobic capacity ($\dot{V}O_2max$) is consistently shown to be the strongest prognostic marker for future cardiovascular health and premature death in cross-sectional studies (36, 54). Furthermore, longitudinal studies demonstrate that improvements in $\dot{V}O_2max$ are associated with substantial reductions in all-cause and cardiovascular mortality during follow-up (9, 41).

Over the past two decades, relatively high volumes of moderate-intensity aerobic exercise (total time commitment ≥150 min per week) have consistently been recommended for improving health markers (20). However, uptake of and adherence to these recommendations remains low in the general population (25), with lack of time identified as one of the main perceived barriers to becoming and remaining physically active (37, 39, 68). Therefore, the seminal finding by Burgomaster *et al.* (12) that a training protocol consisting of repeated brief ‘all-out’ cycle sprints (i.e. Wingate sprints) is associated with aerobic adaptations, has led to substantial interest in the use of (sub)maximal high-intensity interval training (HIIT) and supramaximal sprint interval training (SIT) as time-efficient alternative/adjunct exercise strategies for improving $\dot{V}O_2max$ (21). The most commonly studied SIT protocol consists of 4-7 repeated 30-s Wingate sprints, thus resulting in less than 4 minutes of high-intensity exercise per session (72). Over the past few years, several meta-analyses have reported the efficacy of SIT in increasing $\dot{V}O_2max$ (24, 51, 62, 72). These have concluded that in healthy individuals, SIT improves $\dot{V}O_2max$ to a similar (24) or greater extent (51) than traditional aerobic training, with greater benefits for individuals with lower pre-training $\dot{V}O_2max$ (51, 72).

Although these findings provide strong support for the effectiveness of SIT in improving $\dot{V}O_2$max, surprisingly few efforts have been made to identify 'optimal' SIT protocols, e.g. protocols which will either provide the greatest increase in $\dot{V}O_2$max, or a set increase with the lowest total training volume or time commitment. Weston *et al*. (72) reported a likely small effect of increasing the intervention duration and a possibly moderate effect of increasing the work-to-rest ratio, but no studies have meta-analysed or directly investigated the potential effects of the number of sprint repetitions in a SIT session. This parameter is particularly important as it has a large influence on the total duration of a training session, as well as the level of fatigue (42) and affective responses (19) experienced by the participant, thus influencing the likelihood of individuals taking up and adhering to a specific SIT intervention (26). As the main aim of investigating SIT protocols is generally to identify a time-efficient alternative to aerobic exercise, there is a need to identify the effect of this training parameter on the associated increase in $\dot{V}O_2$max. Recent evidence suggests that the positive effects of SIT on $\dot{V}O_2$max can be attained with fewer sprints (22, 23, 34, 48), and therefore the aim of the present study was to perform a meta-analysis to provide estimates of the modifying effect of the number of sprint repetitions in SIT protocols on the increase in $\dot{V}O_2$max in untrained adult participants following training.

2 METHODS

2.1 Literature Search Criteria and Study Selection

This study was undertaken in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement guidelines (52). We aimed to identify all studies that have examined pre- and post-training $\dot{V}O_2max$ following a period of at least 2 weeks of training consisting of repeated (≥2) ‘all-out’ Wingate cycle sprints or modifications thereof (e.g. studies using 10-s, 15-s, or 20-s ‘all-out’ sprints instead of 30-s Wingate sprints). For this purpose, the electronic databases PubMed and Web of Science were searched for relevant available records up to 1 May 2016, using the 28 possible combinations of the independent variable search terms ‘Wingate’, ‘all-out’, ‘sprint’, and ‘interval training’, and the dependent variable search terms ‘fitness’, ‘aerobic capacity’, ‘aerobic power’, ‘$\dot{V}O_2max$’, ‘$\dot{V}O_2peak$’, ‘oxygen uptake’, and ‘oxygen consumption’. Relevant studies cited in recent meta-analyses were also used (24, 51, 62, 72), as well as our own recent work (50). The following articles were excluded: 1) review articles / commentaries, 2) articles not written in English, 3) studies concerning patients, athletes, or participants with a mean baseline $\dot{V}O_2max$ of >55 $mL \cdot kg^{-1} \cdot min^{-1}$ or a mean age <18 years, 4) animal studies, 5) study-trials in which SIT was combined with another intervention; and 6) SIT studies using non-cycling exercise, intervals shorter than 10 s, or intervals that were not ‘all-out’. Two authors (NBJV and RSM) independently conducted the literature search and data extraction, and any discrepancies were resolved by consensus. The reviewers were not blinded to manuscript journals or authors. After removal of duplicate records, the titles and abstracts of all identified articles were screened for records that were clearly not relevant. These articles were omitted before assessing the full-text versions of the remaining articles for eligibility to be included in the meta-analysis. If more than one article reported data for the same experiment, duplicate data for these participants were only included once. The final dataset included the results of 38 trials from 34 studies (**Figure 1**).

2.2 Data Extraction

Full papers were assessed for mean absolute pre- and post-training $\dot{V}O_2$max. Absolute $\dot{V}O_2$max ($L \cdot min^{-1}$) was used rather than relative $\dot{V}O_2$max ($mL \cdot kg^{-1} \cdot min^{-1}$) as this provides an estimate of true changes in the ability to take up and use oxygen, independent of possible concomitant changes in body mass. Relative $\dot{V}O_2$max was used for the five studies for which absolute $\dot{V}O_2$max data were not available (8, 40, 46, 55, 65). Any data for $\dot{V}O_2$max obtained at intermediate time-points during the intervention were excluded. The corresponding authors of papers without the required data were contacted by email; authors from 23 studies were contacted (1, 2, 5, 6, 10-13, 22, 23, 27, 28, 30, 31, 34, 38, 47, 55, 59-61, 65, 67, 74) and we received raw data from 17 studies (5, 10-13, 22, 23, 27, 28, 30, 38, 47, 55, 59-61, 74). Graph digitizer software (DigitizeIt, Braunschweig, Germany) was used to obtain the data from one study for which absolute pre- and post-training $\dot{V}O_2$max data were only available in a figure (67). The effect of training was expressed as a percentage change-score. Percentage effects of SIT on $\dot{V}O_2$max were converted to factors (= 1 + effect / 100), log transformed for the analysis, and then back transformed to percentages. Effects were weighted using percentage standard errors derived from exact p-values, or from estimated errors of measurement as recommended by Weston *et al*. (72). Under the assumption that studies with similar test protocols and subject characteristics would have similar typical errors of measurement, the typical errors from these studies were averaged (via the weighted mean variance) and assigned to the studies that did not report an exact p value (1, 2, 6, 34, 44, 65, 67). The SE was then calculated via the relationship between typical error and SE (69). Finally, data for the following potential moderators were extracted for each study: participant characteristics (sex, age, body mass index (BMI), baseline $\dot{V}O_2$max), training parameters (intervention duration, total number of training sessions, maximal number of sprint repetitions per training session, sprint duration, sprint/recovery ratio, sprint resistance), and study-type (controlled / uncontrolled; dummy variable). For trials with a no-exercise control group, the effect entered into the meta-analysis was intervention minus control. Data for aerobic exercise comparator groups were not included in the meta-analysis.

2.3 Statistical Analysis

To evaluate the extent of publication bias, a funnel plot of model residuals versus their corresponding standard errors was inspected for evidence of asymmetrical scatter (72). This approach takes into account any heterogeneity explained by the meta-regression, which is not accounted for in standard funnel plots of observed effects vs. their standard errors. No evidence of asymmetrical scatter was apparent (**Figure 2**).

A mixed effects meta-regression model was conducted using the ‘metafor’ package in R (version 3.2.4, R Foundation for Statistical Computing, Vienna, Austria) (70). The overall effect of SIT on $\dot{V}O_2$max was evaluated using the mean values of the covariates. The modifying effects of covariates were evaluated as the difference between levels (e.g. male/female) for nominal variables. For numeric variables, effects were evaluated as the change in $\dot{V}O_2$max associated with a two standard deviation (SD) change in the predictor (i.e. a typically low vs. a typically high value (32)), or a practically relevant value (e.g. three additional SIT sessions would typically constitute an additional week of training). The random effects in the model specified a between-study SD, representing the typical difference in the true value of the effect in different study settings, plus a within-study random effect to account for within-study repeated measurements (a control treatment and/or more than one training treatment) (72). The SD was doubled before interpreting its magnitude with the scale used to interpret fixed effects (63), for the same reason that the magnitude of the effect of a linear covariate is evaluated with two SD of the covariate (32). We performed a sensitivity analysis to determine whether the inference relating to the modifying effect of maximum number of sprints was substantially altered when two potentially influential studies (with 12 and 15 maximum sprints, respectively (31, 61)) were removed from the analysis.

We used magnitude-based inferences to provide an interpretation of the real-world relevance of the outcomes. Uncertainty in effect estimates was expressed as ± 90% confidence limits, and as the likelihood that the true value was beneficial, trivial, or harmful in relation to threshold values for benefit (improved fitness) and harm (reduced fitness) (32). The overall effect of SIT on $\dot{V}O_2$max was interpreted as a clinical outcome, whereby an effect was deemed unclear if the chance that the true value was beneficial was >25%, with odds of benefit relative to odds of harm (odds ratio) of <66. Modifying effects were evaluated mechanistically and deemed unclear if the likelihood that the true value was beneficial *and* harmful were both >5%. Otherwise, the effect was deemed clear, and was qualified with a probabilistic term using the following scale: <0.5%, most unlikely; 0.5-5%, very unlikely; 5-25%, unlikely; 25-75%, possible; 75-95%, likely; 95-99.5%, very likely; >99.5%, most likely. As robust anchors for the smallest worthwhile clinical and practical effects relating to $\dot{V}O_2$max were not available, standardised effect thresholds of 0.2, 0.6 and 1.2 SD were adopted for small, moderate and large effects, respectively (72). Here, the SD related to the average between-subject variances for baseline $\dot{V}O_2$max; these corresponded to magnitude thresholds of 1.0%, 2.9% and 5.8%.

3 RESULTS

Data available for the 34 studies and 38 trials included in the meta-analysis are shown in **Table 1** and **Figure 3**. The meta-analysis indicated an overall likely large effect of an 'average' SIT protocol on $\dot{V}O_2$max (mean ± 90 CL % effect on the increase in $\dot{V}O_2$max: 7.8 ± 4.0%; **Table 2**). A possibly small effect was evident for the modifying effect of the maximum number of sprint repetitions in a training session (-1.2 ± 0.8% decrease per 2 additional sprint repetitions; **Figure 4a**). The percentage chances that the modifying effect was negative, trivial or positive were calculated to be 62.7%, 37.3% and 0.0% respectively. There were possibly small effects of baseline $\dot{V}O_2$max (-1.5 ± 1.9% decrease per 10 $mL \cdot kg^{-1} \cdot min^{-1}$ higher baseline $\dot{V}O_2$max; **Figure 4b**) and age (-1.1 ± 1.2% decrease per 7 y increase; **Figure 4c**). All other modifying effects (intervention duration, number of sessions, sprint duration, recovery time, sprint resistance, BMI, sex, and study type) were unclear or trivial (**Table 2**). Unexplained variance between studies was 2.2 ± 0.8% (likely moderate). The inference relating to the effect of maximum number of sprint repetitions was not altered when the two studies with the highest number of sprint repetitions (31, 61) were removed from the analysis (-1.0 ± 1.1%; possibly small decrease; chances that the modifying effect was negative, trivial or positive of 51.6%, 48.2% and 0.0% respectively).

4 DISCUSSION

The main aim of the present meta-analysis was to examine the modifying effect of the number of sprint repetitions in a SIT session on the increase in $\dot{V}O_2$max following training. Using data from 34 training studies and 418 participants we demonstrate that the improvement in $\dot{V}O_2$max with SIT is not attenuated with fewer sprint repetitions, and possibly even enhanced. Considering the low physical activity levels in the general population (25), and the fact that lack of time is consistently identified as one of the main perceived barriers to becoming and remaining physically active (37, 39, 68), this finding has implications for the design of practical SIT interventions for improving general health. SIT protocols have the potential to be the most time-efficient interventions that are associated with improvements in key health markers, but due to the need for recovery intervals following sprints, this potential can only truly be achieved if the number of sprint repetitions is low. Therefore, our observation that reducing the number of sprint repetitions will not attenuate the increase in $\dot{V}O_2$max associated with SIT, and in fact may possibly improve the effect, is an important novel finding.

Based predominantly on the results of studies investigating the dose-response relationship between regular *aerobic* exercise and improvements in health markers, it has generally been accepted that at a given exercise intensity a greater volume of exercise training (in terms of training duration and frequency) is associated with greater improvements in $\dot{V}O_2$max (20). For example, in a clinical trial comparing low or high-intensity aerobic training protocols with matched energy expenditure (Studies of a Targeted Risk Reduction Intervention through Defined Exercise (STRRIDE I)) the magnitude of change in $\dot{V}O_2$max was greater in the group exercising at a higher intensity (15). Although the volume of exercise used in HIIT and SIT protocols is generally reduced compared to aerobic exercise programmes (11, 45, 60), the principle of a dose-response relationship has not been challenged in these studies directly; it is the interaction between training volume and intensity that is used to justify the lower volume. Thus, HIIT and SIT studies investigating the effects of protocols with a lower intensity or a shorter sprint duration tend to increase the number of sprint repetitions (43, 66). Apart from two studies that demonstrated that reducing sprint duration from 30 s to either 15 s (74) or 10 s (30) does not attenuate the improvement in $\dot{V}O_2$max with SIT, there have been no HIIT or SIT studies that have specifically investigated the dose-response relationship between the volume of high-intensity exercise and health outcomes. Our meta-analysis provides the first evidence that at ‘all-out’ supramaximal exercise intensities the generally accepted positive association between volume of training and magnitude of training adaptations does not hold true. Thus, research into the health benefits of SIT should increase the focus on protocols with fewer sprints.

Due to the relatively low number of studies examining the effects of SIT protocols with fewer than six sprint repetitions, the present meta-analysis was not powerful enough to make conclusions on the optimal number of all-out sprint repetitions. Only two studies have investigated the effects of a SIT protocol incorporating just two sprints (48, 50). As one of these used the largest sample size of all the studies included in the review (n=34 (50)), the mean 10% increase in $\dot{V}O_2$max observed with this protocol (termed reduced-exertion high-intensity interval training, REHIT) appears to be robust. The greatest improvement in absolute $\dot{V}O_2$max (17%) was reported by Gibala’s group (22), who modified the original REHIT protocol to include a third sprint. However, the total duration of this intervention was 12 weeks, whereas at an intermediate measurement-point after 6 weeks the increase in $\dot{V}O_2$max was 12%, very similar to the 10% and 14% improvements observed with the original REHIT protocol (48, 50). Although future studies should determine whether the magnitude of the response for $\dot{V}O_2$max is different between SIT protocols incorporating 2-4 sprints, the data presented in the present manuscript suggest that this difference will be small. If this is indeed the case, then a number of considerations support the use of the smallest number of sprints, i.e. the two sprints used in the REHIT protocol. Firstly, including a warm-up, recovery, and cool-down, this protocol has the potential to be the most time-efficient protocol. Furthermore, a drawback of the use of SIT as a public health intervention is the potential for high associated perceived exertion and negative affective responses (8, 21). In this light it is important to point out that the number of sprint repetitions has been shown to negatively affect both of these parameters (19, 42). Therefore, effective SIT protocols with fewer sprint repetitions will likely offer the best chance of sedentary target populations taking up and adhering to a SIT intervention for improving health (18). With this in mind, the available evidence suggests that two sprints can be recommended as effective at improving the important health marker of $\dot{V}$O2max. It could be argued that considering the apparent linear association between the number of sprint repetitions and improvement in $\dot{V}O_2$max (**Figure 4a**), a single sprint could be expected to produce similar improvements with a lower time-commitment. However, we have recently performed the first study to investigate the effects of a single supramaximal sprint on $\dot{V}O_2$max, and observed no significant increase compared to a no-exercise control condition in response to 4 weeks of training with a sample size of n=15 (64). Further studies are required to confirm whether supramaximal sprints only improve $\dot{V}O_2$max if they are repeated. Furthermore, in light of the fact that the majority of studies that have studied the effects of SIT protocols incorporating 2 or 3 sprint repetitions have used 20-s sprints rather than the more commonly used 30-s sprints (22, 23, 48, 50), further studies are required to investigate the shortest sprint duration that can be used without attenuating the adaptations to $\dot{V}O_2$max.

Our present analysis does not provide an explanation for the possibly negative effect of reducing the maximal number of sprint repetitions on improvements in $\dot{V}O_2$max, but a discussion of possible mechanisms is warranted. The main limiting factor of $\dot{V}O_2$max is generally assumed to be maximal cardiac output, possibly through increased blood volume (7, 53). To date no studies have examined the effect of SIT on blood volume, but there is evidence in favour (17, 71) and against (35) increases in blood volume in response to HIIT. Similarly, there is evidence in favour (3) and against (45) increased maximal cardiac output with SIT, with the latter finding suggesting that the adaptations to SIT for $\dot{V}O_2$max may be peripheral in origin. Indeed, several authors have proposed that improvements in $\dot{V}O_2max$ with SIT are caused by improved skeletal muscle oxygen extraction due to increased mitochondrial density (22, 35, 55, 62, 74). Although it remains unclear whether the improvement in $\dot{V}O_2max$ with SIT is due to central or peripheral adaptations, we propose that both increased blood volume and increased mitochondrial density could plausibly be explained by the rapid glycogen depletion associated with supramaximal exercise (49). Firstly, maximal rates of glycogenolysis in the initial 15 seconds of a supramaximal sprint (56) are associated with the accumulation of metabolic derivatives, resulting in a hypertonic intramyocellular environment, influx of water, and a transient ~15-20% drop in plasma volume within a timespan of just a few minutes (49). This severe disturbance of circulatory homeostasis could be a stimulus for the body to increase blood volume in response to repeated SIT sessions. Secondly, glycogenolysis is associated with the release and activation of glycogen-bound 5' AMP-activated protein kinase (AMPK) (57), which through downstream signalling pathways involving peroxisome proliferator-activated receptor gamma coactivator 1-alpha (PGC1α, a proposed master regulator of aerobic adaptations), could be a mechanism leading to increased mitochondrial density (29). Glycogen breakdown during repeated supramaximal sprints has been shown to be completely attenuated by the time of the third sprint (56), and it is therefore plausible, for both of these speculated mechanisms, that performing just two repeated supramaximal sprints is sufficient to 'saturate' (i.e. maximally activate) the adaptive response. In other words, if either increased blood volume or mitochondrial density underpins the changes in $\dot{V}O_2max$ with SIT, and if rapid glycogen breakdown regulates those adaptations, then no additional improvements would be expected if more than 2-3 sprints are performed in a training session.

Apart from this hypothesis it is also possible that increasing the number of sprint repetitions will result in 'pacing' strategies that affect the 'all-out' nature of the sprints (e.g. reduction of peak and mean power output in initial sprints), or that accumulated fatigue may reduce the effectiveness of later sprints. Furthermore, the fact that increasing the number of sprint repetitions does not enhance the improvement in $\dot{V}O_2$max with SIT provides strong evidence against a role for the magnitude of the acute effects of supramaximal sprints on oxygen transfer, energy turnover, or total energy use, as part of the stimulus for improving $\dot{V}O_2$max with SIT, because for each of these factors the stimulus should be greater with more sprint repetitions.

A number of limitations to the present meta-analysis should be noted. Firstly, in order to be of use as a practical intervention for preventing and/or treating inactivity-related chronic disease, SIT interventions should also be effective at improving for example insulin sensitivity and glycaemic control, blood pressure, blood lipid profile, and body composition. Therefore, one limitation is that only $\dot{V}O_2$max was included as an outcome measure in the present analysis. Whereas insufficient data for a meta-analysis is available for the effects of SIT on blood pressure (14, 23, 73), blood lipid profile (4, 73), and body composition (66, 73), the effect of SIT on insulin sensitivity and glycaemic control has received more attention (4, 22, 23, 48, 50, 58, 73). However, the methods used to assess the effects of SIT on these parameters have varied, with different studies using oral glucose tolerance tests (4, 48, 50, 73), intravenous glucose tolerance tests (22), euglycemic hyperinsulinemic clamps (58), or continuous glucose monitoring (23). This means that a meta-analysis of the effects of the number of sprint repetitions in a SIT protocol on insulin sensitivity and glycaemic control is also currently not feasible. Nonetheless, the improvements in insulin sensitivity and glycaemic control observed to date with SIT protocols incorporating two (48) or three sprints (22, 23) are encouraging.

Secondly, due to the number of available SIT studies the power of our meta-analysis is insufficient to conclude with certainty that the modifying effect of the number of sprint repetitions is negative; i.e. it remains possible that in reality performing more sprints will result in the same improvements in $\dot{V}O_2$max (a chance of approximately 1 in 3). However, this is not of major importance to the significance of our findings: even ‘no effect’ of the number of sprint repetitions would lead to the logical conclusion that performing SIT protocols with more than 2 or 3 sprints is unnecessary for improving $\dot{V}O_2max$ in sedentary individuals. Based on the present analysis, the chance that in reality the effect of performing more sprints is positive was calculated as 0.0%.

A final limitation of our meta-analysis is that only SIT interventions using all-out intensities were included. Optimising time-efficient interventions aimed at improving general health requires consideration of various parameters, and exercise intensity is undoubtedly one of the key parameters affecting the effectiveness of HIIT and SIT protocols. However, due to the large range of intensities used in SIT and HIIT protocols (~80%-350% of $\dot{V}O_2max$) we felt it was important to attempt to 'control' for this variable in the present analysis by including only studies that used 'all-out' cycling exercise. Nonetheless, there is a clear need for studies examining the effect of the number of sprint repetitions at lower exercise intensities, e.g. in HIIT studies.

In conclusion, in the present meta-analysis we demonstrate that SIT is possibly more effective at improving $\dot{V}O_2max$ if fewer sprint repetitions are performed in a training session. Considering the proclaimed aim of SIT to provide a time-efficient alternative / adjunct to high-volume moderate-intensity aerobic exercise, this finding has important implications for the design of practical SIT interventions. We put forward that SIT research should move away from further characterising the commonly used 4-7 x 30-s Wingate protocol, and towards establishing acceptable and effective protocols. This will require more studies to examine the modifying effects of a range of training parameters (including number of sprint repetitions, sprint duration, sprint intensity, and training frequency) on adaptations to key health markers, as well as exercise enjoyment and acceptability, perceived exertion, and the potential to cause negative affective responses.

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Figure 1: Flow diagram of the study selection process

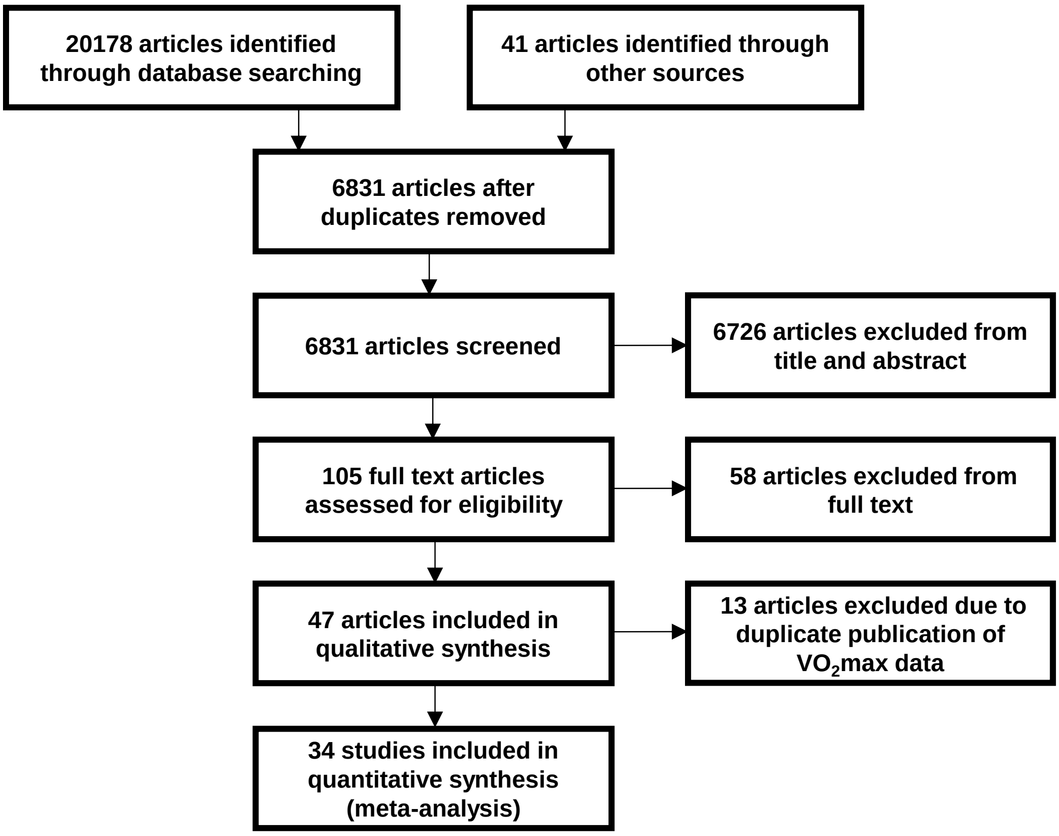

Figure 2: Funnel plot of model residuals versus their corresponding standard errors, with 90% confidence interval region

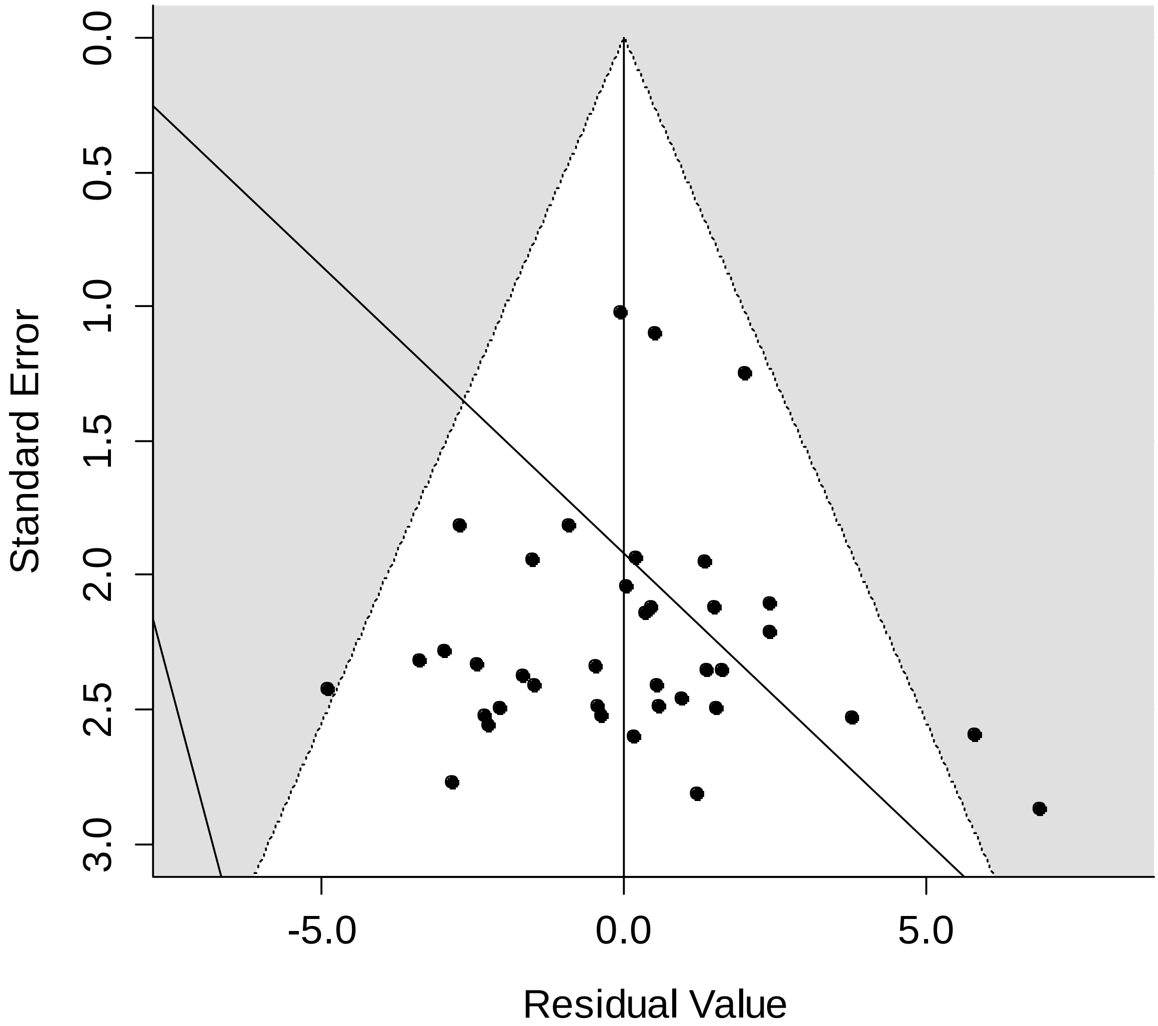

Figure 3: Main effects of SIT on $\dot{V}O_2max$

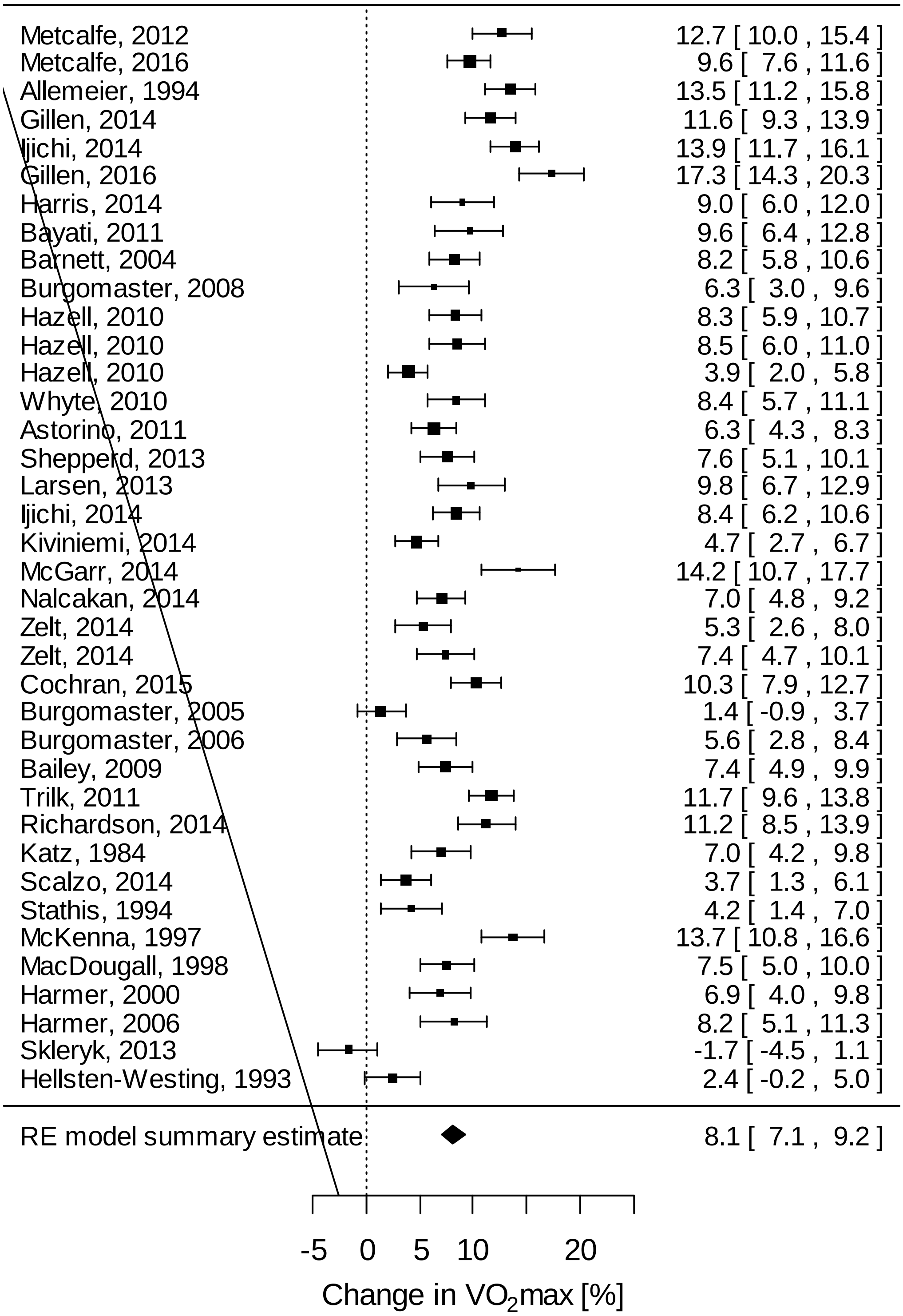

Figure 4: Modifying effects of number of sprint repetitions (A), baseline $\dot{V}O_2max$ (B), and age (C) on the effect of SIT on $\dot{V}O_2max$. Data-points represent individual trials included in the meta-analysis, and the size of the data-point is proportional to study weighting. Solid and dotted lines represent the effect of the moderator ± 90% confidence limits respectively.

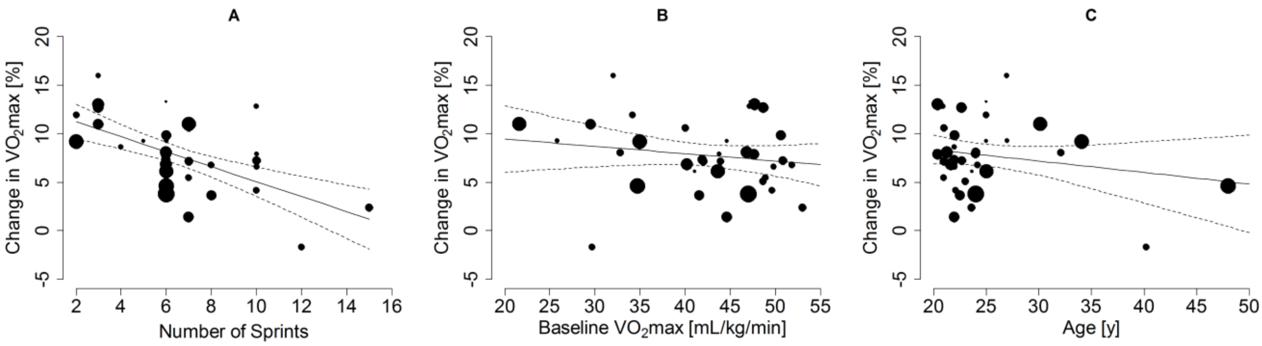

Table 1: Training effects, training protocol parameters, and participant characteristics for the studies included in the meta-analysis

Reference	Study design	SIT-group sample size (n)	Proportion of men	Mean baseline $\dot{V}O_2max$ ($mL \cdot kg^{-1} \cdot min^{-1}$)	Mean age (y)	Mean BMI ($kg \cdot m^{-2}$)	Training duration (weeks)	Total training sessions	Sprint duration (s)	Recovery duration (s)	Resistance (% of BM)	Sprint repetitions		Effect on $\dot{V}O_2max$ (%)	
												Min	Max	Mean	SE
Metcalfe (47)	C	11	0.45	34.2	25.0	23.5	6	18	20	200	7.5	1	2	12.7	2.8
Metcalfe (48)	NC	34	0.50	35.0	34.1	24.6	6	18	20	200	5.0	1	2	9.6	1.5
Allemeier (1)	C	11	1.00	48.7	22.7	24.8	6	15	30	1200	7.5	3	3	13.5	2.0
Gillen (21)	NC	14	0.50	29.5	30.0	-	6	18	20	120	5.0	3	3	11.6	2.0
Ijichi (33)	C	10	1.00	47.7	20.4	21.0	4	20	30	600	5.0	3	3	13.9	1.8
Gillen (20)	C	9	1.00	32.0	27.0	27.0	12	36	20	120	5.0	3	3	17.3	3.3
Harris (27)	C	6	0.00	35.0	22.0	23.6	4	12	30	270	7.5	4	4	9.0	3.4
Bayati (7)	C	8	1.00	44.6	25.0	23.7	4	12	30	240	7.5	3	5	9.6	3.9
Barnett (5)	C	8	1.00	47.6	20.4	-	8	24	30	180	-	3	6	8.2	2.1
Burgomaster (10)	C	10	0.50	41.0	23.6	23.6	6	18	30	270	7.5	4	6	6.3	4.0
Hazell (28)	C	13	0.81	47.0	24.0	24.7	2	6	30	240	10.0	4	6	8.3	2.2
Hazell (28)	C	13	0.81	47.0	24.0	24.7	2	6	10	240	10.0	4	6	8.5	2.4
Hazell (28)	C	13	0.81	47.0	24.0	24.7	2	6	10	120	10.0	4	6	3.9	1.3
Whyte (68)	NC	10	1.00	32.8	32.1	30.3	2	6	30	270	6.5	4	6	8.4	2.6
Astorino (2)	C	20	0.55	43.6	25.0	24.1	2	6	30	300	7.5	4	6	6.3	1.5
Shepperd (56)	C	8	1.00	41.9	22.0	24.8	6	18	30	270	7.5	4	6	7.6	2.3
Larsen (39)	NC	8	1.00	25.8	27.0	26.8	2	6	30	240	7.5	4	6	9.8	3.5
Ijichi (33)	C	10	1.00	46.8	21.3	22.2	4	10	30	600	5.0	6	6	8.4	1.8
Kiviniemi (37)	C	13	1.00	34.7	48.0	25.6	2	6	30	240	7.5	4	6	4.7	1.4
McGarr (45)	C	8	0.75	47.2	25.0	-	2	8	30	240	7.5	4	6	14.2	4.5
Nalcakan (52)	C	8	1.00	40.2	21.7	25.5	7	21	30	270	7.5	4	6	7.0	1.8
Zelt (69)	C	11	1.00	48.6	23.0	25.0	4	12	30	270	7.5	4	6	5.3	2.6
Zelt (69)	C	12	1.00	43.9	22.0	26.0	4	12	15	285	7.5	4	6	7.4	2.7
Cochran (12)	C	12	1.00	50.6	22.0	25.7	6	18	30	240	7.5	4	6	10.3	2.1
Burgomaster (11)	C	8	0.75	44.6	22.0	25.6	2	6	30	240	7.5	4	7	1.4	2.0
Burgomaster (9)	C	8	1.00	48.9	21.0	23.8	2	6	30	240	7.5	4	7	5.6	2.8
Bailey (4)	C	8	0.63	42.0	21.0	23.7	2	6	30	240	7.5	3	7	7.4	2.4
Trilk (63)	C	14	0.00	21.6	30.1	35.7	4	12	30	240	5.0	4	7	11.7	1.6
Richardson (54)	C	9	0.56	40.0	21.0	23.8	2	6	30	240	7.5	4	7	11.2	2.7
Katz (34)	NC	8	1.00	51.8	24.2	-	8	32	30	240	-	8	8	7.0	2.9
Scalzo (55)	NC	21	0.52	41.5	22.5	22.4	3	9	30	240	7.5	4	8	3.7	2.1
Stathis (61)	NC	8	0.75	49.6	22.1	-	7	21	30	180	-	3	10	4.2	2.9
McKenna (46)	NC	8	1.00	47.1	20.9	23.7	7	21	30	180	7.5	4	10	13.7	3.2
MacDougall (43)	NC	12	1.00	50.8	22.7	24.0	7	21	30	180	7.5	4	10	7.5	2.4
Harmer (25)	NC	7	1.00	49.8	22.0	23.5	7	21	30	180	7.5	4	10	6.9	3.1
Harmer (26)	C	7	0.71	43.7	24.0	23.8	7	21	30	180	7.5	4	10	8.2	3.6
Skleryk (57)	C	8	1.00	29.7	40.2	32.2	2	6	10	80	5.0	8	12	-1.7	2.9
Hellsten-Westing (29)	NC	11	1.00	53.0	23.6	-	6	18	10	50	7.0	15	15	2.4	2.5

Abbreviations: BM - body mass, BMI - body mass index, C - controlled, NC - not controlled, SE - standard error, SIT - sprint interval training

Table 2 Main effect of SIT on $\dot{V}O_2max$ and modifying effects

	Effect on $\dot{V}O_2max$ (mean %, ± 90% CL)	Inference
Main effect:	7.8 ± 4.0	Likely large increase
Modifying effects:		
2 more sprint repetitions*	-1.2 ± 0.8	Possibly small decrease
3 more training sessions*	0.7 ± 0.4	Likely trivial change
10 s longer sprint duration*	0.6 ± 1.3	Possibly trivial change
60 s longer recovery interval duration*	0.2 ± 0.3	Most likely trivial change
3% of BM greater sprint resistance	1.0 ± 2.3	Unclear
10 $mL·kg^{-1}·min^{-1}$ lower baseline $\dot{V}O_2max$	1.5 ± 1.9	Possibly small increase
7 years higher age	-1.1 ± 1.2	Possibly small decrease
6.2 $kg·m^{-2}$ higher BMI	0.8 ± 2.7	Unclear
Female sex	-0.2 ± 3.5	Unclear
Uncontrolled study	-0.9 ± 2.1	Unclear

*The reference condition is an intervention using 14 SIT sessions and a maximum of 7 repeated 30-s sprints with 240 s recovery. Effects of SIT are presented as the % change compared to pre-training. *, indicates a practically relevant value was chosen to evaluate the effect magnitude; other numeric modifiers were evaluated as a 2 x SD change in the parameter. Abbreviations: BMI: body mass index, CL: confidence limits, SIT: sprint interval training, $\dot{V}O_2max$: maximal aerobic capacity.*