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SYSTEMATIC REVIEW

Sprint Interval Training Effects on Aerobic Capacity: A Systematic Review and Meta-Analysis

Nicholas H. Gist · Michael V. Fedewa · Rod K. Dishman · Kirk J. Cureton

Abstract

Background Sprint interval training (SIT) involving repeated 30-s "all out" efforts have resulted in significantly improved skeletal muscle oxidative capacity, maximal oxygen uptake, and endurance performance. The positive impact of SIT on cardiorespiratory fitness has far-reaching health implications.

Objective The objective of this study was to perform a systematic review of the literature and meta-analysis to determine the effects of SIT on aerobic capacity.

Methods A search of the literature was conducted using the key words 'sprint interval training', 'high intensity intermittent training/exercise', 'aerobic capacity', and 'maximal oxygen uptake'. Seventeen effects were analyzed from 16 randomized controlled trials of 318 participants. The mean ± standard deviation number of participants was 18.7 ± 5.1. Participant age was 23.5 ± 4.3 years.

Results The effect size calculated for all studies indicates that supramaximal-intensity SIT has a small-to-moderate effect (Cohen's $d = 0.32$, 95 % CI 0.10–0.55; $z = 2.79$, $P < 0.01$) on aerobic capacity with an aggregate improvement of ~ 3.6 mL·kg^{-1}·min^{-1} (~ 8 % increase). The effect is moderate to large in comparison with no-exercise control groups (Cohen's $d = 0.69$, 95 % CI 0.46–0.93; $z = 5.84$, $P < 0.01$) and not different when compared with endurance training control groups (Cohen's $d = 0.04$, 95 % CI -0.17 to 0.24; $z = 0.36$, $P = 0.72$).

Conclusion SIT improves aerobic capacity in healthy, young people. Relative to continuous endurance training of moderate intensity, SIT presents an equally effective alternative with a reduced volume of activity. This evaluation of effects and analysis of moderating variables consolidates the findings of small-sample studies and contributes to the practical application of SIT to improve cardiorespiratory fitness and health.

1 Introduction

The development of new exercise interventions aimed at reducing health problems (cardiovascular disease, hyperinsulinemia, obesity, hypertriglyceridemia, and hypertension) associated with physical inactivity is a far-reaching research effort that holds great value. Epidemiological studies have shown that low cardiorespiratory fitness is associated with higher rates of cardiovascular disease, type 2 diabetes mellitus, cancer, and all-cause mortality [1–6]. Cardiorespiratory fitness, typically assessed via a measure of maximal oxygen uptake ($VO_{2\max}$), has a negatively linear relationship with increasing age up to 45 years, with reported declines of ~ 8 % per decade with accelerated reduction of up to 20 % per decade at age 70 years [7, 8]. In a meta-analysis including only studies of women, the findings highlighted age-related decreases in $VO_{2\max}$ in both sedentary and previously active endurance athletes [9]. The importance of improvement or attenuation of age-related decline in $VO_{2\max}$ extends beyond athletic performance.

Although high-intensity interval training (HIT) is commonly used by elite athletes to enhance performance,

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such activity is not typically prescribed for the general population. A synthesis of studies examining the effects of exercise intensity on further improvements in performance in already highly trained athletes highlights its efficacy [10]. The inclusion of aerobic-type exercise for recreational athletes, sedentary populations, and diseased populations has traditionally been limited to moderate-intensity endurance activities with recommended durations of 30–60 min/day or 20–60 min/day of less frequent vigorous exercise [11]. The efficacy of HIT with respect to cardiorespiratory and metabolic adaptations has led to greater recent research interest in the effects of supramaximal HIT, or sprint interval training (SIT) that requires maximal effort during short periods of activity [12]. As lack of time is a commonly cited reason for physical inactivity [13], the apparent time-efficient aspect of SIT has significant implications for exercise adherence. Additionally, SIT may provide an alternative to longer-duration endurance training with similar improvements in cardiorespiratory fitness.

In studies utilizing repeated Wingate Anaerobic Tests, in which the exercise bout involves 30 s of "all out" cycling against a braking force on a specialized cycle ergometer, exercise participants completed 4–6 sprints separated by 4 min of recovery [14–21]. This model of SIT, with as little as 15 min (cumulative time of sprints) of "all out" effort during six sessions across 2 weeks, resulted in significantly improved $V\mathrm{O}_{2\mathrm{max}}$, skeletal muscle oxidative capacity, and endurance performance [22–24]. Others have added to the body of research by using the same protocol of cycling or by applying the 30-s:4-min interval to other modalities such as running and rowing [25–30]. The findings of these studies have highlighted the potential impact of SIT on cardiorespiratory fitness, as well as several other variables.

Additional support for the equally effective benefits of SIT when compared with traditional endurance training protocols has been provided in randomized controlled trials (RCTs) performed by Burgomaster et al. [31] and Gibala et al. [32], in which the effects of SIT were similar to moderate-to-vigorous intensity continuous endurance training. Specifically, the positive effects on aerobic capacity and selected markers of skeletal muscle metabolism (carbohydrate and lipid metabolism, cytochrome oxidase activity, muscle buffering capacity, muscle glycogen content) were not different between groups despite the significantly reduced time commitment and training volume of SIT [31, 32].

Based on what is known regarding the potential benefits of low-volume SIT, a systematic review of the available literature and a quantitative synthesis of studies can inform about the typical and variable effects of this type of exercise on cardiorespiratory fitness. Although several researchers have reported the positive impact of SIT on various health- and performance-related dependent variables, many did not include a control group [15, 33–38] or lacked a measure of aerobic capacity [23, 32, 39, 40]. The objectives of this review and meta-analysis were to estimate the population effect of SIT of maximal or greater intensity (expressed relative to $V\mathrm{O}_{2\mathrm{max}}$ or peak power output) on aerobic capacity and to assess whether those effects vary by participant type or study characteristics. The scope of this review has been limited to the inclusion of studies using the repeated Wingate protocol based on its recent frequent use and apparent impact despite the very low training volume. Further, protocols involving a different intensity, work duration, or recovery duration may have different effects. This evaluation of effects and analysis of moderating variables may enhance the findings of several small-sample studies and contribute to the practical application of time-efficient SIT as another option to improve cardiorespiratory fitness in the adult population.

2 Methods

2.1 Literature Search

The review and analysis was conducted in accordance with PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-analyses) Statement guidelines [41]. A systematic search of the research literature was conducted for RCTs studying the effects of SIT interventions on aerobic capacity. The search included articles published prior to 1 January 2013, as well as theses/dissertations completed and available by the same date. PubMed, MEDLINE, and Web of Science databases were searched using the terms 'sprint interval training', 'high intensity intermittent training/exercise', 'aerobic capacity', and 'maximal oxygen uptake'. Reference lists from retrieved studies were also reviewed.

2.2 Inclusion and Exclusion Criteria

Participants of any age were included. Studies meeting the following inclusion criteria were considered for review: (1) available in English; (2) participants were randomly assigned to a SIT group or control group; (3) training intensity classified as "all out," "supramaximal," "maximal," or "$\geq 100\ \%\ V\mathrm{O}_{2\mathrm{max}}$"; (4) SIT work:rest ratio of 30-s:4-min (rest interval of 3–5 min); and (5) laboratory assessment of $V\mathrm{O}_{2\mathrm{max}}$ or peak oxygen uptake ($V\mathrm{O}_{2\mathrm{peak}}$). Studies were excluded for the following reasons: (1) assessment included only an endurance performance measure; (2) animal subjects; or (3) training intensity did not meet the “supramaximal” or “maximal” threshold.

2.3 Study Selection

A search of electronic databases and a scan of article reference lists revealed 303 relevant studies (Fig. 1). Based on a review of the title or abstract or lack of control group in the experimental design, 264 articles were dismissed. Forty-one full-text articles were evaluated, and 16 were included for the meta-analysis. Each study was read and coded for descriptive variables: country, age, sex, body mass index, training status (sedentary, recreational, and trained), type of control group (no exercise, endurance training), control group exercise mode and intensity, experimental group exercise mode and intensity, work:rest ratio, and length of intervention.

2.4 Data Collection

Aerobic capacity data were extracted in the forms of pre- and post-training intervention means, standard deviations (SDs), and sample sizes for SIT and control conditions. Dependent variables included $VO_{2\mathrm{max}}$ or $VO_{2\mathrm{peak}}$ reported in $\mathrm{mL{\cdot}kg^{-1}{\cdot}min^{-1}}$ or $\mathrm{L{\cdot}min^{-1}}$ (if relative values were not reported). In studies that reported intermediate and post-intervention values, only final values for aerobic capacity were compared with baseline.

2.5 Study Characteristics

Seventeen effects were collected from 16 RCTs [16–19, 28, 30, 31, 42–50] of 318 participants. Two effects were calculated and included from a study by Bailey et al. [16] because the experimental design included a sprint training group, an endurance training group, and a no-exercise control group, thus permitting a comparison of SIT to the endurance training as well as the no-exercise controls. Study characteristics are presented as mean ± SD unless otherwise stated. The number of participants was 18.7 ± 5.1. Participant age was 23.5 ± 4.3 years. Six effects involved studies of men only; four included exclusively women; seven enrolled both men and women. Aerobic capacity was a primary outcome for nine of the studies. The mode of sprint exercise for interventions primarily involved cycling (nine studies); six studies administered a sprint interval running protocol, and one study used rowing. Training intervention length was 4.8 ± 2.3 weeks with 2.9 ± 0.4 sessions per week. There were four studies conducted in Canada, four in the USA, two in the UK, two in Australia, two in Iran, one in Denmark, and one in Norway.

2.6 Meta-Analysis

To estimate the magnitude of the impact of SIT on $VO_{2\mathrm{max}}$, effect sizes (ES) were calculated as Cohen’s *d* by

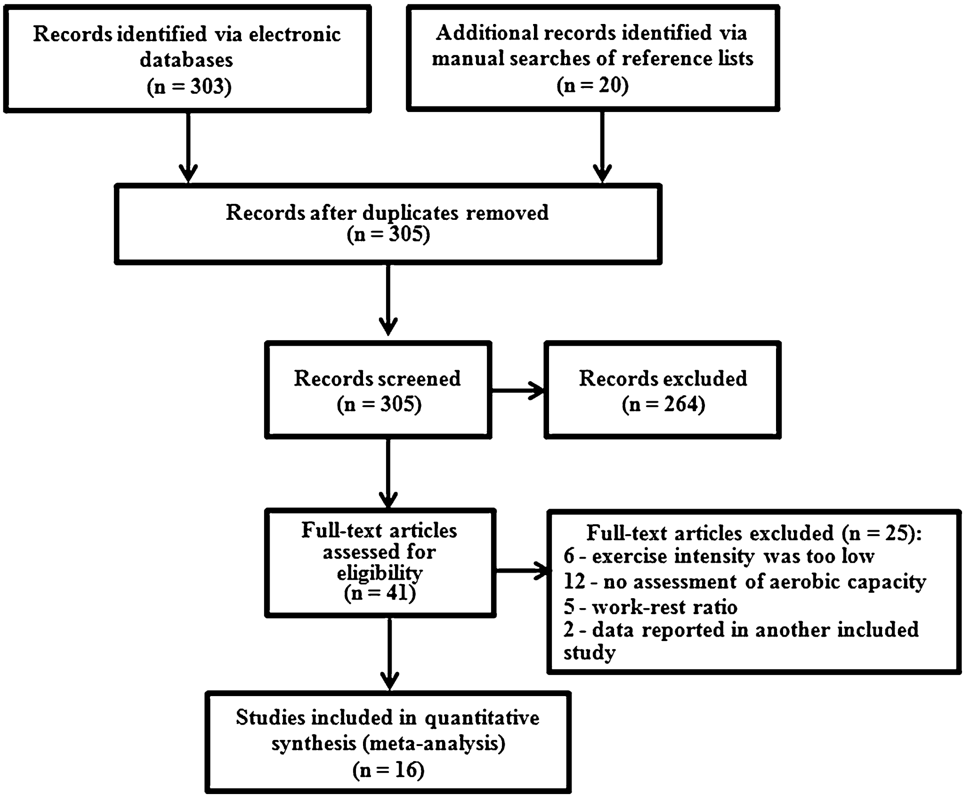


Fig. 1 Flow chart of study selection

subtracting the mean change in the control group from the mean change in the experimental group and dividing by the pooled SD of baseline values [51]. Aggregated effects were calculated using a random effects model with each effect weighted by its degrees of freedom. The random effects model was applied because of variability in several experimental factors (e.g., length of intervention, type of control group, mode of training, participant characteristics) across studies. The aggregated mean ES was interpreted as small (0.2), medium (0.5), or large (0.8). Consistency (i.e., homogeneity) of effects was assessed using Q and I^2 [52, 53].

2.7 Data Synthesis and Analysis

Using SPSS® macros (MeanES, MetaReg; SPSS® 20.0, IBM Corp., Armonk, NY, USA), an aggregated mean ES, Cohen's d, associated 95 % confidence intervals and moderator effects of control group type, participant fitness level, intervention length, additional training, and mode of training were calculated [54]. Distribution of ES was determined to be heterogeneous if Q reached a significance level of $P < 0.05$ and the sampling error accounted for less than 75 % of the observed variance [52]. An I^2 statistic was also calculated to assess heterogeneity of effects [53]. In order to determine the number of unpublished studies of null findings necessary to negate the significant ES of included studies, a fail-safe number was calculated to address publication bias [55]. As an explorative tool, a funnel plot of standard error versus ES was developed to address the potential of publication bias relating to study sample size. A two-way (effects × raters) intraclass correlation coefficient (ICC) for absolute agreement was calculated to assess inter-rater reliability in the determination of ES [56]. An ICC (2, 2) of 0.98 was calculated for all effects, and differences in ES calculation were resolved prior to final analysis.

2.8 Moderator Variables

Five potential moderators were selected a priori based on their theoretical or empirical relation to changes in aerobic capacity: type of control group, baseline fitness level of study participants, length of training intervention, inclusion of additional training, and mode of training. Planned contrast weights were assigned to each level of moderating variable. For type of control group, levels were: no exercise and endurance exercise; participant baseline activity level: sedentary, recreational or trained; length of intervention levels were: <6 and ≥6 weeks; inclusion of training in addition to SIT: yes or no; and mode of training: cycling, running or rowing. Multiple linear regression analysis was used to determine the independent effects of moderator variables on variation in ES. Statistical programming macros for a random model using maximum likelihood parameter estimates were used to determine significance levels and compute effects sizes and confidence intervals [54].

3 Results

3.1 Description of Included Studies

Seventeen effects were analyzed from 16 RCTs with a total of 318 participants. Study characteristics are summarized in Table 1.

3.2 Meta-Analysis

Twelve effects (~71 %) were greater than zero and the Cohen's d range of effects for all studies was –0.39 to 1.22 (Table 2). A forest plot depicting the individual ES, random effects mean Cohen's d, and associated 95 % confidence intervals is shown in Fig. 2. Mean ES Cohen's d was 0.32 (95 % CI 0.10–0.55; $z = 2.79$, $P < 0.01$). The significant improvement in aerobic capacity following SIT was heterogeneous ($Q_{16} = 59.87$; $P < 0.01$) [57] with moderate inconsistency of effects ($I^2 = 74.95$, 95 % CI 68.02–80.37) [53]. The fail-safe number of effects was 28, and although sample size range was only 11–29 participants, visual examination of the funnel plot (Fig. 3) indicates lack of publication bias.

3.3 Moderator Analysis

Planned contrasts were applied to examine the individual impact of moderators: type of control group, length of the SIT intervention, and physical activity level of the study participants. The overall meta-regression model was significant ($Q_5 = 22.09$; $P < 0.01$; $R^2 = 0.55$; $Q_{11} = 18.01$; $P = 0.08$). Only the type of control group accounted for significant variation in the overall effect of SIT on aerobic capacity ($\beta = -0.33$; $z = -3.57$; $P < 0.01$). Effects were not significant when the type of control included moderate-intensity continuous endurance exercise (Cohen's $d = 0.04$; 95 % CI -0.17 to 0.24; $z = 0.36$, $P = 0.72$); effects of SIT were moderate-to-large and statistically significant when compared with no-exercise control groups (Cohen's $d = 0.69$; 95 % CI 0.46–0.93; $z = 5.84$, $P < 0.01$). Effects were not significantly different when moderating by fitness level, length of intervention, inclusion of additional training, or mode of training.

Table 1 Characteristics of studies examining the effect of sprint interval training on aerobic capacity

Study	Sample size	Sex	Fitness level	Type of control	Training mode	Intervention length (wk)	Training frequency (sessions/week)		Training intensity		Training duration (min)
							Control	SIT	Control	SIT	Control
Cocks et al. [47]	16	M	Sedentary	Endurance training	Cycling	6	5	3	65 % VO_{2max}	All out	40–60
Carr [43]	20	F	Trained	Endurance training	Rowing	4	3	3	65 % VO_{2max}	Maximal	30
Iaia et al. [28]	17	M	Trained	Endurance training	Running	4	4	3.5[a]	Moderate	All out	50–55
Burgomaster et al. [31]	20	MF	Recreational	Endurance training	Cycling	6	5	3	65 % VO_{2max}	All out	40–60
MacPherson et al. [30]	20	MF	Recreational	Endurance training	Running	6	3	3	65 % VO_{2max}	All out	30–60
Rowan [49]	11	F	Trained	Endurance training	Running	5	2	2	80 % VO_{2max}	All out	40
Sandvei et al. [50]	23	MF	Recreational	Endurance training	Running	8	3	3	70–80 % HR_{max}	Maximal	30–60
Laursen et al. [45]	21	M	Trained	Endurance training	Cycling	4	NR	2	Low-to-moderate	175 % PPO	NR
Barnett et al. [42]	16	M	Recreational	No exercise	Cycling	8	NA	3	NA	All out	NA
Astorino et al. [46]	29	MF	Recreational	No exercise	Cycling	2	NA	3	NA	All out	NA
Bailey et al. [16]	12	MF	Recreational	Endurance training	Cycling	2	3	3	90 % GET	All out	15–25
Bailey et al. [16]	12	MF	Recreational	No exercise	Cycling	2	NA	3	NA	All out	NA
Reid [48]	16	F	Recreational	No exercise	Running	6	NA	3	NA	All out	NA
Esfarjani and Laursen [44]	11	M	Trained	Endurance training	Running	10	4	2	75 % VO_{2max}	130 % VO_{2max}	60
Trilk et al. [19]	28	F	Sedentary	No exercise	Cycling	4	NA	3	NA	All out	NA
Hazell et al. [18]	22	MF	Recreational	No exercise	Cycling	2	NA	3	NA	All out	NA
Bayati et al. [17]	16	M	Recreational	No exercise	Cycling	4	NA	3	NA	All out	NA

F female only, *GET* gas exchange threshold, HR_{max} maximal heart rate, *M* male only, *MF* male and female, *NA* not applicable, *NR* not reported, *PPO* peak power output, *SIT* sprint interval training, VO_{2max} maximal oxygen uptake

[a] Every other day

4 Discussion

The aggregated findings indicate that SIT is effective (mean ES Cohen's $d = 0.32$) in improving aerobic capacity. The effect is moderate-to-large in comparison with no-exercise control groups (Cohen's $d = 0.69$) and not different when compared with endurance training control groups (Cohen's $d = 0.04$). The aggregate improvement equates to an approximately 3.6 $mL \cdot kg^{-1} \cdot min^{-1}$ or 8 % increase in VO_{2max} relative to no-exercise controls and results in similar improvements to traditional endurance-type exercise of moderate-to-vigorous intensity. In a prospective study, Blair et al. [58] calculated that men who improved fitness may reduce mortality risk by 44 % relative to those who remained unfit. An increase of the magnitude reported in this meta-analysis could prove beneficial in reducing risk for cardiovascular disease in the context of epidemiological studies that highlight the relationships between low cardiorespiratory fitness and all-cause mortality. This review and quantitative analysis supports the prescription of supramaximal SIT as an alternative method to improve cardiorespiratory health.

The central and peripheral physiological adaptations associated with endurance training are well-known [59]; however, with regard to centrally and peripherally mediated adaptations, the precise mechanisms leading to improved VO_{2max} following SIT require further

Table 2 Baseline and post-training maximal oxygen uptake data, percentage change, and Cohen's *d* effect sizes

Study	Group	Baseline VO_{2max} (mL·kg^{-1}·min^{-1})	Post-training VO_{2max} (mL·kg^{-1}·min^{-1})	ΔVO_{2max} (%)	Cohen's *d* effect size (95 % CI)
Cocks et al. [47]	Control	41.70	48.20	13.49	−0.39 (−1.38 to 0.60)
	SIT	41.90	45.10	7.10	
Carr [43]	Control	45.00	45.80	1.75	−0.34 (−1.22 to 0.55)
	SIT	45.80	44.80	−2.23	
Iaia et al. [28]	Control	56.10	56.40	0.53	−0.31 (−1.27 to 0.65)
	SIT	54.80	53.50	−2.43	
Burgomaster et al. [31]	Control	41.00	45.00	8.89	−0.17 (−1.04 to 0.71)
	SIT	41.00	44.00	6.82	
MacPherson et al. [30]	Control	44.00	49.50	11.11	−0.02 (−0.90 to 0.86)
	SIT	46.80	52.20	10.34	
Rowan [49]	Control	50.64	52.31	3.19	0.10 (−1.09 to 1.29)
	SIT	50.68	53.04	4.45	
Sandvei et al. [50]	Control	47.90	49.70	3.62	0.14 (−0.68 to 0.96)
	SIT	50.90	53.50	4.86	
Laursen et al. [45]	Control	4.92[a]	4.96[a]	0.81	0.28 (−0.58 to 1.14)
	SIT	4.91[a]	5.06[a]	2.96	
Barnett et al. [42]	Control	3.91[a]	4.07[a]	3.93	0.31 (−0.67 to 1.30)
	SIT	3.78[a]	4.09[a]	7.58	
Astorino et al. [46]	Control	42.70	43.40	1.61	0.31 (−0.48 to 1.10)
	SIT	43.60	46.00	5.22	
Bailey et al. [16]	Control	43.00	43.00	0.00	0.58 (−0.42 to 1.58)
	SIT	42.00	45.00	6.67	
Bailey et al. [16]	Control	47.00	46.00	−2.17	0.60 (−0.40 to 1.61)
	SIT	42.00	45.00	6.67	
Reid [48]	Control	51.50	51.60	0.19	0.67 (−0.49 to 1.82)
	SIT	45.30	48.10	5.82	
Esfarjani and Laursen [44]	Control	51.80	52.90	2.08	0.74 (−0.49 to 1.96)
	SIT	51.70	54.90	5.83	
Trilk et al. [19]	Control	20.50	20.40	−0.49	0.82 (0.06 to 1.60)
	SIT	21.60	24.50	11.84	
Hazell et al. [18]	Control	45.20	45.30	0.22	0.96 (0.06 to 1.85)
	SIT	48.70	53.00	8.11	
Bayati et al. [17]	Control	45.10	44.70	−0.89	1.22 (0.16 to 2.29)
	SIT	44.60	48.90	8.79	

SIT sprint interval training, VO_{2max} maximal oxygen uptake, ΔVO_{2max} change in VO_{2max}

[a] VO_{2max} values reported only in L·min^{-1}

examination. Gibala and McGee [60] suggested that performance improvements reported after only six sessions of SIT are possible evidence that peripheral adaptations are primarily responsible given the lack of improvement in VO_{2max} in cited research. In a study comparing endurance running and SIT running, MacPherson et al. [30] reported that post-training enhancements in stroke volume (SV) and maximal cardiac output (Q_{max}) were only observed in the endurance training group, whereas a group by time interaction in skeletal muscle arterial-venous oxygen difference (a-vO$_2$ diff) suggested VO_{2max} improvement following SIT was due to peripheral adaptations. Although high-intensity training was submaximal in another study, Daussin et al. [61] reported that interval training was optimal in improving both central cardiorespiratory and peripheral skeletal muscle adaptations when compared with a continuous training protocol. The numerous benefits of traditional endurance training should not be discounted; however, these findings support the use of SIT as an alternative method of training that induces physiological adaptations that enhance VO_{2max}. A combination of both methods may be ideal to elicit both central and peripheral changes that optimize cardiorespiratory fitness.

Many researchers have highlighted the time savings associated with low-volume SIT compared with longer-duration endurance training. During a 2-week study

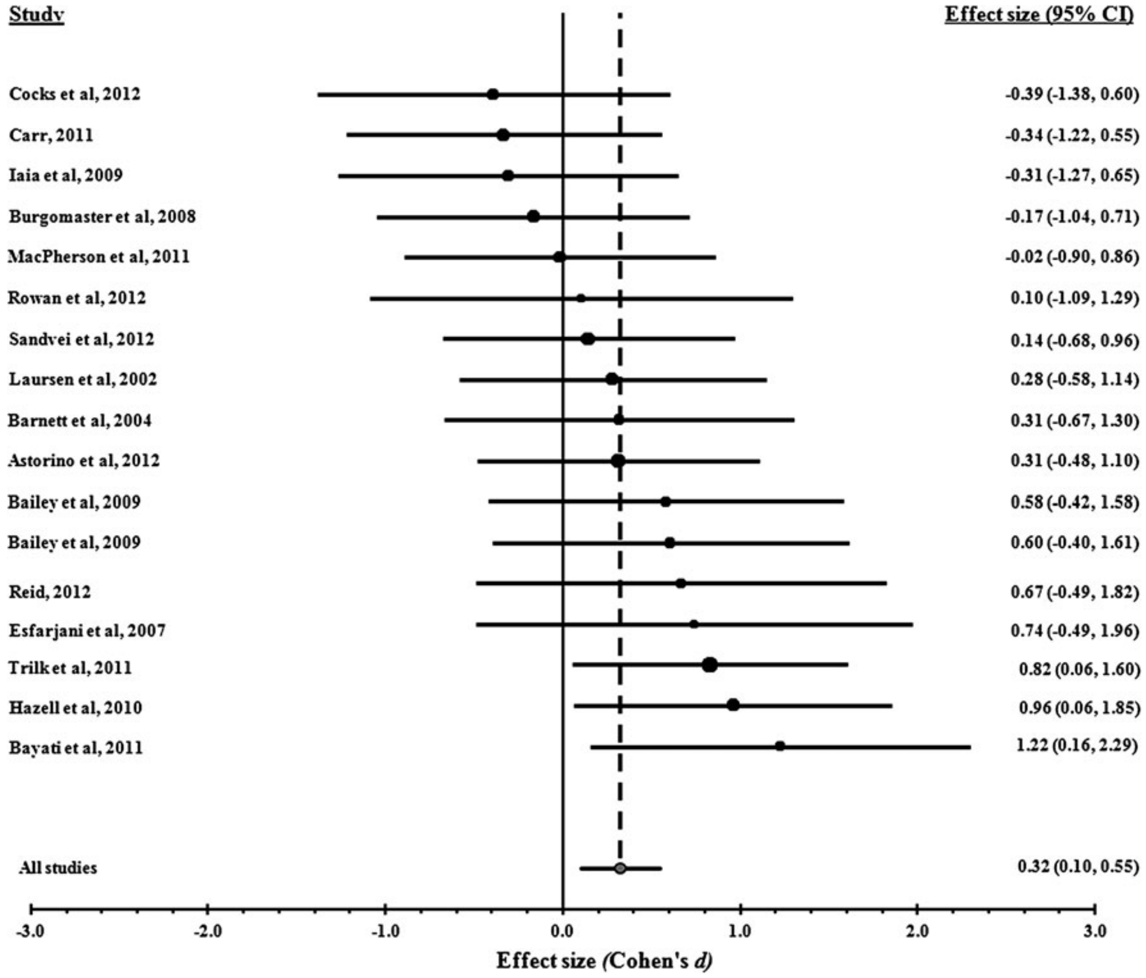
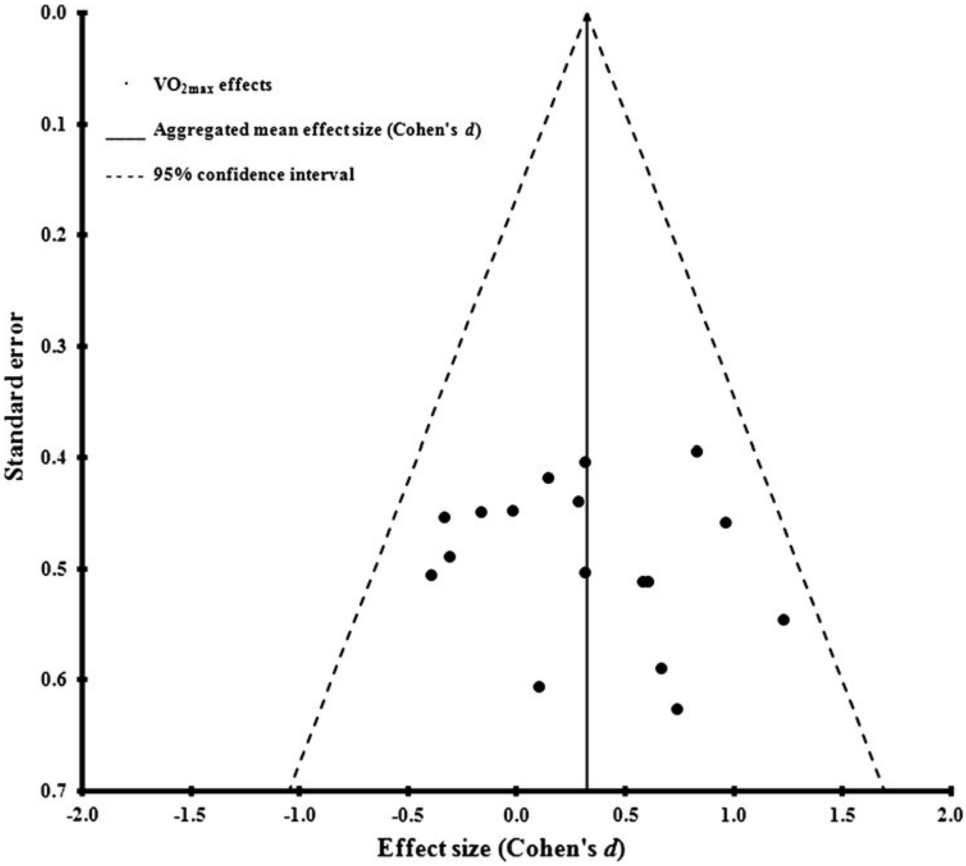


Fig. 2 Forest plot of Cohen's *d* effect sizes and corresponding 95 % confidence intervals. The aggregated Cohen's *d* is the random effects mean effect size weighted by degrees of freedom. *CI* confidence interval

comparing low- and high-volume training interventions, Gibala and colleagues reported that participants in the low-volume SIT group spent only 15 min (135 min including recovery) exercising while those in the high-volume endurance training group spent 630 min exercising [62]. Despite completing a training volume of only 10 % that of the endurance training group, the SIT group had similar improvements in oxidative capacity and exercise performance. By design, the SIT group workouts were only ~21 % of the total time spent exercising in the endurance training group; however, improvements in oxidative capacity and exercise performance were similar. Given the commonly reported reason of "lack of time" for exercise [13], the time-efficient aspect of low-volume SIT has significant implications for participation in and adherence to this type of activity. While time efficiency was a noted positive aspect in several of the included studies, the addition of rest intervals reveals that SIT time savings may not be so large. For example, six 30-s sprints and six 4-min recovery intervals requires the individual to be active for 27 min. Assuming similar time allocation for appropriate warm-up and cool-down periods, 30–60 min of continuous moderate-to-vigorous endurance-type training is a typical recommendation for improving cardiorespiratory fitness and compares favorably to the SIT example described above [11]. Those who choose to engage in SIT may realize time savings by sprinting fewer sessions per week rather than performing similar duration sessions 5–6 times per week. Sprint frequency, intensity, and recovery time requires further examination to balance individual goals for cardiorespiratory fitness improvement with time commitment.

A limitation of included studies was the young age (23.2 ± 4.3 years) and normal health of participants. Jackson et al. [7] highlighted the accelerated decline in cardiorespiratory fitness after age 45 years in men and women. Further study of the impact of SIT on older populations is needed to not only support its efficacy across age but also to determine its feasibility relative to musculoskeletal limitations, exercise tolerance, and protocol

Fig. 3 Funnel plot of Cohen's *d* effect size versus study sample size (standard error). The aggregated Cohen's *d* is the random effects mean effect size weighted by degrees of freedom. *VO_{2max}* maximal oxygen uptake



adherence. In a study to determine the effectiveness of HIT (85–95 % heart rate reserve) in coronary artery disease patients 56 ± 7 years old, Warburton and colleagues [63] reported improvements in aerobic fitness similar to controls completing moderate-intensity endurance training. Although excluded from the current analysis due to insufficient intensity (90–95 % peak heart rate), interval training improved aerobic capacity 46 % in congestive heart failure patients 76.5 ± 9 years old with an ES of 3.14 relative to no-exercise controls and 2.84 when compared with moderate-intensity continuous exercise controls. Tjonna and colleagues [64] reported greater reduction of metabolic syndrome risk factors in a group completing near-maximal interval training when compared with continuous moderate exercise. These significant improvements occurred after training periods of 4–12 weeks with only three sessions per week. In separate studies by Trilk et al. [19] and Whyte et al. [38], SIT using the repeated Wingate protocol with 4–4.5 min active recovery was well-tolerated in 30- to 32-year-old sedentary overweight/obese participants and resulted in significant improvement in VO_{2max}, circulatory function, mean power output, insulin sensitivity, resting fat oxidation, and systolic blood pressure. Although not all of these designs incorporated SIT, the results of these studies provide further support for the use of low-volume, high-intensity aerobic training interventions designed to improve cardiorespiratory fitness. With appropriate stratification and mitigation of risk, future studies should incorporate SIT to assess its effectiveness to increase VO_{2max} in healthy *and* unhealthy groups of all ages.

The duration of training interventions in the majority of included studies was less than 6 weeks, which leaves much to be determined regarding the impact of continued participation in SIT on not only further improvements in VO_{2max} but also on the time course of physiological adaptations, participant adherence, and injury rates. Whether supramaximal intensity training can be sustained for periods longer than those shown in this analysis is unknown. As discussed previously, the time course of physiological adaptations may be further elucidated through longer training interventions that specifically examine central and peripheral changes at various time points throughout the study. Furthermore, the majority of included RCTs required participants to perform sprints on a cycle, while six studies used running, and only one study used a rowing ergometer. The non-weight-bearing nature of stationary cycling, coupled with minimal eccentric contraction of leg muscles, seems to mitigate risk of injury and discomfort; however, well-designed RCTs using various modes of SIT are needed to increase the knowledge of effects across exercise type. Additionally, longer studies of all age ranges are necessary to determine the impact of SIT in older populations and to further assess exercise adherence.

5 Conclusion

This systematic review and meta-analysis indicates that SIT is a beneficial training methodology to improve $VO_{2\max}$ among healthy and young people. Relative to continuous endurance training of moderate-to-vigorous intensity, SIT presents an equally effective alternative with a much lower volume of activity and potentially reduced time commitment. This evaluation of effects and analysis of moderating variables consolidates the findings of small-sample studies and contributes to the practical application of SIT as another option to improve cardiorespiratory fitness and other health-related outcomes.

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