Schoenmakers *et al. BMC Sports Science, Medicine and Rehabilitation* (2026) 18:358
https://doi.org/10.1186/s13102-026-01766-x

BMC Sports Science, Medicine and Rehabilitation

RESEARCH **Open Access**

Time spent at or near $\dot{V}O_2$max during high-intensity interval training - a systematic review and meta-analysis

Patrick Schoenmakers[1*], Kelly Murray[1], Jamie White[1,5], Guilherme Matta[2] and Arthur Henrique Bossi[3,4]

Abstract

Background High-intensity interval training (HIIT) is widely recognised as an effective strategy to improve cardiorespiratory fitness and endurance performance. Time spent at or near maximal oxygen uptake (t$\dot{V}O_2$max) has emerged as a key marker of the adaptive potential of HIIT, yet HIIT configurations that maximise t$\dot{V}O_2$max remain unclear.

Objective This systematic review and meta-analysis examined acute t$\dot{V}O_2$max responses across various HIIT protocols, aiming to identify configurations with the greatest potential to stimulate training adaptations.

Methods PubMed and Scopus were systematically searched to September 2025 for studies reporting t$\dot{V}O_2$max during HIIT, defined as time spent at or above ≥ 80% $\dot{V}O_2$max. Associations between protocol characteristics and t$\dot{V}O_2$max were evaluated using ANCOVAs and linear mixed-effects models, while random-effects meta-analyses compared standardised mean differences (SMDs) across HIIT configurations, recovery modalities (active vs passive), and exercise intensity distributions in work intervals.

Results The literature search yielded 86 unique articles, in which t$\dot{V}O_2$max was determined for a total of 239 HIIT protocols. Protocols with long work intervals (≥ 2 min) elicited significantly greater t$\dot{V}O_2$max than short (≤ 30 s) or moderate (> 30 s to < 2 min) work intervals, and linear mixed-effects models confirmed a positive relationship between cumulative HIIT duration and time ≥ 90% and ≥ 95% $\dot{V}O_2$max when longer work intervals were used. Protocols incorporating variable-intensity work intervals further increased t$\dot{V}O_2$max compared to even-paced formats (SMD = 0.80, $p < .01$). In contrast, recovery modality (active vs passive) showed no effect on t$\dot{V}O_2$max.

Conclusions t$\dot{V}O_2$max exhibits considerable variability, and its dose–response relationship with long-term adaptations requires further investigation. Nevertheless, HIIT protocols with longer and variable-intensity work intervals maximise t$\dot{V}O_2$max, providing researchers, practitioners, and athletes with a firmer foundation for understanding how specific protocols shape the physiological demands and adaptive potential of a workout.

Keywords HIIT, Exercise prescription, t$\dot{V}O_2$max, Endurance Training

*Correspondence:
Patrick Schoenmakers
ppscho@essex.ac.uk
[1]School of Sport, Rehabilitation, and Exercise Sciences, University of Essex, Colchester CO4 3SQ, United Kingdom
[2]Juiz de Fora, Minas Gerais, Brazil
[3]School of Applied Sciences, Edinburgh Napier University, Edinburgh EH11 4BN, United Kingdom
[4]Mountain Bike Centre of Scotland, Glentress, Peebles EH45 8NB, United Kingdom
[5]University of Regina, Faculty of Kinesiology and Health Studies, Regina SK S4S 0A2, Canada

Introduction

High-intensity interval training (HIIT) is by no means a new phenomenon, but instead a training concept long employed by athletes to improve their cardiorespiratory fitness, metabolic functioning, and performance [1–4]. Pioneering work in the 1960s on the acute physiological responses to HIIT laid the scientific foundations for the programming of HIIT sessions comprising both long and short work intervals [5, 6], with the first intervention studies emerging in the 1970s [7, 8]. Research interest renewed from the mid-1990s [9], and HIIT is now considered a time-efficient and effective strategy to improve an individuals' maximum oxygen uptake ($\dot{V}O_2$max), where meta-analyses have shown the magnitude of adaptations appear moderated by baseline fitness and HIIT configurations [10–13]. These meta-analyses have further shown that HIIT interventions incorporating long work intervals (≥ 2 min; LI-HIIT) elicit larger improvements in $\dot{V}O_2$max than interventions implementing repeated short (≤ 30 s; SI-HIIT) or moderate duration (> 30 s to < 2 min; MI-HIIT) work intervals [10–13]. HIIT has also been shown to enhance performance in recreational and trained athletes [13–16], with negligible differences between SI-HIIT, MI-HIIT and LI-HIIT on 30-s Wingate performance [13, 16], but greater improvements in time trial performance (i.e., 2-km rowing, 3-km running, and 40-km cycling) following LI-HIIT compared to SI-HIIT [13, 15].

$\dot{V}O_2$max is a key physiological determinant and strong predictor of endurance performance [17], and HIIT has been shown to elicit greater improvements in $\dot{V}O_2$max compared to (continuous) moderate-intensity training in interventions of similar duration [18, 19]. However, given the high demands of HIIT, only a limited proportion (~10–20%) of total training is, or can be, performed in this manner [20], as evident from training intensity distributions in recreational and trained endurance athletes [21, 22]. Accordingly, careful programming of these sessions is essential to fully realise their physiological and performance benefits.

In HIIT, repeated periods of vigorous exercise (work intervals) are alternated with recovery periods (recovery intervals), and a complex interplay between the number of repetitions and the exercise intensity and duration of both work and recovery intervals determine the physiological demand of a session [2, 3, 23]. The manipulation of these variables allows for virtually limitless customisation of HIIT protocols, enabling precise tailoring to specific training goals and individual needs. As demanding work intervals are required to drive training adaptations, multiple studies have sought to optimise the intensity and duration of work intervals (e.g. [24–26]). However, if recovery intervals do not provide sufficient respite relative to the demands of the work intervals, premature fatigue and incomplete HIIT sessions may occur [27]. Studies have thus increasingly focused on understanding the acute responses to manipulations in recovery intensities and durations as well (e.g. [28, 29]). In addition to these factors, the exercise intensity distribution within work intervals has recently been suggested to influence time spent at higher fractions of $\dot{V}O_2$max [30]. For example, in 14 well-trained cyclists, Bossi et al. [31] demonstrated that, despite being matched for mean power output and duration, variable-intensity cycling HIIT, incorporating three 30-s efforts within 5-min work intervals, elicited ~43% longer time ≥ 90% $\dot{V}O_2$max compared with constant-intensity intervals. Yet, in the absence of comprehensive investigations, it remains challenging to draw definitive conclusions about the most effective HIIT configurations.

The intermittent profile of HIIT allows athletes to maximise 1) time at high work rates and 2) time at or near their $\dot{V}O_2$max (t$\dot{V}O_2$max - [3]). Typically, t$\dot{V}O_2$max, or time in the *'red zone'*, refers to the accumulated duration in which athletes reach metabolic demands equivalent to, or above 90% $\dot{V}O_2$max. It can also be described more broadly, as the total time spent at metabolic rates that lie within the severe intensity domain, that is, above the second lactate (LT2) or ventilatory thresholds (VT2). At these exercise intensities, the oxygen delivery and utilisation systems are maximally stressed, and by doing so, HIIT can enhance the metabolic and physiological overload of a training session compared with continuous training [32–35]. This stimulus has been shown to promote central and peripheral adaptations associated with improvements in $\dot{V}O_2$max, including expansion of red blood cell and stroke volume, mitochondrial content, and skeletal muscle capillarisation [18, 36]. Whilst the dose-response relationship between t$\dot{V}O_2$max per HIIT session and subsequent improvements in physiological function and performance remains unclear, it is generally accepted that both the mean $\dot{V}O_2$ and the time sustained at high fractions of $\dot{V}O_2$max are key indicators to characterise the adaptive potential of HIIT protocols [3, 32, 37–39]. Although not yet conclusively demonstrated through empirical research, Buchheit and Laursen [3] indicated that 5–7 min of exercise in the *'red zone'* per HIIT session may be sufficient to induce adaptations for team-sport athletes, whereas trained endurance athletes may require more than 10 min at t$\dot{V}O_2$max. Given the recognition of t$\dot{V}O_2$max as a valuable indicator of adaptive stimulus, identifying HIIT protocols that maximise t$\dot{V}O_2$max is essential to inform future research as well as training program implementation.

The present systematic review and meta-analysis aims to synthesise the available evidence from HIIT studies that have reported t$\dot{V}O_2$max. In the light of the growing variety of HIIT protocols found in the literature, spanning different exercise modalities, configurations, and athletic populations, our review seeks to update and expand upon the foundational review of Midgley and McNaughton [32], which examined tVO_2max during intermittent running protocols. Furthermore, we aim to identify which HIIT configurations are most likely to meet the minimal tVO_2max per session as proposed by Buchheit and Laursen [3]. This review, therefore, endeavours to inform both future research and evidence-based practice, offering refined guidance for the design of HIIT protocols that optimise physiological and performance adaptations.

Methods

This systematic review was performed according to the latest Preferred Reporting Items for Systematic Reviews and Meta-Analyses statement [40].

Literature search

A literature search was performed in the PubMed and Scopus databases on the 23rd of September 2025. The search was conducted using the Boolean operators 'AND' and 'OR' and combinations of the following keywords: ('tVO_2max', OR 't90VO_2max ', OR 'time near' OR 'time above' OR 'time at') AND ('VO_2max' OR 'VO_2peak' OR 'oxygen uptake' OR 'oxygen consumption') AND 'interval training'.

After duplicates were removed, titles of relevant articles were screened before an examination of abstracts, which was then followed by full text reviews (see Fig. 1). To identify studies that were potentially overlooked by the database search, reference lists of included studies were screened. Only peer-reviewed journal articles, written in English, were included in this systematic review.

Eligibility criteria and outcome measures

Studies were included if they reported tVO_2max during HIIT sessions and were conducted in apparently healthy human participants. No restrictions were placed on training status and age of participants, nor the exercise modality. The primary outcome of this systematic review was tVO_2max. As the demarcation between the heavy and severe exercise intensity domains varies between individuals and is not fixed at 90% VO_2max, studies reporting time at or above 80% VO_2max were included.

No minimum HIIT session duration, number of intervals or work interval intensity was imposed, as the aim of the review was to capture the full range of HIIT protocols

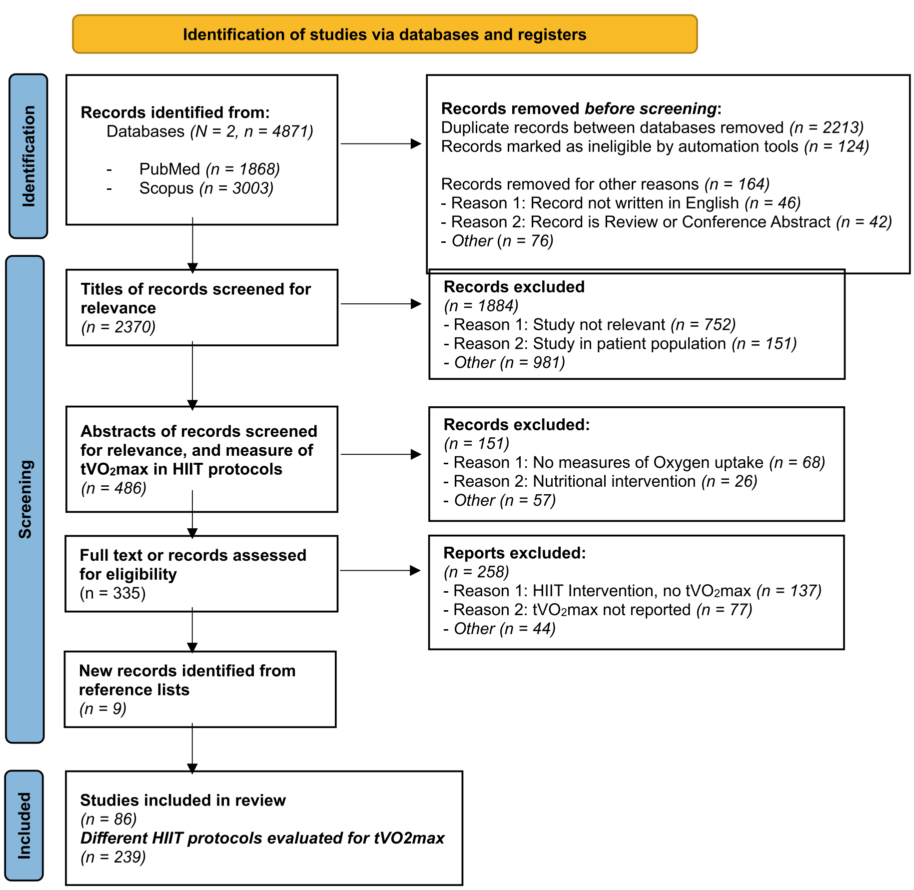

Fig. 1 PRISMA flow diagram of systematic search process

reported across the literature. Studies incorporating additional interventions (e.g. nutritional supplementation or environmental conditions such as hypoxia) were included where a control or baseline HIIT condition could be extracted independently.

Studies were excluded if they did not report t$\dot{V}O_2$max, measured t$\dot{V}O_2$max during only continuous (non-interval) exercise, involved clinical populations, or were not original peer-reviewed research articles written in English.

Data extraction

Data were extracted into two dedicated spreadsheets. Firstly, descriptive data for each included study was collected: author, year of publication, exercise modality and participant characteristics (sample size, sex, age, height, body mass, $\dot{V}O_2$max, and peak exercise intensity; see Table 1). Additionally, we collated information of every HIIT protocol, including the number of work-recovery cycles (repetitions), work interval duration and intensity, recovery interval duration and intensity, cumulative HIIT protocol duration (combining the duration of both the work and recovery intervals), and the isolated total work interval duration (see Table 2). Data extraction was undertaken by PS, after which JW and KM checked the data independently. When data in any of the variables were unclear or incomplete, authors were contacted for clarification. When study authors did not respond to requests for clarification, protocol characteristics reported in the original publications were used to calculate total training- or isolated work interval durations (see Supplementary Table S1). In line with the Cochrane Handbook for Systematic Reviews of Interventions [120], sample means and standard deviations (SD) of several studies were calculated from standard errors, confidence intervals (CI), medians, and interquartile ranges using established formulae. Freely available online software was used to obtain data from studies where data were only published in figures (WebPlotDigitizer, Version 4.8).

Study quality and risk of bias assessment

The quality of included studies was assessed using the Physiotherapy Evidence Database scale (PEDro scale), of which items 5, 6, and 7 were omitted due to the inherent difficulty of blinding researchers, assessors, and participants in exercise interventions. Items 2 and 10, concerning between-group randomisation and statistical comparison, respectively, were interpreted in the context of within-group study designs. These modifications reduced the maximum attainable PEDro score to 7. Using this adjusted scale, ratings of 6 and 7 were classified as “excellent quality”, 5 as “good quality”, 4 as “moderate quality”, and 0 to 3 as “poor quality” [121].

Bias in the included studies was evaluated using the Cochrane Risk of Bias Tool for Randomized Crossover Trials (RoB-2). The risk of bias was rated as *‘low’, ‘some concerns’*, or *‘high’* across domains such as randomisation processes, carryover effects, and the selection and reporting of t$\dot{V}O_2$max [122]. Graphical summaries of the RoB-2 results were created using robvis software [123].

Statistical analysis

Results are presented as mean ± SD. Time ≥ 90% and ≥ 95% $\dot{V}O_2$max were prioritised for quantitative analyses as the most frequently reported variables, while time ≥ 80%, ≥ 85% and 100% $\dot{V}O_2$max were included for descriptive comparison. Analysis of covariance (ANCOVA), with cumulative HIIT protocol duration as a covariate and sample size as a weighting factor, were used to compare time ≥ 90% and ≥ 95% $\dot{V}O_2$max across SI-HIIT, MI-HIIT and LI-HIIT protocols [10]. Tukey's post hoc testing was performed to identify pairwise differences between HIIT categories. Time to exhaustion during exhaustive HIIT protocols was compared between studies incorporating active versus passive recovery intervals, using repeated measures analysis of variance (ANOVA). These statistical analyses were run in JASP (Version 0.17.2.1), with significance levels set at $p \leq .05$.

A linear mixed-effects modelling approach was employed to examine associations between cumulative HIIT protocol duration and time ≥ 90% and ≥ 95% $\dot{V}O_2$max. For protocols involving exercise to exhaustion, cumulative HIIT protocol duration was averaged across individual study participants. Similarly, time ≥ 90% and ≥ 95% $\dot{V}O_2$max were averaged across participants within each trial. Random intercepts were specified to account for clustering of observations within studies, and observations were weighted by sample size to reflect the precision of the group-level estimates. For between-participant designs, each intervention arm was treated as a separate study [38, 39, 71, 73, 124]. Model building proceeded sequentially. First, a base model with cumulative HIIT protocol duration as a fixed effect was fitted. The potential contribution of exercise modality (i.e. running, cycling, kayaking, rowing, swimming, and cross-country skiing) was then tested by comparing the base model to a model including modality. Next, the effect of work interval duration was evaluated by comparing a model including cumulative HIIT protocol duration and work interval duration as a categorical variable. Finally, a potential interaction between these variables was assessed by comparing an additive model to one including the interaction term. Model comparisons were conducted using likelihood ratio tests. The adjusted intraclass correlation coefficient (ICC) and the marginal and conditional coefficients of determination (R^2) were

Table 1 Participant characteristics, and measures of $t\dot{V}O_2max$ reported in included studies

	N	Sex (M:F)	Age (years)	Height (cm)	Body Mass (kg)	$\dot{V}O_2max$ ($L{\cdot}min^{-1}$ or $ml{\cdot}kg{\cdot}min^{-1}$)	Peak exercise intensity	Variables reported
Cycling								
Zuniga et al. [41] [A]	12	7:5	26.8 ± 4	174 ± 8	74.2 ± 9	47.6 ± 5.5	314 ± 22 W	t ≥ 95% $\dot{V}O_2$max
Nicolò et al. [42]	13	13:0	19 ± 2	174 ± 5	65 ± 5	63.1 ± 4.2	330 ± 35 W	t ≥ 90% $\dot{V}O_2$max, t ≥ 95% $\dot{V}O_2$max
Lisbôa et al. [43]	8	8:0	22.1 ± 2.9	174 ± 4.6	72.6 ± 5.3	47.6 ± 8.8	256 ± 23 W	t ≥ 90% $\dot{V}O_2$max, t ≥ 95% $\dot{V}O_2$max
Zadow et al. [44] [B]	15	15:0	39 ± 8	181 ± 4.9	79.4 ± 8.2	59.8 ± 6.5	436 ± 27 W	t ≥ 85% $\dot{V}O_2$max
Zafeiridis et al. [45]	12	12:0	24 ± 3.2	179 ± 5	77.3 ± 9.6	49.3 ± 5.1	261 ± 29 W	t ≥ 80% $\dot{V}O_2$max
Rønnestad & Hansen [46]	13	13:0	29 ± 2	179 ± 6	73.4 ± 5.1	66.7 ± 6.1	375 ± 41 W	t ≥ 90% $\dot{V}O_2$max
Turnes et al. [39] [LOW]	11	10:1	22 ± 2	175 ± 6	76 ± 6	47.0 ± 5.4	265 ± 45 W	t ≥ $\dot{V}O_2$max – 1SD (≈ t ≥ 90% $\dot{V}O_2$max)
[UP]	10	9:1	23 ± 3	174 ± 7	78 ± 8	48.5 ± 5.4	269 ± 37 W	t ≥ $\dot{V}O_2$max – 1SD (≈ t ≥ 90% $\dot{V}O_2$max)
Combes et al. [47]	12	12:0	24 ± 5	180 ± 6	76 ± 10	43 ± 6	282 ± 31 W	t ≥ 90% $\dot{V}O_2$max
Rønnestad et al. [48]	10	10:0	24 ± 7	180 ± 5	73.2 ± 6.2	78.6 ± 6.2	471 ± 29 W	t ≥ 90% $\dot{V}O_2$max
Shi et al. [49] [C]	13	13:0	26.2 ± 6.2	173 ± 7.3	60.8 ± 3.8	61.3 ± 9.1	NR	t ≥ 80% $\dot{V}O_2$max, t ≥ 85% $\dot{V}O_2$max, t ≥ 90% $\dot{V}O_2$max, t ≥ 95% $\dot{V}O_2$max, t ≥ $\dot{V}O_2$max
Boynton et al. [50]	11	11:0	34 ± 9.8	181 ± 5	75.8 ± 8	69.6 ± 6.7	NR	t ≥ 90% $\dot{V}O_2$max
Lisbôa et al. [51]	11	11:0	28 ± 5	175 ± 5	74 ± 7	63 ± 4	334 ± 37 W	t ≥ 95% $\dot{V}O_2$max
Almquist et al. [52] [B]	8	8:0	25.3 ± 6.1	181 ± 4.5	74.8 ± 3.8	73.9 ± 7	6.2 ± 0.5 $W{\cdot}kg^{-1}$	t ≥ 90% $\dot{V}O_2$max
Bossi et al. [31]	14	14:0	24 ± 6	184 ± 5	75 ± 5.2	69.2 ± 6.6	430 ± 35 W	t ≥ 90% $\dot{V}O_2$max
Vaccari et al. [53]	12	12:0	41 ± 11	NR	76 ± 10	4.32 ± 0.47	356 ± 40 W	t ≥ 90% $\dot{V}O_2$max
Dall'Agnol et al. [54]	11	11:0	34.4 ± 6.2	177 ± 4.4	74.7 ± 8.1	55.7 ± 7.4	316 ± 32 W	t ≥ 90% $\dot{V}O_2$max, t ≥ 95% $\dot{V}O_2$max
Beltrami et al. [55]	15	14:1	29 ± 5	180 ± 6	74 ± 6	62 ± 6	410 ± 37 W	t ≥ 90% $\dot{V}O_2$max
Fennell & Hopker [56]	14	14:0	33 ± 13	177 ± 5.9	70.6 ± 8.1	62 ± 9	370 ± 56 W	t ≥ 80% $\dot{V}O_2$max, t ≥ 90% $\dot{V}O_2$max, t ≥ 95% $\dot{V}O_2$max
Fennell & Hopker [29]	16	16:0	32 ± 13	178 ± 5.2	72.4 ± 9.1	60 ± 7	373 ± 57 W	t ≥ 80% $\dot{V}O_2$max, t ≥ 90% $\dot{V}O_2$max, t ≥ 95% $\dot{V}O_2$max
Ksoll et al. [57]	24	24:0	24.3 ± 3.6	181 ± 5.1	75.9 ± 7.6	54.1 ± 5.3	360 ± 45 W	t ≥ 80% $\dot{V}O_2$max
McKee et al. [58] [B]	16	13:3	41 ± 8	177 ± 5	74.6 ± 8	55.1 ± 5	345 ± 52 W	t ≥ 90% $\dot{V}O_2$max
Sousa et al. [59]	10	10:0	34.9 ± 8.4	175 ± 6.9	73.2 ± 9.5	51.9 ± 7.8	NR	t ≥ 90% $\dot{V}O_2$max
Balci et al. [60] [B]	8	8:0	22.1 ± 3.1	175 ± 5.2	66.2 ± 8.5	64 ± 5.6	5.5 ± 0.3 $W{\cdot}kg^{-1}$	t ≥ 90% $\dot{V}O_2$max, t ≥ 95% $\dot{V}O_2$max
Bogdanis et al. [61] [B]	11	11:0	28 ± 6	177± 7	70.4 ± 10.6	47.1± 6.6	242 ± 50 W	t ≥ 80% $\dot{V}O_2$max, t ≥ 85% $\dot{V}O_2$max, t ≥ 90% $\dot{V}O_2$max, t ≥ 95% $\dot{V}O_2$max
Duc et al. [62]	12	12:0	27 ± 9	182 ± 4	72.7 ± 5.3	72.5 ± 8	375 ± 58 W	t ≥ 90% $\dot{V}O_2$max
Järvinen et al. [63]	15	10:5	25.5 ± 3.3	178 ± 10.8	81.4 ± 10.5	38.9 ± 7.1	NR	t ≥ 90% $\dot{V}O_2$max
Wommer et al. [64]	10	10:0	27.6 ± 5	179 ± 5.8	80.2 ± 14.1	48.4 ± 8.1	327 ± 39 W	t ≥ 90% $\dot{V}O_2$max
Bossi et al. [65]	18	16:2	38 ± 11	177 ± 7	71.6 ± 7.9	54.3 ± 8.9	5.01 ± 0.8 $W{\cdot}kg^{-1}$	t ≥ 90% $\dot{V}O_2$max, t ≥ 95% $\dot{V}O_2$max
Bossi et al. [66] [B]	13	13:0	25 ± 6	184 ± 5	75 ± 5	69.7 ± 7.1	431 ± 38 W	t ≥ 90% $\dot{V}O_2$max
Miller et al. [67]	8	7:1	26.8 ± 5.7	173 ± 7.7	75.4 ± 16.1	56.9 ± 6.6	NR	t ≥ 90% $\dot{V}O_2$max
Norouzi et al. [68]	10	10:0	22.8 ± 4.3	180 ± 7.5	72.9 ± 9.5	64.8 ± 5.1	382 ± 57.1 W	t ≥ 95% $\dot{V}O_2$max
Twist et al. [69]	11	11:0	20 ± 0.8	181 ± 12	82.3 ± 12	42.8 ± 5	251 ± 23 W	t ≥ 90% $\dot{V}O_2$max
Bossi et al. [70]	22	18:4	36 ± 12	178 ± 10	75.2 ± 14	51.6 ± 5.3	352 ± 55 W	t ≥ 90% $\dot{V}O_2$max,t ≥ 95% $\dot{V}O_2$max
Odden et al. [38]	22	19:3	22.6 ± 6	180 ± 8	71.9 ± 9.3	67.1 ± 6.4	5.8 ± 0.6 $W{\cdot}kg^{-1}$	t ≥ 90% $\dot{V}O_2$max
Urianstad et al. [71] [♀]	11	0:11	23.8 ± 5	172 ± 8.1	66.6 ± 9.5	62.5 ± 6.4	5.9 ± 1 $W{\cdot}kg^{-1}$	t ≥ 90% $\dot{V}O_2$max
[♂]	8	8:0	21 ± 1.4	179 ± 4.8	67.3 ± 3.6	81 ± 5.2	6.8 ± 0.4 $W{\cdot}kg^{-1}$	t ≥ 90% $\dot{V}O_2$max
Appelhans et al. [72]	12	12:0	24 ± 2	178 ± 5	73 ± 10	68 ± 6.8	358 ± 51 W	t ≥ 90% $\dot{V}O_2$max

Table 1 (continued)

	N	Sex (M:F)	Age (years)	Height (cm)	Body Mass (kg)	$\dot{V}O_2max$ (L·min^{-1} or ml·kg·min^{-1})	Peak exercise intensity	Variables reported
Boynton et al. [73] [HIIT_13°]	10	7:3	33 ± 6	177 ± 10	71.5 ± 13.5	56.9 ± 11.2	352 ± 59 W	t ≥ 90% $\dot{V}O_2$max
[HIIT_35°]	10	7:3	36 ± 12	175 ± 8	70.1 ± 11.4	57.3 ± 9.5	346 ± 63 W	t ≥ 90% $\dot{V}O_2$max
Çabuk et al. [74]	12	12:0	20 ± 1	176 ± 5	65.9 ± 6	54 ± 6.2	294 ± 16 W	t ≥ 80% $\dot{V}O_2$max, t ≥ RCP
Raimundo et al. [75]	15	15:0	32 ± 5	176 ± 6	83 ± 13	3.05 ± 0.52	~ 306 W	t ≥ 90% $\dot{V}O_2$max, t ≥ 95% $\dot{V}O_2$max
Twist et al. [76]	16	16:0	20.9 ± 0.9	180 ± 7	75.7 ± 6.2	50.6 ± 6.2	301 ± 47 W	t ≥ 90% $\dot{V}O_2$max
Jumping (and Running)								
Ducrocq et al. [77]	13	9:4	21.2 ± 1.9	173 ± 9	67.4 ± 9.4	55 ± 7	14.4 ± 1.8 km·h^{-1}	t ≥ 90% $\dot{V}O_2$max
Kayaking								
Paquette et al. [78]	13	8:5	22 ± 3	NR	71.5 ± 8.3	51.8 ± 7.7	122 ± 36 W	t ≥ 90% $\dot{V}O_2$max, t ≥ 95% $\dot{V}O_2$max
Rowing								
Patterson et al. [79]	8	0:8	20 ± 1.6	NR	71 ± 8.8	3.46 ± 0.64	NR	t ≥ 95% $\dot{V}O_2$max
Faelli et al. [80] [C]	10	10:0	15.7 ± 0.7	180 ± 5.3	68.8 ± 8.2	60.1 ± 6.0	297 ± 39.4 W	t ≥ 90% $\dot{V}O_2$max
Running								
Billat et al. [34]	8	8:0	34 ± 6	175 ± 5	69 ± 4	59.8 ± 5.4	18.5 ± 1.2 km·h^{-1}	t ≥ $\dot{V}O_2$max – 2.1, (≈ t ≥ 95% $\dot{V}O_2$max)
Demarie et al. [33] [A]	15	12:3	44.6 ± 7	173 ± 7	67.6 ± 5	56.3 ± 4.4	16.6 ± 1.1 km·h^{-1}	t ≥ $\dot{V}O_2$max
Billat et al. [81]	7	7:0	51 ± 6	175 ± 5	71 ± 4	52.1 ± 6	15.9 ± 1.8 km·h^{-1}	t ≥ $\dot{V}O_2$max
Dupont et al. [82]	9	9:0	25 ± 2.8	179 ± 6	73.8 ± 7.9	54.1 ± 6.8	16.7 ± 1.3 km·h^{-1}	t ≥ 90% $\dot{V}O_2$max, t ≥ 95% $\dot{V}O_2$max
Millet et al. [83]	8	UNS	22.6 ± 5	175 ± 3.9	65.9 ± 6.3	71.2 ± 4.2	19.9 ± 0.9 km·h^{-1}	t ≥ 90% $\dot{V}O_2$max, t ≥ 95% $\dot{V}O_2$max
Millet et al. [84]	7	UNS	21.9 ± 2.9	174 ± 3.7	64.7 ± 5.8	71.1 ± 4.9	19.8 ± 0.9 km·h^{-1}	t ≥ 90% $\dot{V}O_2$max
Dupont & Berthoin [85]	12	12:0	23.6 ± 3.7	177 ± 4.6	71.6 ± 8.3	57.8 ± 7.1	17.2 ± 1.8 km·h^{-1}	t ≥ 90% $\dot{V}O_2$max, t ≥ 95% $\dot{V}O_2$max
Tardieu-Berger et al. [86] [C]	11	11:0	16.6 ± 1.3	177 ± 6.6	63 ± 7.3	62.6 ± 3.6	17.7 ± 1.0 km·h^{-1}	t ≥ 90% $\dot{V}O_2$max, t ≥ 95% $\dot{V}O_2$max
Midgley et al. [87]	22	16:6	38 ± 7.1	174 ± 7	70.1 ± 7.8	3.87 ± 0.47	16.2 ± 2 km·h^{-1}	t ≥ 90% $\dot{V}O_2$max, t ≥ 95% $\dot{V}O_2$max
Midgley et al. [88]	9	9:0	38.2 ± 8.8	174 ± 7	74.5 ± 10.8	4.09 ± 0.54	16.3 ± 1.2 km·h^{-1}	t ≥ 95% $\dot{V}O_2$max, t ≥ $\dot{V}O_2$max
Rozenek et al. [89]	12	12:0	20.4 ± 1.2	169 ± 4.8	70.7 ± 5.2	56.9 ± 4.3	16.3 ± 1.1 km·h^{-1}	t ≥ 90% $\dot{V}O_2$max
Thevenet et al. [37], and Thevenet et al. [90]	8	8:0	15.9 ± 1.4	171 ± 4	57.7 ± 4.8	57.4 ± 6.1	17.9 ± 0.4 km·h^{-1}	t ≥ 90% $\dot{V}O_2$max, t ≥ 95% $\dot{V}O_2$max
Thevenet et al. [91]	9	9:0	16.6 ± 1	158 ± 7	63.4 ± 7.8	64.9 ± 4.2	17.7 ± 0.9 km·h^{-1}	t ≥ 90% $\dot{V}O_2$max, t ≥ 95% $\dot{V}O_2$max
O'Brien et al. [92]	17	14:3	21.9 ± 3.9	NR	74 ± 11.3	57.4 ± 8.7	NR	t ≥ 90% $\dot{V}O_2$max
Wakefield & Glaister [93] [B]	7	7:0	22 ± 5	182 ± 5.6	86.4 ± 11.4	51.5 ± 5.1	NR	t ≥ 95% $\dot{V}O_2$max
Zafeiridis et al. [94]	9	9:0	14 ± 0.6	173 ± 6	60.5 ± 7.2	55.5 ± 4.6	15 ± 0.5 km·h^{-1}	t ≥ 80% $\dot{V}O_2$max, t ≥ 85% $\dot{V}O_2$max, t ≥ 90% $\dot{V}O_2$max, t ≥ 95% $\dot{V}O_2$max
Zafeiridis et al. [95][B] [YA]	10	10:0	13.2 ± 0.3	159 ± 8	47.8 ± 7.1	57.9 ± 3.5	14.5 ± 1.4 km·h^{-1}	t ≥ 80% $\dot{V}O_2$max, t ≥ 90% $\dot{V}O_2$max, t ≥ 95% $\dot{V}O_2$max
[MEN]	10	10:0	21 ± 1.6	175 ± 4	70.9 ± 4.9	58 ± 3.7	15.6 ± 1.2 km·h^{-1}	t ≥ 80% $\dot{V}O_2$max, t ≥ 90% $\dot{V}O_2$max, t ≥ 95% $\dot{V}O_2$max
Buchheit et al. [96]	8	8:0	18.6 ± 5.3	173 ± 11.3	58.2 ± 12.1	62.4 ± 5.2	19.5 ± 0.8 km·h^{-1}	t ≥ 90% $\dot{V}O_2$max
Abderrahman et al. [97] [G1 - PAS]	9	9:0	20.4 ± 0.6	181 ± 3.5	74.1 ± 8.8	58.7 ± 4.2	15.5 ± 1 km·h^{-1}	t ≥ 90% $\dot{V}O_2$max, t ≥ 95% $\dot{V}O_2$max
[G2 – ACT]	9	9:0	20.9 ± 0.8	179 ± 3.3	76.8 ± 8.3	59.4 ± 7.5	16.1 ± 1.2 km·h^{-1}	t ≥ 90% $\dot{V}O_2$max, t ≥ 95% $\dot{V}O_2$max
De Aguiar et al. [98]	7	7:0	22.4 ± 3.1	175 ± 5	77.2 ± 5.7	50.3 ± 3.5	14.2 ± 1.2 km·h^{-1}	t ≥ 95% $\dot{V}O_2$max
Panissa et al. [99] [Moderate]	7	7:0	23 ± 5	181 ± 6	86.9 ± 6.2	45.3 ± 4	17.8 ± 1.9 km·h^{-1}	t ≥ 90% $\dot{V}O_2$max

Table 1 (continued)

	N	Sex (M:F)	Age (years)	Height (cm)	Body Mass (kg)	$\dot{V}O_2max$ (L·min^{-1} or ml·kg·min^{-1})	Peak exercise intensity	Variables reported
[High]	7	7:0	28 ± 6	180 ± 6	75.1 ± 7.7	60.2 ± 6.2	21.1 ± 1.6 km·h^{-1}	t ≥ 90% $\dot{V}O_2$max
Panasci et al. [100]	15	15:0	22 ± 1	176 ± 6	66 ± 7	53 ± 0.6	18.6 ± 1 km·h^{-1}	t ≥ 90% $\dot{V}O_2$max
Smilios et al. [101]	11	11:0	22.1 ± 1	178 ± 8	76.3 ± 8.4	52 ± 4	16 ± 1.5 km·h^{-1}	t ≥ 80% $\dot{V}O_2$max, t ≥ 90% $\dot{V}O_2$max, t ≥ 95% $\dot{V}O_2$max
Baquet et al. [102]	11	5:6	9.6 ± 0.8	138 ± 7	37.7 ± 11.2	44.5 ± 6.2	10.4 ± 1 km·h^{-1}	t ≥ 80% $\dot{V}O_2$max, t ≥ 90% $\dot{V}O_2$max
Schoenmakers & Reed [103]	12	12:0	34 ± 11	180 ± 6	74 ± 6	53 ± 7	NR	t ≥ 90% $\dot{V}O_2$max, t ≥ 95% $\dot{V}O_2$max
Ducrocq et al. [77]	13	9:4	21.2 ± 1.9	173 ± 9	67.4 ± 9.4	55 ± 7	14.4 ± 1.8 km·h^{-1}	t ≥ 90% $\dot{V}O_2$max
Myrkos et al. [104]	12	12:0	22.1 ± 1	175 ± 6.7	70.5 ± 6.2	59.1 ± 4.9	16.7 ± 0.8 km·h^{-1}	t ≥ 80% $\dot{V}O_2$max, t ≥ 90% $\dot{V}O_2$max, t ≥ 95% $\dot{V}O_2$max
Beltrami et al. [55]	15	12:3	30 ± 4	177 ± 10	68 ± 10	58 ± 4	17.1 ± 1.5 km·h^{-1}	t ≥ 90% $\dot{V}O_2$max
José Arantes et al. [105] [B,C]	11	11:0	25.5 ± 4.1	174 ± 9	64.9 ± 8.2	55.9 ± 1.4	18.2 ± 0.3 km·h^{-1}	t ≥ 90% $\dot{V}O_2$max
Germano et al. [106] [B]	8	8:0	28 ± 3.7	174 ± 3.7	75 ± 10.5	49.5 ± 5.9	14.9 ± 1.6 km·h^{-1}	t ≥ 80% $\dot{V}O_2$max, t ≥ 85% $\dot{V}O_2$max, t ≥ 90% $\dot{V}O_2$max, t ≥ 95% $\dot{V}O_2$max
Sánchez-Otero et al. [107]	11	11:0	36.6 ± 6.9	175 ± 7.2	71.3 ± 10.3	59.3 ± 5.3	18.7 ± 1.1 km·h^{-1}	t ≥ 90% $\dot{V}O_2$max
Bok et al.[108] [C]	17	17:0	23.6 ± 1.1	180 ± 5.9	78.2 ± 8.1	54.1 ± 3	17.4 ± 0.9 km·h^{-1}	t ≥ 90% $\dot{V}O_2$max
Held et al. [109] [A]	17	9:8	25.8 ± 5	175 ± 7	63.2 ± 4.5	63.3 ± 4.5	NR	t ≥ 90% $\dot{V}O_2$max
Twist et al. [69]	11	11:0	20 ± 0.8	181 ± 12	82.3 ± 12	48.1 ± 6.5	13.2 ± 1.4 km·h^{-1}	t ≥ 90% $\dot{V}O_2$max
Varela-Sanz et al. [110]	8	8:0	36.7 ± 7.1	177 ± 5.9	73.8 ± 8.4	58.2 ± 3.4	18.4 ± 0.1 km·h^{-1}	t ≥ 90% $\dot{V}O_2$max
Vaccari et al. [111]	9	9:0	35 ± 11	NR	79 ± 8	52 ± 5	15.2 ± 1.6 km·h^{-1}	t ≥ 90% $\dot{V}O_2$max
Fleckenstein et al. [112] [A]	12	7:5	22.3 ± 2.3	NR	NR	59.1 ± 2.4	NR	t ≥ 90% $\dot{V}O_2$max, t ≥ 95% $\dot{V}O_2$max
Swimming								
Bentley et al.[113]	8	5:3	18.4 ± 1.8	179 ± 6.8	66.9 ± 6.5	55.7 ± 5.8	1.42 ± 0.06 m·s^{-1}	t ≥ 90% $\dot{V}O_2$max
Libicz et al. [114] [B]	10	10:0	22.8 ± 4.1	181 ± 7.9	72.3 ± 6.6	53 ± 6.7	1.22 ± 0.06 m·s^{-1}	t ≥ 95% $\dot{V}O_2$max
Almeida et al. [115]	12	7:5	15.3 ± 1.4	169 ± 10	58.9 ± 9.8	59.2 ± 4.2	1.27 ± 0.09 m·s^{-1}	t ≥ VT_2, t ≥ 90% $\dot{V}O_2$max, t ≥ 95% $\dot{V}O_2$max
Almeida et al. [116]	22	13:9	16.1 ± 1.7	173 ± 10.2	65.5 ± 10.6	55.2 ± 5.6	1.26 ± 0.09 m·s^{-1}	t ≥ VT_2, t ≥ 90% $\dot{V}O_2$max
Cross Country Skiing								
Rønnestad et al. [117]	11	11:0	23.5 ± 3.5	184 ± 6	77.9 ± 7.2	70.6 ± 5.7	12.6 ± 0.9 km·h^{-1}	t ≥ 90% $\dot{V}O_2$max
Rønnestad et al. [118]	10	10:0	25 ± 3	186 ± 4	81.1 ± 5	69.6 ± 3.5	16 ± 0.6 km·h^{-1}	t ≥ 90% $\dot{V}O_2$max
Rønnestad et al. [119]	12	12:0	21.2 ± 2.9	182 ± 5	75.1 ± 4.1	69.6 ± 4.3	18.4 ± 1 km·h^{-1}	t ≥ 90% $\dot{V}O_2$max

Abbreviations: *NR* Not reported, *RCP* Respiratory compensation point, *SD* Standard deviation, *t* Time, *UNS* Unspecified, *$\dot{V}O_2max$* Maximum oxygen uptake (at times $\dot{V}O_2$peak), *VT_2* Second ventilatory threshold

[A] – Demographics calculated from available group data

[B] – Data extracted from figure

[C] – Data calculated from Standard Error to SD

All data are presented as mean ± SD

calculated. These analyses were performed in R (Version 4.4.1), with significance levels set at $p \leq .05$.

Meta-analyses were conducted to calculate standardised mean differences (SMD) alongside two-sided 95% CIs for t$\dot{V}O_2$max across different HIIT protocols. *Within-study* comparisons assessed t$\dot{V}O_2$max between 1) SI-HIIT, MI-HIIT, and LI-HIIT protocols, 2) passive versus active recovery intervals, and 3) even-paced versus variable-intensity work intervals. When reported, time ≥ 90% VO_2max was used as the outcome measure. If this metric was not available, the closest alternative threshold (e.g., time ≥ 85% or ≥ 95% VO_2max) was used (see Table

Table 2 HIIT protocol characteristics of included studies, and measures of t$\dot{V}O_2$max reported

Study [group identifier]	High-intensity interval training Protocol					Total Training Duration (s)	Work Interval Duration (s)	$\dot{V}O_2$max ≥ 5 min	$\dot{V}O_2$max ≥ 10 min
	Repetitions	Work Duration	Work Intensity	Recovery Duration	Recovery Intensity				
Cycling									
Zuniga et al. [41] [A]	TTE	F, 30 s	90% MAP	F, 30 s	50% MAP	1530 ± 318	765 ± 159	✓ (+)	
	TTE	F, 3 min	90% MAP	F, 3 min	50% MAP	1272 ± 408	636 ± 204		
	TTE	F, 30 s	MAP	F, 30 s	50% MAP	1146 ± 360	573 ± 180	✓ (+)	
	TTE	F, 3 min	MAP	F, 3 min	50% MAP	834 ± 288	417 ± 144		
Nicolò et al. [42]	TTE	F, 30 s	135% MAP	F, 30 s	PAS	2280 ± 780	1140 ± 390		
	TTE	F, 40 s	135% MAP	F, 20 s	PAS	600 ± 180	402 ± 121	✓	
Lisbôa et al. [43]	TTE	I, 60% T_{low}, 82.5 ± 8.8 s	CPO, I_{high}	I, 60% T_{low}, 82.5 ± 8.8 s	30% MAP	450 ± 66	225 ± 33		
	TTE	I, T_{low}, 137.5 ± 14.6 s	DPO, I_{high}	I, T_{low}, 137.5 ± 14.6 s	30% MAP	742 ± 118	371 ± 89		
Zadow et al. [44] [B]	3	F, 3 min	*'All out'*	F, 3 min	50% PO_{AT}	1080	540	✓ (-)	
	3	F, 3 min	CPO *'All out'*	F, 3 min	50% PO_{AT}	1080	540	✓ (-)	
	3	F, 3 min	A-CPO, *'All out'*	F, 3 min	50% PO_{AT}	1080	540	✓ (-)	
Zafeiridis et al. [45]	TTE	F, 30 s	110% MAP	F, 30 s	PAS	1740 ± 150	870 ± 150		
	TTE	F, 2 min	95% MAP	F, 2 min	PAS	2160 ± 120	1080 ± 60	✓ (-)	
Rønnestad & Hansen [46]	TTE	F, 30 s	MAP	F, 15 s	50% MAP	1385 ± 547	928 ± 365	✓	✓
	TTE	I, 50% T_{max}, 170 ± 54 s	MAP	I, 25% T_{max}, 85 ± 54 s	50% MAP	827 ± 285	554 ± 191	✓	
	TTE	I, 80% T_{max}, 272 ± 86 s	MAP	I, 25% T_{max}, 136 ± 43 s	50% MAP	642 ± 191	430 ± 128	✓	
Turnes et al. [39] [LOW]	4	F, 5 min	105% CP	F, 1 min	PAS	1440	1200		
	7	F, 5 min	105% CP	F, 1 min	PAS	2520	2100		
[UP]	2 * 4	F, 80 s	I_{high}	F, 160 s (/10 min between sets)	PAS	1920 (/2520)	640		
	2 * 7	F, 80 s	I_{high}	F, 160 s (/10 min between sets)	PAS	3360 (/3960)	1120		
Combes et al. [47]	30	F, 1 min	70% MAP	F, 1 min	PAS	3600	1800	✓	
Rønnestad et al. [48]	6	F, 5 min	Isoeffort Max	F, 2.5 min	50% $PO_{Interval}$	2700	1800	✓	
	6	F, 5 min	Isoeffort Max (+ vibration)	F, 2.5 min	50% $PO_{Interval}$	2700	1800	✓	✓
Shi et al. [49]	40	F, 6 s	Max	F, 15 s	PAS	840	240	✓	
	40	F, 6 s	Max	F, 30 s	PAS	1440	240		
	40	F, 6 s	Max	F, 1 min	PAS	2640	240		
	8	F, 30 s	Max	F, 4 min	PAS	2160	240		

Table 2 (continued)

Study [group identifier]	High-intensity interval training Protocol					Total Training Duration (s)	Work Interval Duration (s)	$\dot{V}O_2max$ ≥ 5 min	$\dot{V}O_2max$ ≥ 10 min
	Repetitions	Work Duration	Work Intensity	Recovery Duration	Recovery Intensity				
Boynton et al. [50] [5^{0}], [13^{0}], [22^{0}], and [35^{0}]	4	F, 5 min	Isoeffort Max	F, 5 min	PAS, then 'volition', then 50% MAP	2700	1200	1 x ✓	
Lisbôa et al. [51]	TTE	I, 60% T_{low}, 74 ± 16 s	CPO, P_{high}	I, 60% T_{low}, 74 ± 16 s	30% MAP	548 ± 32	274 ± 16		
	TTE	I, T_{low}, 124 ± 27 s	DPO, $P_{high > 105\% CP}$	I, T_{low}, 124 ± 27 s	30% MAP	1265 ± 446	632 ± 223	✓ (+)	
Almquist et al. [52] B	3 * 13	F, 30 s	MAX	F, 15 s (/NR between sets)	50% $PO_{Interval}$	1755 (/NR)	1170	✓	✓
	4	F, 5 min	Isoeffort Max	F, 2.5 min	50% $PO_{Interval}$	1800	1200	✓	
Bossi et al. [31]	6	F, 5 min	CPO, 84% MAP	F, 2.5 min	30% MAP	2700	1800		
	6	F, 5 min	VPO, 84% MAP	F, 2.5 min	30% MAP	2700	1800	✓	
Vaccari et al. [53]	TTE	F, 30 s	117% CP	F, 20 s	83% CP	714 ± 265	478 ± 178		
	TTE	F, 3 min	117% CP	F, 2 min	83% CP	664 ± 282	445 ± 189		
	TTE	F, 3-, 2-, 1 min, 40-, 30 s	117% CP	F, 2 min, 80-, 40-, 30-, 20 s	83% CP	798 ± 185	535 ± 124	✓	
Dall'Agnol et al. [54]	4	F, 4 min	Isoeffort Max	F, 1 min	~90 W	1200	960		
	4	F, 4 min	Isoeffort Max	F, 2 min	~90 W	1440	960	✓	
	4	F, 8 min	Isoeffort Max	F, 2 min	~90 W	2400	1920	✓	
	4	F, 8 min	Isoeffort Max	F, 4 min	~90 W	2880	1920	✓	✓
Beltrami et al. [55]	4	F, 4 min	CPO, 85% MAP	F, 3 min	ACT	1680	960	✓	
	4	F, 4 min	DPO, 85% MAP	F, 3 min	ACT	1680	960	✓	
Fennell & Hopker [56]	6	F, 4 min	Isoeffort Max	F, 2 min	PAS	2160	1440	✓	✓
	6	F, 4 min	Isoeffort Max	F, 2 min	80% PO_{LT}	2160	1440	✓	✓
	6	F, 4 min	Isoeffort Max	F, 2 min	110% PO_{LT}	2160	1440	✓	✓
	3	F, 8 min	Isoeffort Max	F, 4 min	PAS	2160	1440	✓	✓
	3	F, 8 min	Isoeffort Max	F, 4 min	80% PO_{LT}	2160	1440	✓	✓
	3	F, 8 min	Isoeffort Max	F, 4 min	110% PO_{LT}	2160	1440	✓	✓
Fennell & Hopker [29]	6	F, 4 min	Isoeffort Max	F, 2 min	PAS	2160	1440	✓	✓
	6	F, 4 min	Isoeffort Max	I, mVO_2 Recovery, 205 ± 79 s	PAS	2670 ± 438	1440	✓	✓
	3	F, 8 min	Isoeffort Max	F, 4 min	PAS	2160	1440	✓	✓
	3	F, 8 min	Isoeffort Max	I, mVO_2 Recovery, 200 ± 81 s	PAS	2040 ± 243	1440	✓	✓
Ksoll et al. [57]	30	F, 30 s	80% MAP	F, 30 s	85% GET	1800	900		

Table 2 (continued)

Study [group identifier]	High-intensity interval training Protocol					Total Training Duration (s)	Work Interval Duration (s)	$\dot{V}O_2max$ ≥ 5 min	$\dot{V}O_2max$ ≥ 10 min
	Repetitions	Work Duration	Work Intensity	Recovery Duration	Recovery Intensity				
	5	F, 3 min	80% MAP	F, 3 min	85% GET	1800	900	✓ (-)	
McKee et al. [58] B [Intervals commenced at 1) Beginning, 2) Middle, or 3) End of the session]	3	F, 3 min	90% MAP	F, 3 min	40% PO_{VT}	1080	540		
Sousa et al. [59]	2 * 6	F, 10 s	MAX	F, 20 s (/3 min between sets)	ACT	360 (/540)	120	In %'s	
	6	F, 1 min	90% Δ (PO_{VT} – MAP)	F, 1 min	50% MAP	720	360	In %'s	
Balci et al. [60] B	16	F, 45 s	110% MAP	F, 45 s	35% MAP	1440	720	✓	
	3	F, 3 min	95% MAP	F, 3 min	35% MAP	1440	720	✓	
	6	F, 30 s	MAX	F, 3.5 min	35% MAP	1440	180		
Bogdanis et al. [61] B	48	F, 10 s	MAP	F, 15 s	15% MAP	1200	480		
	16	F, 30 s	MAP	F, 45 s	15% MAP	1200	480		
	8	F, 1 min	MAP	F, 1.5 min	15% MAP	1200	480		
Duc et al. [62]	6	F, 5 min	VPO, 90% MAP	F, 2.5 min	30 - 40% MAP	2700	1800	✓	
	6	F, 5 min	VPO, 90% MAP (+ vibration)	F, 2.5 min	30 - 40% MAP	2700	1800	✓	✓
Järvinen et al. [63]	2 * 10	F, 30 s	MAP	F, 30 s (/4 min between sets)	50% MAP	1200 (/1440)	600	✓	✓
Wommer et al. [64]	8	F, 1 min	CPO, MAP	F, 1 min	80% PO_{LT}	960	480		
	8	F, 1 min	DPO, MAP	F, 1 min	80% PO_{LT}	960	480	✓	
	8	F, 1 min	IPO, MAP	F, 1 min	80% PO_{LT}	960	480	✓	
Bossi et al. [65]	TTE	F, 4 min	70% Δ	F, 2 min	20% $PO_{Interval}$	1835 ± 947	1262 ± 623	✓	
	TTE	F, 4 min	85% MAP	F, 2 min	20% $PO_{Interval}$	1423 ± 840	990 ± 549	✓	
	TTE	F, 4 min	120% $PO_{20k\,TT}$	F, 2 min	20% $PO_{Interval}$	1007 ± 803	715 ± 524	✓	
	TTE	F, 4 min	80% W'	F, 2 min	20% $PO_{Interval}$	1087 ± 848	767 ± 554	✓	
Bossi et al. [66] B	6	F, 5 min	VPO, 84% MAP (+ vibration)	F, 2.5 min	30% MAP	2700	1800	✓	
Miller et al. [67]	3	F, 4 min	CPO, 60% W'	F, 3 min	ACT, 50 W	1440	720	In %'s	
	3	F, 4 min	DPO, 60% W'	F, 3 min	ACT, 50 W	1440	720	In %'s	
Norouzi et al. [68]	16 - 18	F, 1 min	105% MAP	F, 1 min	30% MAP	1992 ± 151	996 ± 76		
	4 - 7	I, 50% T_{max}, 89 ± 19 s	I_{high}	I, T_{max}, 178 ± 38 s	30% MAP	1433 ± 215	539 ± 84		
	4 - 6	F, 3 min	95% MAP	F, 3 min	30% MAP	1681 ± 346	841 ± 173		
Twist et al. [69]	3 * 12	F, 15 s	120% MAP	F, 15 s (/5 min between sets)	PAS	1080 (/1680)	540		
Bossi et al. [70]	TTE	F, 4 min	70% Δ (W_{GET} + 70% W_{GET} – MAP)	F, 2 min	20% $PO_{Interval}$	1099 ± 503	777 ± 332	✓	
	TTE	F, 4 min	70% Δ (W_{GET} + 70% W_{GET} – MAP)	F, 2 min	20% $PO_{Interval}$	1262 ± 502	886 ± 337	✓	

Table 2 (continued)

Study [group identifier]	High-intensity interval training Protocol					Total Training Duration (s)	Work Interval Duration (s)	$\dot{V}O_2max$ ≥ 5 min	$\dot{V}O_2max$ ≥ 10 min
	Repetitions	Work Duration	Work Intensity	Recovery Duration	Recovery Intensity				
	TTE	F, 4 min	70% Δ (W_{GET} + 70% W_{GET} – MAP)	F, 2 min	20% $PO_{Interval}$	1240 ± 784	869 ± 516	✓	
	TTE	F, 4 min	70% Δ (W_{GET} + 70% W_{GET} – MAP)	F, 2 min	20% $PO_{Interval}$	1274 ± 639	891 ± 425	✓	
Odden et al. [38]	5	F, 8 min	CPO, PO_{40kmTT}	F, 3 min	35% PO_{40kmTT}	3300	2400	✓	✓
	5	F, 8 min	VPO, PO_{40kmTT}	F, 3 min	90% PO_{40kmTT}	3300	2400	✓	
	5 * 11	F, 30 s	118% PO_{40kmTT}	F, 15 s (/3 min between sets)	60% PO_{40kmTT}	3300	2400	✓	
Urianstad et al. [71] [♀ and ♂]	6	F, 8 min	CPO, PO_{40kmTT}	F, 3 min	35% PO_{40kmTT}	3960	2880	2 x ✓	2 x ✓
	6	F, 8 min	VPO, PO_{40kmTT}	F, 3 min	35% PO_{40kmTT}	3960	2880	2 x ✓	2 x ✓
	6 * 11	F, 30 s	118% PO_{40kmTT}	F, 15 s (/3 min between sets)	60% PO_{40kmTT}	3960	2880	2 x ✓	2 x ✓
Appelhans et al. [72]	6	F, 5 min	84% MAP	F, 2.5 min	60% MAP [B]	2505	1755		
	6	F, 5 min	Isoeffort Max	F, 2.5 min	60% MAP [B]	2505	1755	✓	✓
	3 * 13	F, 30 s	MAP	F, 15 s (/6:15 between sets)	50% MAP	1755 (/2505)	1170	✓	
	3 * 13	F, 30 s	Isoeffort Max	F, 15 s (/6:15 between sets)	50% MAP	1755 (/2505)	1170	✓	✓
Boynton et al. [73] [HIIT_13 and HIIT_35]	5	F, 4 min	Isoeffort Max	F, 5 min	PAS, then 'volition', then 50% MAP	2700	1200	2 x ✓	1 x ✓
Çabuk et al. [74]	4 * 3	F, 10 s	MAX	F, 10 s (/3:40 between sets)	Unloaded cycling	720	120		
	4 * 2	F, 15 s	MAX	F, 15 s (/3:45 between sets)	Unloaded cycling	720	120		
	4	F, 30 s	MAX	F, 4 min	Unloaded cycling	720	120		
Raimundo et al. [75]	10	F, 1 min	85% MAP	F, 30 s	PAS	900	600		
	5	F, 2 min	85% MAP	F, 1 min	PAS	900	600		
Twist et al. [76]	2 * 12	F, 15 s	120% MAP	F, 15 s (/5 min between sets)	PAS	720 (/1020)	360		
	2 * 6	F, 30 s	120% MAP	F, 30 s (/5 min between sets)	PAS	720 (/1020)	360		
Jumping									
Ducrocq et al. [77]	22	F, 15 s	7 Drop jumps	F, 15 s	PAS	660	330		
	22	F, 15 s	9 Drop jumps	F, 15 s	PAS	660	330		

Table 2 (continued)

Study [group identifier]	High-intensity interval training Protocol					Total Training Duration (s)	Work Interval Duration (s)	$\dot{V}O_2max$ ≥ 5 min	$\dot{V}O_2max$ ≥ 10 min
	Repetitions	Work Duration	Work Intensity	Recovery Duration	Recovery Intensity				
Kayaking									
Paquette et al. [78]	2 * 20	F, 15 s	110% MAP	F, 15 s (/5 min between sets)	30% MAP	1200 (/1500)	600	✓	
	2 * 10	F, 30 s	110% MAP	F, 30 s (/5 min between sets)	30% MAP	1200 (/1500)	600	✓	
	6	F, 30 s	Max	F, 3.5 min	*Choice*	1440	180		
	6	F, 1 min	130% MAP	F, 3 min	*Choice*	1440	360		
Rowing									
Patterson et al. [79]	TTE	F, 30 s	MAP	F, 15 s	PAS	1857 ± 204	1242 ± 150		
	TTE	F, 1 min	MAP	F, 30 s	ACT	2604 ± 729	1734 ± 540		
	TTE	F, 1 min	MAP	F, 1 min	ACT	4992 ± 1632	2496 ± 816		
	TTE	F, 2 min	MAP	F, 1 min	ACT	1752 ± 718	1152 ± 474		
	TTE	F, 2 min	MAP	F, 2 min	ACT	3108 ± 1260	1554 ± 630		
	TTE	F, 3 min	MAP	F, 1.5 min	ACT	1596 ± 495	1056 ± 324		
	TTE	F, 3 min	MAP	F, 3 min	ACT	2640 ± 1020	1320 ± 510	✓ (+)	
Faelli et al. [80] C	25	F, 30 s	MAP	F, 30 s	20% MAP	1500	750	✓	
	4	F, 4 min	90% MAP	F, 3 min	30% MAP	1680	960	✓	✓
Running									
Billat et al. [34]	TTE	F, 30 s	vVO_2max	F, 30 s	50% vVO_2max	1140 ± 360	570 ± 180	✓ (+)	
Demarie et al. [33] A	TTE	I, 50% T_{max}, 312 ± 43 s	50% Δ (V_{LT} + vVO_{2max})	I, 25% T_{max}, 156 ± 21 s	25% Δ (V_{LT} + vVO_{2max})	1766 ± 465	1178 ± 310	✓ (+)	✓ (+)
Billat et al. [81]	TTE	F, 15 s	90% vVO_2max	F, 15 s	80% vVO_2max	1260 ± 360	630 ± 180	✓ (+)	✓ (+)
	TTE	F, 15 s	vVO_2max	F, 15 s	70% vVO_2max	1080 ± 300	540 ± 150	✓ (+)	✓ (+)
	TTE	F, 15 s	110% vVO_2max	F, 15 s	60% vVO_2max	540 ± 180	270 ± 90	✓ (+)	
Dupont et al.[82]	TTE	F, 15 s	110% MAV	F, 15 s	PAS	1396 ± 710	698 ± 355	✓	
	TTE	F, 15 s	120% MAV	F, 15 s	PAS	694 ± 468	347 ± 234	✓	
	TTE	F, 15 s	130% MAV	F, 15 s	PAS	334 ± 140	167 ± 70		
	TTE	F, 15 s	140% MAV	F, 15 s	PAS	200 ± 100	100 ± 50		
Millet et al. [83]	3 * 7.8	F, 30 s	vVO_2max	F, 30 s (/5 min between sets)	50% vVO_2max	1414 ± 294 (/2014)	707 ± 147		
	3 * 3.9	F, 1 min	vVO_2max	F, 30 s (/5 min between sets)	50% vVO_2max	1058 ± 196 (/1658 ± 294)	707 ± 147	✓	
	3 * 2	I, 50% T_{max}, 117.8 ± 25 s	vVO_2max	I, 50% T_{max}, 117.8 ± 25 s (/5 min between sets)	50% vVO_2max	1414 ± 294 (/2014 ± 294)	707 ± 147	✓	
Millet et al. [84]	3 * 8	F, 30 s	vVO_2max	F, 30 s (/5 min between sets)	50% vVO_2max	1451 ± 237 (/2051 ± 237)	731 ± 119		
	3 * 8	F, 30 s	105% vVO_2max	F, 30 s (/5 min between sets)	50% vVO_2max	1451 ± 237 (/2051 ± 237)	731 ± 119	✓	

Table 2 (continued)

Study [group identifier]	High-intensity interval training Protocol					Total Training Duration (s)	Work Interval Duration (s)	$\dot{V}O_2max$ ≥ 5 min	$\dot{V}O_2max$ ≥ 10 min
	Repetitions	Work Duration	Work Intensity	Recovery Duration	Recovery Intensity				
Dupont & Berthoin [85]	TTE	F, 15 s	120% MAV	F, 15 s	50% MAV	445 ± 79	228 ± 40		
	TTE	F, 15 s	120% MAV	F, 15 s	PAS	745 ± 171	378 ± 86	✓	
Tardieu-Berger et al. [86] [C]	TTE	F, 30 s	110% MAV	F, 30 s	50% MAV	622 ± 186	311 ± 93	✓	
	TTE, n * 6	F, 30 s	110% MAV	F, 30 s (/4 min between sets)	50% MAV	960 ± 338 (/1440 ± 338)	480 ± 169		
Midgley et al. [87]	TTE	F, 30 s	105% vVO_2max	F, 30 s	60% vVO_2max	831 ± 238	426 ± 119	✓	
	TTE	F, 30 s	105% vVO_2max	F, 30 s	60% vVO_2max	898 ± 333	462 ± 168	✓	
Midgley et al. [88]	TTE	F, 30 s	105% vVO_2max	F, 30 s	60% vVO_2max	1110 ± 468	555 ± 234	✓ (+)	
Rozenek et al. [89]	TTE	F, 15 s	vVO_2max	F, 15 s	50% vVO_2max	1059 ± 35	530 ± 17		
	TTE	F, 30 s	vVO_2max	F, 15 s	50% vVO_2max	771 ± 36	531 ± 18		
	TTE	F, 1 min	vVO_2max	F, 15 s	50% vVO_2max	621 ± 30	516 ± 15	✓	
Thevenet et al. [37], and Thevenet et al. [90]	TTE	F, 30 s	105% MAV	F, 30 s	50% MAV	1072 ± 388	536 ± 194	✓	✓
	TTE	F, 30 s	105% MAV	F, 30 s	67% MAV	705 ± 320	357 ± 178	✓	
	TTE	F, 30 s	105% MAV	F, 30 s	84% MAV	394 ± 81	197 ± 40	✓	
	TTE	F, 30 s	105% MAV	F, 30 s	PAS	2145 ± 829	1073 ± 415	✓	
Thevenet et al. [91]	TTE	F, 30 s	MAV	F, 30 s	50% MAV	1440 ± 169	720 ± 84	✓	
	TTE	F, 30 s	110% MAV	F, 30 s	50% MAV	653 ± 184	326 ± 92		
O'Brien et al. [92]	10	F, 1 min	MAV	F, 1 min	50% MAV	1200	600		
	5	F, 2 min	MAV	F, 2 min	50% MAV	1200	600		
Wakefield & Glaister [93] [B]	TTE	F, 20 s	105% vVO_2max	F, 20 s	PAS	3294 ± 426	1640 ± 220		
	TTE	F, 25 s	105% vVO_2max	F, 20 s	PAS	3246 ± 300	1825 ± 175		
	TTE	F, 30 s	105% vVO_2max	F, 20 s	PAS	2622 ± 624	1590 ± 360		
	TTE	F, 20 s	115% vVO_2max	F, 20 s	PAS	2346 ± 684	1180 ± 340		
	TTE	F, 25 s	115% vVO_2max	F, 20 s	PAS	1740 ± 390	975 ± 225		
	TTE	F, 30 s	115% vVO_2max	F, 20 s	PAS	1188 ± 324	720 ± 180		
Zafeiridis et al. [94]	TTE	F, 30 s	110% MAV	F, 30 s	50% MAV	930 ± 462	480 ± 231		
	TTE	F, 3 min	95% MAV	F, 3 min	35% MAV	1700 ± 504	936 ± 270	✓	
Zafeiridis et al. [95] [B] [YA – SI]	TTE	F, 30 s	110% MAV	F, 30 s	50% MAV	708 ± 154	381 ± 65	✓	
[YA – LI]	TTE	F, 3 min	95% MAV	F, 3 min	35% MAV	1579 ± 554	882 ± 274	✓	✓
[Men – SI]	TTE	F, 30 s	110% MAV	F, 30 s	50% MAV	1087 ± 215	519 ± 155	✓	
[Men – LI]	TTE	F, 3 min	95% MAV	F, 3 min	35% MAV	1590 ± 349	882 ± 179	✓	
Buchheit et al. [96]	5	F, 3 min	90% vVO_2max	F, 1.5 min	NR, *Rest*	1350	900	✓	
Abderrahman et al. [97] [G1 – PAS, Pre]	TTE	F, 30 s	105% MAV	F, 30 s	PAS	1883 ± 788	942 ± 394	✓	
[G1 – PAS, Post]	TTE	F, 30 s	105% MAV	F, 30 s	PAS	3015 ± 1095	1508 ± 548	✓	
[G2 – ACT, Pre]	TTE	F, 30 s	105% MAV	F, 30 s	50% MAV	923 ± 188	462 ± 194	✓	
[G2 – ACT, Post]	TTE	F, 30 s	105% MAV	F, 30 s	50% MAV	1163 ± 118	582 ± 59	✓	✓

Table 2 (continued)

Study [group identifier]	High-intensity interval training Protocol					Total Training Duration (s)	Work Interval Duration (s)	$\dot{V}O_2max$ ≥ 5 min	$\dot{V}O_2max$ ≥ 10 min
	Repetitions	Work Duration	Work Intensity	Recovery Duration	Recovery Intensity				
De Aguiar et al. [98]	TTE	F, 30 s	CV, 105% ICV	F, 15 s	PAS	2159 ± 689	1439 ± 518		
	TTE	F, 30 s	CV, 125% ICV	F, 15 s	PAS	426 ± 101	284 ± 76		
	TTE	F, 30 s	DV, 125–105% ICV	F, 15 s	PAS	1576 ± 203	1051 ± 153		
Panissa et al. [99] [Moderate]	~13	F, 1 min	MAV	F, 1 min	PAS	1618 ± 174	809 ± 87	In %'s	
[High]	~11	F, 1 min	MAV	F, 1 min	PAS	1365 ± 104	682 ± 52	In %'s	
Panasci et al. [100]	15	F, 30 s	MAV (track)	F, 30 s	PAS	900	450	In %'s	
	15	F, 30 s	MAV (treadmill)	F, 30 s	PAS	900	450	In %'s	
	15	F, 30 s	115% MAV	F, 30 s	PAS	900	450		
Smilios et al. [101]	4	F, 4 min	90% MAV	F, 2 min	35% MAV	1440	960	✓	
	4	F, 4 min	90% MAV	F, 3 min	35% MAV	1680	960	✓	
	4	F, 4 min	90% MAV	F, 4 min	35% MAV	1920	960	✓	
Baquet et al. [102]	TTE	F, 15 s	120% MAV	F, 15 s	50% MAV	402 ± 184	201 ± 92		
	TTE	F, 15 s	120% MAV	F, 15 s	PAS	1244 ± 430	622 ± 215		
Schoenmakers & Reed [103]	6	F, 4 min	Isoeffort Max	F, 1 min	*Free to select either walking/standing*	1800	1440	✓	✓
	6	F, 4 min	Isoeffort Max	F, 2 min	*Free to select either walking/standing*	2160	1440	✓	✓
	6	F, 4 min	Isoeffort Max	F, 3 min	*Free to select either walking/standing*	2520	1440	✓	✓
	6	F, 4 min	Isoeffort Max	I, Perceived Readiness, 100 ± 34 s	*Free to select either walking/standing*	2040 ± 204	1440	✓	✓
Ducrocq et al. [77]	22	F, 15 s	120% MAV	F, 15 s	PAS	660	330		
Myrkos et al. [104]	TTE	F, 1 min	MAV	F, 30 s	PAS	1065 ± 332	713 ± 222	✓	
	TTE	F, 1 min	MAV	F, 1 min	PAS	1823 ± 482	912 ± 241	✓	
	TTE	F, 2 min	MAV	F, 1 min	PAS	844 ± 119	565 ± 80	✓	
	TTE	F, 2 min	MAV	F, 2 min	PAS	1197 ± 311	599 ± 156	✓	
Beltrami et al. [55]	4	F, 4 min	CV, 85% MAV	F, 3 min	ACT	1680	960	✓	✓
	4	F, 4 min	DV, 85% MAV	F, 3 min	ACT	1680	960	✓	✓
José Arantes et al. [105] [B, C]	TTE	F, 30 s	110% MAV	F, 30 s	PAS	1463 ± 286	737 ± 139		
	TTE	F, 40 s	110% MAV	F, 20 s	PAS	416 ± 100	281 ± 66		
	TTE	F, 40 s	110% MAV	F, 40 s	PAS	1043 ± 230	526 ± 115		
Germano et al. [106] [B]	5	I, T_{max}, 120 ± 19 s	vVO_2max	F, 2 min	V_{VT}	1200 ± 174	600 ± 87	✓	
	5	I, T_{max}, 155 ± 20 s	vVO_2max	F, 2 min	PAS	1375 ± 176	775 ± 99	✓	
	5	I, T_{max}, 106 ± 24 s	vVO_2max	F, 8 min	V_{VT}	2930 ± 663	530 ± 120	✓	✓
	5	I, T_{max}, 188 ± 44 s	vVO_2max	F, 8 min	PAS	3338 ± 772	938 ± 217	✓	✓

Table 2 (continued)

Study [group identifier]	High-intensity interval training Protocol					Total Training Duration (s)	Work Interval Duration (s)	$\dot{V}O_2max$ ≥ 5 min	$\dot{V}O_2max$ ≥ 10 min
	Repetitions	Work Duration	Work Intensity	Recovery Duration	Recovery Intensity				
Sánchez-Otero et al. [107]	4	F, 2 min	MAV	F, 2 min	80% V_{LT}	960	480		
	4	F, 2 min	MAV	F, 2 min	PAS	960	480		
Bok et al. [108] [B]	20	F, 15 s	110% vVO_2max	F, 15 S	PAS	600	300		
	20	F, 15 s	Δ15% ASR	F, 15 S	PAS	600	300		
	20	F, 15 s	Δ25% ASR	F, 15 S	PAS	600	300		
Held et al. [109] [A]	4	F, 5 min	Isoeffort Max	F, 90 s	PAS	1560	1200	✓	
	4	F, 5 min	Isoeffort Max (8% incline)	F, 90 s	PAS	1560	1200	✓	
Twist et al. [69]	3 * 12	F, 15 s	120% vVO_2max	F, 15 s (/5 min between sets)	PAS	1080 (/1680)	540		
Varela-Sanz et al. [110]	TTE	F, 2 min	MAV	F, 2 min	80% V_{VT}	2670 ± 916	1395 ± 458	✓	✓
	TTE	F, 2 min	MAV	F, 2 min	PAS	3210 ± 764	1665 ± 382	✓	✓
Vaccari et al. [111]	TTE	F, 30 s	CV_6, ~ vVO_2max	F, 20 s	66% CV	678 ± 116	407 ± 70		
	TTE	F, 3 min	CV_6, ~ vVO_2max	F, 2 min	66% CV	673 ± 115	404 ± 69	✓	
	TTE	F, 3-, 2-, 1 min, 40-, 30 s	CV_6, ~ vVO_2max	F, 2 min, 80-, 40-, 30-, 20 s	66% CV	998 ± 129	599 ± 77	✓	
Fleckenstein et al. [112] [A]	24	F, 30 s	vVO_2max	F, 30 s	55% vVO_2max	1440	720		
	4	F, 3 min	95% vVO_2max	F, 3 min	50% vVO_2max	1440	720	✓	
Swimming									
Bentley et al. [113]	16	F, 100 m, 75 ± 3 s	Δ25% (Velocity difference between $V_{VT\ and\ vVO2max}$)	F, NR, '15 s'	NR, likely PAS	1434 ± 64	1194 ± 54	✓	
	4	F, 400 m, 303 ± 11 s	Δ25% (Velocity difference between $V_{VT\ and\ vVO2max}$)	F, NR, '75 s'	NR, likely PAS	1512 ± 55	1212 ± 44	✓	
Libicz et al. [114] [B]	16	F, 50 m, 40 ± 2 s	vVO_2max	F, 15 s	NR, likely PAS	880 ± 47	640 ± 36		
	8	F, 100 m, 81 ± 4 s	vVO_2max	F, 30 s	NR, likely PAS	890 ± 52	650 ± 37		
Almeida et al. [115]	8	F, 100 m, 78 ± 5 s	MAV	F, 15 s	NR, likely PAS	750 ± 60	630 ± 45		
	4	F, 200 m, 157 ± 4 s	MAV	F, 30 s	NR, likely PAS	750 ± 60	630 ± 45		
Almeida et al. [116]	TTE	F, 100 m, 79 ± 6 s	MAV	F, 15 s	PAS	1206 ± 591	1014 ± 497	✓	
Cross Country Skiing									
Rønnestad et al. [117]	5	F, 5 min	CV, 90% MAV	F, 3 min	ACT	2400	1500	✓	✓
	5	F, 5 min	DV, 90% MAV	F, 3 min	ACT	2400	1500	✓	✓
Rønnestad et al. [118]	5	F, 5 min	CV, 90% MAV (8% incline)	F, 3 min	$V_{LT\ +\ (20\%\ of\ difference}$ $V_{LT\ -\ MAV)}$	2400	1500	✓	✓

Table 2 (continued)

Study [group identifier]	High-intensity interval training Protocol					Total Training Duration (s)	Work Interval Duration (s)	$\dot{V}O_2max$ ≥ 5 min	$\dot{V}O_2max$ ≥ 10 min
	Repetitions	Work Duration	Work Intensity	Recovery Duration	Recovery Intensity				
	5	F, 5 min	DV, 90% MAV (8% incline)	F, 3 min	V_{LT} + (20% of difference V_{LT-MAV})	2400	1500	✓	✓
	5	F, 5 min	VV, 90% MAV (8% incline)	F, 3 min	V_{LT} + (20% of difference V_{LT-MAV})	2400	1500	✓	✓
Rønnestad et al. [119] [First – Second - Last]	6	F, 5 min	VV, 90% MAV (7% incline)	F, 3 min	PAS, then ACT	2880	1800	3 x ✓	3 x ✓

Abbreviations: *A-CPO* Athlete controlled constant power output, *ACT* Active recovery, *ASR* Anaerobic speed reserve, *CP* Critical power, *CPO* Constant power output, *CV* Critical velocity, *DPO* Decreasing power output, *DV* Decreasing velocity, *F* Fixed duration, *GET* Gas exchange threshold, *I* Individualised duration, *ICV* Intensity at critical velocity, *IPO* Increasing power output, I_{high} and P_{high} Highest intensity at which VO_2max is still achieved, *MAP* Maximal aerobic power, *MAV* Maximal aerobic velocity, *Max* Maximal effort, *mVO₂* Muscle O_2 recovery benchmark, *NR* Not reported, *PAS* Passive recovery, PO_{AT} Power output at aerobic threshold, $PO_{Interval}$ Power output of work interval, PO_{LT} Power output at lactate threshold, PO_{VT} Power output at ventilatory threshold, $PO_{20/40kmTT}$ Power output from time trial performance, T_{low} and T_{max} Time to exhaustion at maximal exercise intensities, *TTE* Time to exhaustion, V_{LT} Velocity at lactate threshold, V_{VT} Velocity at ventilatory threshold, *V O₂max* Maximum oxygen uptake, *VPO* Variable power output, *VV* Variable velocity, *vV O₂max* – Velocity at VO_2max OR Lowest velocity that elicits VO_2max

[A] – Demographics calculated from available group data

[B] – Data extracted from figure

[C] – Data calculated from Standard Error to SD

Note: All data are presented as mean ± SD,

✓ = time ≥ 90% VO_2max exceeds 5 min, or 10 min

✓ (+) = time ≥ 95% or ≥ $\dot{V}O_2$max exceeds 5 min, or 10 min (time ≥ 90% $\dot{V}O_2$max not reported)

✓ (-) = time ≥ 80% or ≥ 85% $\dot{V}O_2$max exceeds 5 min, or 10 min (time ≥ 90% $\dot{V}O_2$max not reported)

2). An inverse variance random-effects model was used to account for differences in sample sizes and heterogeneity among studies [125, 126]. In studies with more than one of the above comparisons, the sample size was proportionately divided to facilitate comparison across interventions. As t$\dot{V}O_2$max may be affected by work interval duration [10], and exercise intensity distribution [30], these factors were examined in subcategory analyses using Chi^2 tests. Effect sizes were interpreted according to Hopkins et al. [127]: SMD/Hedges' $g < 0.2$ = trivial, 0.2–0.59 = small, 0.6–1.19 = moderate, 1.2–1.99 = large. Heterogeneity was assessed using the I^2 statistic, with values of <25%, 25%–75%, and >75% representing low, moderate, and high levels of heterogeneity, respectively. All analyses were carried out using RevMan (Version 5.3), with significance levels set at $p \leq .05$.

Results

Study selection and characteristics

A total of 86 studies were included in the present investigation (see Fig. 1 and Table 1), and t$\dot{V}O_2$max was determined for a total of 239 HIIT protocols (see Table 2). In the included studies, t$\dot{V}O_2$max was most commonly expressed as time ≥ 90% $\dot{V}O_2$max [31, 38, 39, 46–48, 50, 52, 53, 55, 58, 62–64, 66, 69, 71–73, 76, 77, 80, 84, 89, 90, 92, 96, 105, 107–111, 113, 117–119], but also as time ≥ 80% $\dot{V}O_2$max [45, 57, 74], time ≥ 85% VO_2max [44], time ≥ 95% $\dot{V}O_2$max [34, 41, 51, 68, 79, 93, 98, 114], time ≥ 100% $\dot{V}O_2$max [33, 81], or by a combination of variables [29, 37, 42, 43, 49, 54, 56, 60, 61, 65, 70, 75, 78, 82, 83, 85–88, 91, 94, 95, 97, 102–104, 106, 112, 115, 116]. In two studies, partially duplicated data were identified and excluded from further analysis [66, 90].

Twenty-two studies reported t$\dot{V}O_2$max in absolute values and worked out t$\dot{V}O_2$max as a fraction of either the cumulative HIIT protocol duration [37, 46, 65, 76, 82, 90, 91, 105] or total work interval duration [34, 43, 50, 54, 64, 68, 69, 74, 82, 98, 114, 116]. In two studies, it was unclear how the reported fraction was calculated [51, 97], and four studies only reported t$\dot{V}O_2$max as a fraction with no further explanation [59, 67, 99, 100].

Indexed for t$\dot{V}O_2$max, 133 HIIT protocols accumulated t$\dot{V}O_2$max ≥ 5 min, of which 48 protocols achieved t$\dot{V}O_2$max ≥ 10 min (see Table 2 and Supplementary Table S2 for absolute t$\dot{V}O_2$max reported in all included studies).

Study quality and risk of bias assessment

Study quality, as assessed by the PEDro scale, had a rating of 5.6 ± 0.7, indicating included studies were, on average, of good to excellent quality. Risk of bias was generally low across the included studies (see Fig. 2). Across all studies, objective physiological measures were obtained using reputable cardiopulmonary exercise testing devices [128].

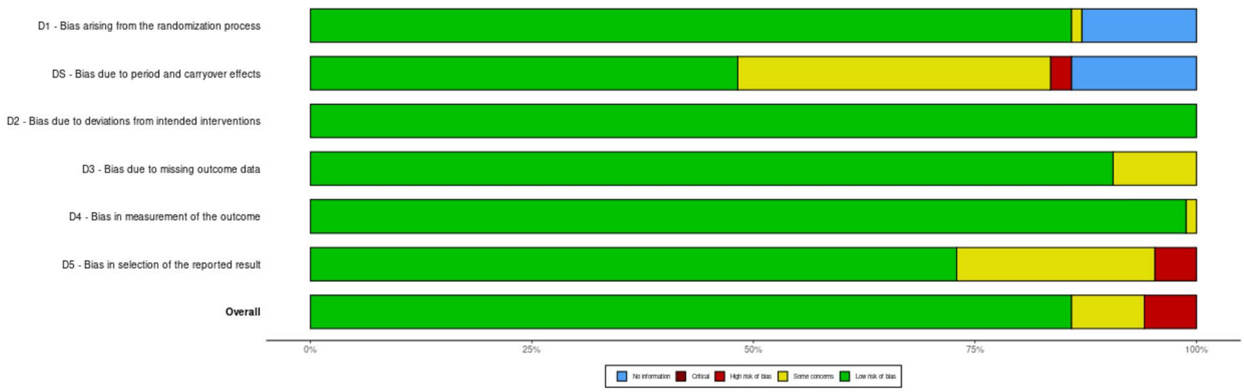

Fig. 2 Risk of bias summary plot of Rob-2 assessments

Table 3 Time ≥ 90% $\dot{V}O_2$max between HIIT protocols

	SI-HIIT (*n*=62)	MI-HIIT (*n*=35)	LI-HIIT (*n*=86)
Time ≥ 90% $\dot{V}O_2$max (s)	336 ± 273	322 ± 174	555 ± 234*
Total work interval duration (s)	659 ± 586	694 ± 355	1296 ± 566*
Cumulative HIIT protocol duration (s)	1390 ± 838	1431 ± 887	2058 ± 799*

t$\dot{V}O_2$max of HIIT jumping protocols [77], protocols with variable work interval durations [53, 111], and studies with t$\dot{V}O_2$max reported as fraction with no further explanation were excluded [59, 67, 99, 100]

*p <.01, LI-HIIT vs SI-HIIT and MI-HIIT

Some concern on bias arose from studies incorporating multiple HIIT sessions, as training adaptations may have increased $\dot{V}O_2$max, subsequently influencing t$\dot{V}O_2$max. Individual results of the PEDro scale and RoB-2 can be found in Supplementary Table S3.

Time ≥ 90% $\dot{V}O_2$max

Time ≥ 90% $\dot{V}O_2$max was reported for 183 HIIT protocols and was different between SI-HIIT, MI-HIIT and LI-HIIT protocols (see Table 3; [F(2,179) = 8.038, p <.001]), after adjusting for the different cumulative HIIT protocol durations across these subcategories [F(2,180) = 14.21, p <.001]. Post hoc tests indicated greater time ≥ 90% $\dot{V}O_2$max in LI-HIIT compared to both SI-HIIT and MI-HIIT (p <.01 and p <.001 respectively), with differences of moderate magnitude (Hedges' g = 0.87 and 1.06 respectively). Total work interval duration differed between subcategories [F(2,180) = 30.54, p <.001], with longer durations in LI-HIIT compared to SI-HIIT and MI-HIIT (p <.001).

In the linear mixed-effects models, adding exercise modality did not improve model fit compared with the base model, containing cumulative HIIT protocol duration alone ($\chi^2(5)$ = 8.80, p = 0.117). Including work interval duration did not further improve model fit compared with the base model ($\chi^2(2)$ = 5.31, p = 0.070). However, including the interaction between work interval length and cumulative HIIT protocol duration improved fit relative to the base model ($\chi^2(4)$ = 10.39, p = 0.034). The interaction model was therefore retained (see Fig. 3, panel A). Time ≥ 90% $\dot{V}O_2$max was associated with cumulative HIIT protocol duration among SI-HIIT, increasing by approximately 0.15 s for each additional second of HIIT (p <.001). The slope for MI-HIIT was flatter compared with SI-HIIT, with a difference of −0.112 s per second of HIIT (p = 0.027). The slope for LI-HIIT was not different from the slope for SI-HIIT (p = 0.483). Model-predicted equations are as follows:

SI-HIIT: Time ≥ 90%$\dot{V}O_2$max = 135.4 + 0.15 × Cumulative HIIT duration
MI-HIIT: Time ≥ 90%$\dot{V}O_2$max = 309.6 + 0.04 × Cumulative HIIT duration
LI-HIIT: Time ≥ 90%$\dot{V}O_2$max = 254.7 + 0.13 × Cumulative HIIT duration

The marginal R^2 for the final model was 0.064, indicating that cumulative HIIT protocol duration and work interval length accounted for approximately 6.4% of the variance in time ≥ 90% $\dot{V}O_2$max across all HIIT protocols. The conditional R^2 was 0.162, meaning that the combination of fixed (i.e. cumulative HIIT duration and work interval length) and random effects (i.e. study-level variability) accounted for 16.2% of the total variance. The adjusted ICC was 0.104, indicating that approximately 10.4% of the total variance in time ≥ 90% $\dot{V}O_2$max was attributable to clustering within studies. This suggests a modest but non-negligible degree of dependence among observations originating from the same study, which justifies the inclusion of a random intercept for study in the model.

Time ≥ 95% $\dot{V}O_2$max

One hundred and seventeen HIIT protocols evaluated time ≥ 95% $\dot{V}O_2$max (see Table 4). Time ≥ 95% $\dot{V}O_2$max was significantly different between SI-HIIT, MI-HIIT and LI-HIIT protocols [F(2,113) = 22.459, p <.001], after

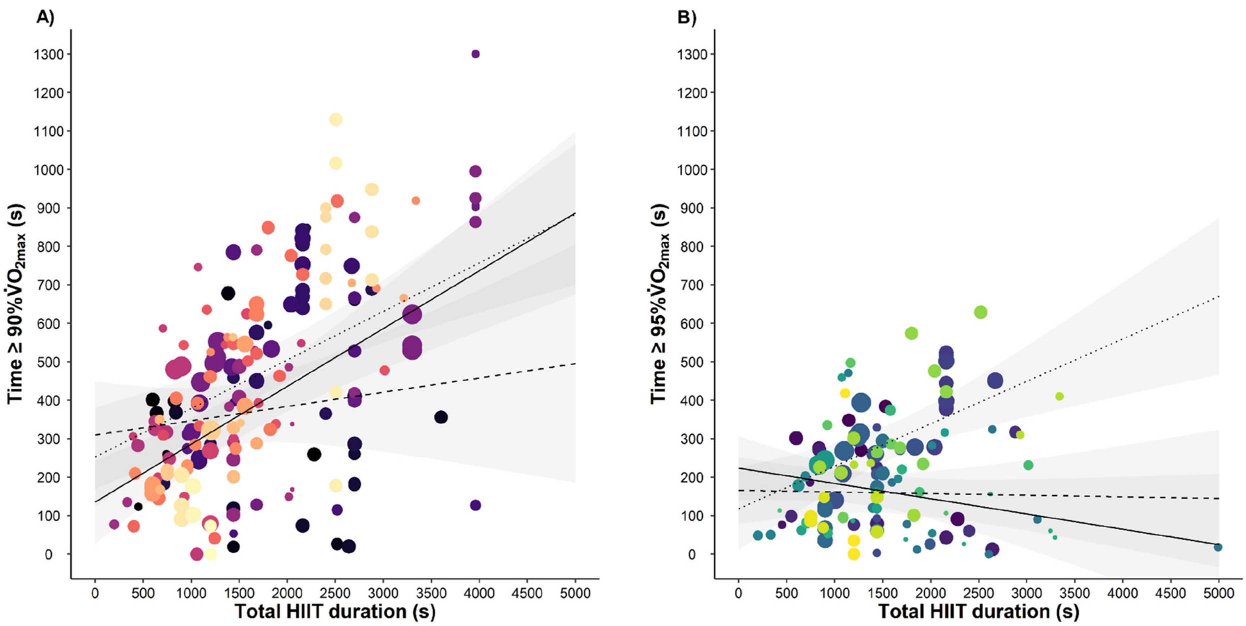

Fig. 3 Relationship between cumulative HIIT duration and time ≥ 90%$\dot{V}O_{2max}$ (panel **A**) and time ≥ 95%$\dot{V}O_{2max}$ (panel **B**). Each point represents a HIIT protocol, coloured by study and sized by sample size. The lines show model predictions based on work interval length (solid for SI-HIIT, dashed for MI-HIIT, and dotted for LI-HIIT protocols). Shaded areas represent 95% confidence intervals around fixed-effect predictions

Table 4 Differences in time ≥ 95% $\dot{V}O_2$max between HIIT protocols

	SI-HIIT (*n*=46)	MI-HIIT (*n*=27)	LI-HIIT (*n* =44)
Time ≥ 95% $\dot{V}O_2$max (s)	162 ± 140	137 ± 94	319 ± 132*
Total work interval duration (s)	673 ± 434	762 ± 483	1084 ± 371*
Cumulative HIIT protocol duration (s)	1476 ± 736	1497 ± 985	1749 ± 584

*p <.001, LI-HIIT vs SI-HIIT and MI-HIIT

adjusting for non-significant differences in cumulative HIIT protocol durations [F(2,114) = 1.174, p = 0.185]. Post hoc tests revealed time ≥ 95% $\dot{V}O_2$max was higher in LI-HIIT compared to both SI-HIIT and MI-HIIT, with differences of moderate to large magnitude (Hedges' g = 1.15 and 1.52 respectively). Total work interval duration was different between the subcategories [F(2,114) = 11.31, p <.001], with longer total work interval durations in LI-HIIT compared to both SI-HIIT and MI-HIIT (p <.001).

In the linear mixed-effects models, including work interval length improved model fit compared with the model with cumulative HIIT protocol duration alone ($\chi^2(2)$ = 21.07, p <.001), whereas adding exercise modality did not ($\chi^2(4)$ = 4.72, p = 0.317). Including the interaction between work interval length and cumulative HIIT protocol duration further improved fit relative to the additive model ($\chi^2(2)$ = 16.13, p <.001). The interaction model was therefore retained (see Fig. 3, panel B). Time ≥ 95% $\dot{V}O_2$max was not associated with cumulative HIIT protocol duration among SI-HIIT protocols (p = 0.117). The nearly zero slope for MI-HIIT was not different from the slope for SI-HIIT (p = 0.309). The slope for LI-HIIT increased by approximately 0.15 s per second of HIIT compared with SI-HIIT (p <.001). Model-predicted equations are as follows:

SI-HIIT: Time ≥ 95%$\dot{V}O_2$max = 223.5 – 0.040 × Cumulative HIIT duration
MI-HIIT: Time ≥ 95%$\dot{V}O_2$max = 165.4 – 0.004 × Cumulative HIIT duration
LI-HIIT: Time ≥ 95%$\dot{V}O_2$max = 126.4 + 0.107 × Cumulative HIIT duration

The marginal R^2 for the final model was 0.072, indicating that cumulative HIIT protocol duration and work interval length accounted for approximately 7.2% of the variance in time ≥ 95% $\dot{V}O_2$max across all HIIT protocols. The conditional R^2 was 0.138, meaning that the combination of fixed (i.e. cumulative HIIT duration and work interval length) and random effects (i.e. study-level variability) accounted for 13.8% of the total variance. The adjusted ICC was 0.071, indicating that approximately 7.1% of the total variance in time ≥ 95% $\dot{V}O_2$max was attributable to clustering within studies. Again, this suggests a modest but non-negligible degree of dependence among observations originating from the same study, which justifies the inclusion of a random intercept for study in the model.

Meta-analysis results

Work interval duration

The meta-analysed effect for t$\dot{V}O_2$max across the included studies, which compared SI-HIIT, MI-HIIT, and LI-HIIT protocols, indicated small differences in t$\dot{V}O_2$max (SMD = 0.45 [95% CI: 0.15–0.75], Z = 2.97, p <.001). Heterogeneity among studies was high (I^2 = 76%, p <.01). Subcategory analysis revealed differences ($\chi^2(2)$ = 7.71, p <.02; I^2 = 74%), with LI-HIIT eliciting greater t$\dot{V}O_2$max than MI-HIIT (Z = 3.30, p <.001*)*, and MI-HIIT compared to SI-HIIT (Z = 2.01, p = 0.04, see Fig. 4).

Active vs passive recovery intervals

No differences in t$\dot{V}O_2$max were observed when comparing active to passive recovery intervals (see Fig. 5, SMD = −0.15 [95% CI: −0.42 to 0.13], Z = 1.04, p =.30). In exhaustive HIIT protocols [37, 85, 102, 106, 110], the number of completed work-recovery cycles, and with that, time spent at high exercise intensities was notably greater when passive recovery intervals were incorporated (909 ± 443 s vs. 582 ± 433 s; F(5) = 27.433, p <.01, Hedges' g = 0.67).

	Longer Work Interval			Shorter Work Interval				Std. Mean Difference	
Study or Subgroup	Mean	SD	Total	Mean	SD	Total	Weight	IV, Random, 95% CI	Year
1.4.1 SI-HIIT vs MI-HIIT									
Patterson 1997 (2:1)	78	138	8	12	36	8	2.2%	0.62 [-0.39, 1.63]	1997
Millet 2003 (1/2 Tlim)	486	176	8	149	133	4	1.7%	1.89 [0.38, 3.41]	2003
Millet 2003 (1 min)	531	187	8	149	133	4	1.6%	2.04 [0.48, 3.60]	2003
Rozenek 2007 (30 s)	324	118	6	248	173	12	2.2%	0.46 [-0.54, 1.45]	2007
Rozenek 2007 (15 s)	324	118	6	0.01	0.01	12	1.3%	4.68 [2.69, 6.67]	2007
Nicolo 2014	401	191	13	259	226	13	2.4%	0.66 [-0.14, 1.45]	2014
Zafeiridis 2015	445	235	12	162	174	12	2.3%	1.32 [0.42, 2.22]	2015
Paquette 2019 (30 s)	246	102	7	408	276	13	2.3%	-0.67 [-1.61, 0.28]	2019
Paquette 2019 (15 s)	246	102	7	486	372	13	2.3%	-0.74 [-1.70, 0.21]	2019
Jose Arantes 2021 (2:1)	209	25	11	274	48	6	2.0%	-1.79 [-3.00, -0.58]	2021
Jose Arantes 2021 (1:1)	284	73	11	274	48	6	2.2%	0.14 [-0.85, 1.14]	2021
Sousa 2021	11.3	4.9	10	14.7	7.1	10	2.3%	-0.53 [-1.43, 0.36]	2021
Bogdanis 2022 (30 s)	73	77	6	0.1	0.1	11	2.0%	1.56 [0.40, 2.72]	2022
Bogdanis 2022 (10 s)	73	77	6	0.1	0.1	11	2.0%	1.56 [0.40, 2.72]	2022
Subtotal (95% CI)			**119**			**135**	**29.0%**	**0.66 [0.02, 1.31]**	
Heterogeneity: Tau² = 1.18; Chi² = 65.40, df = 13 (P < 0.00001); I² = 80%									
Test for overall effect: Z = 2.01 (P = 0.04)									
1.4.2 MI-HIIT vs LI-HIIT									
Patterson 1997 (1:1)	324	222	8	18	48	8	2.0%	1.80 [0.59, 3.02]	1997
Patterson 1997 (2:1)	186	168	8	0.1	0.1	8	2.1%	1.48 [0.34, 2.62]	1997
Bentley 2005	341	328	11	564	494	11	2.4%	-0.51 [-1.36, 0.34]	2005
Lisboa 2015	259	75	8	123	48	8	1.9%	2.04 [0.77, 3.32]	2015
Lisboa 2019	323	227	11	98	65	11	2.3%	1.30 [0.36, 2.23]	2019
Germano 2019 (2 min recovery)	236	153	8	232	102	8	2.2%	0.03 [-0.95, 1.01]	2019
Germano 2019 (8 min recovery)	410	176	8	310	176	8	2.2%	0.54 [-0.47, 1.54]	2019
Almeida 2021	218	122	12	208	124	12	2.4%	0.08 [-0.72, 0.88]	2021
Norouzi 2022 (1 min)	272	127	5	26	37	10	1.6%	3.01 [1.36, 4.66]	2022
Norouzi 2022 (50% TTF at Ihigh)	272	127	5	208	111	10	2.1%	0.52 [-0.58, 1.61]	2022
Balci 2022	553	36	8	394	83	8	1.8%	2.35 [0.99, 3.71]	2022
Subtotal (95% CI)			**92**			**102**	**23.1%**	**1.03 [0.42, 1.64]**	
Heterogeneity: Tau² = 0.75; Chi² = 35.71, df = 10 (P < 0.0001); I² = 72%									
Test for overall effect: Z = 3.30 (P = 0.0010)									
1.4.3 SI-HIIT vs LI-HIIT									
Zafeiridis 2010	392	276	9	149	147	9	2.2%	1.05 [0.04, 2.05]	2010
Zuniga 2011 (90%)	270	192	12	384	468	12	2.4%	-0.31 [-1.11, 0.50]	2011
Zafeiridis 2011 [Men]	502	280	10	333	199	10	2.3%	0.67 [-0.24, 1.57]	2011
Zafeiridis 2011 [YA]	625	234	10	309	204	10	2.2%	1.38 [0.38, 2.38]	2011
Zuniga 2011 (100%)	276	144	12	348	348	12	2.4%	-0.26 [-1.07, 0.54]	2011
Ronnestad 2016 (80% Tmax)	366	127	13	678	270	7	2.1%	-1.60 [-2.67, -0.52]	2016
Ronnestad 2016 (50% Tmax)	397	156	13	678	270	7	2.2%	-1.34 [-2.37, -0.31]	2016
Vaccari 2020	179	145	12	183	225	12	2.4%	-0.02 [-0.82, 0.78]	2020
Almquist 2020	595	200	8	848	351	8	2.2%	-0.84 [-1.87, 0.20]	2020
Ksoll 2021	377	254	24	122	371	24	2.7%	0.79 [0.20, 1.38]	2021
Faelli 2022	790	60	10	493	109	10	1.8%	3.23 [1.81, 4.65]	2022
Vaccari 2023	349	111	9	167	188	9	2.2%	1.12 [0.11, 2.14]	2023
Urianstad 2024 (♀ - VPO)	925	806	11	995	814	6	2.2%	-0.08 [-1.08, 0.91]	2024
Urianstad 2024 (♀ - CPO)	863	833	11	995	814	6	2.2%	-0.15 [-1.15, 0.84]	2024
Odden 2024 (CPO)	623	595	22	530	603	11	2.5%	0.15 [-0.57, 0.88]	2024
Odden 2024 (VPO)	543	608	22	530	603	11	2.5%	0.02 [-0.70, 0.74]	2024
Urianstad 2024 (♂ - VPO)	906	651	8	1,300	713	4	2.0%	-0.54 [-1.77, 0.69]	2024
Urianstad 2024 (♂ - CPO)	902	699	8	1,300	713	4	2.0%	-0.52 [-1.75, 0.70]	2024
Fleckenstein 2025	328	147	12	201	268	12	2.4%	0.57 [-0.25, 1.39]	2025
Appelhans 2025 (isoeffort)	1,016	312	12	1,130	204	12	2.4%	-0.42 [-1.23, 0.39]	2025
Appelhans 2025 (fixed)	178	159	12	420	259	12	2.4%	-1.09 [-1.96, -0.22]	2025
Subtotal (95% CI)			**260**			**208**	**47.9%**	**0.06 [-0.32, 0.44]**	
Heterogeneity: Tau² = 0.56; Chi² = 73.62, df = 20 (P < 0.00001); I² = 73%									
Test for overall effect: Z = 0.33 (P = 0.74)									
Total (95% CI)			**471**			**445**	**100.0%**	**0.45 [0.15, 0.75]**	
Heterogeneity: Tau² = 0.79; Chi² = 190.13, df = 45 (P < 0.00001); I² = 76%									
Test for overall effect: Z = 2.97 (P = 0.003)									
Test for subgroup differences: Chi² = 7.71, df = 2 (P = 0.02), I² = 74.0%									

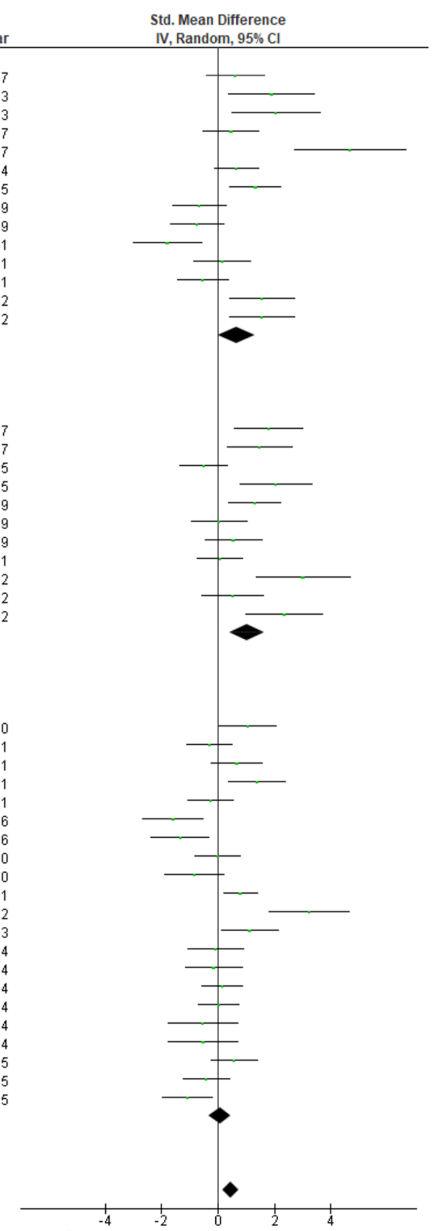

Fig. 4 Forest plot of t$\dot{V}O_2$max across SI-, MI-, and LI-HIIT protocols

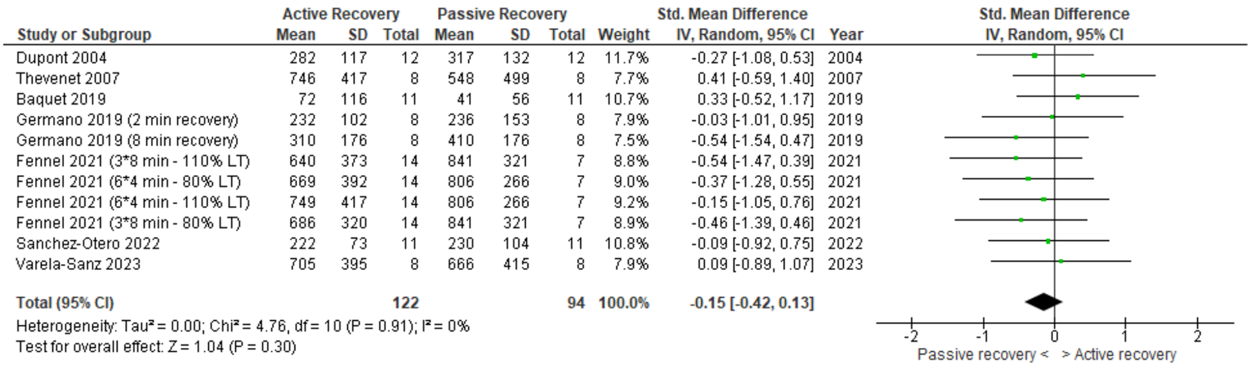

Fig. 5 Forest plot of t$\dot{V}O_2$max across HIIT protocols, comparing active to passive recovery intervals

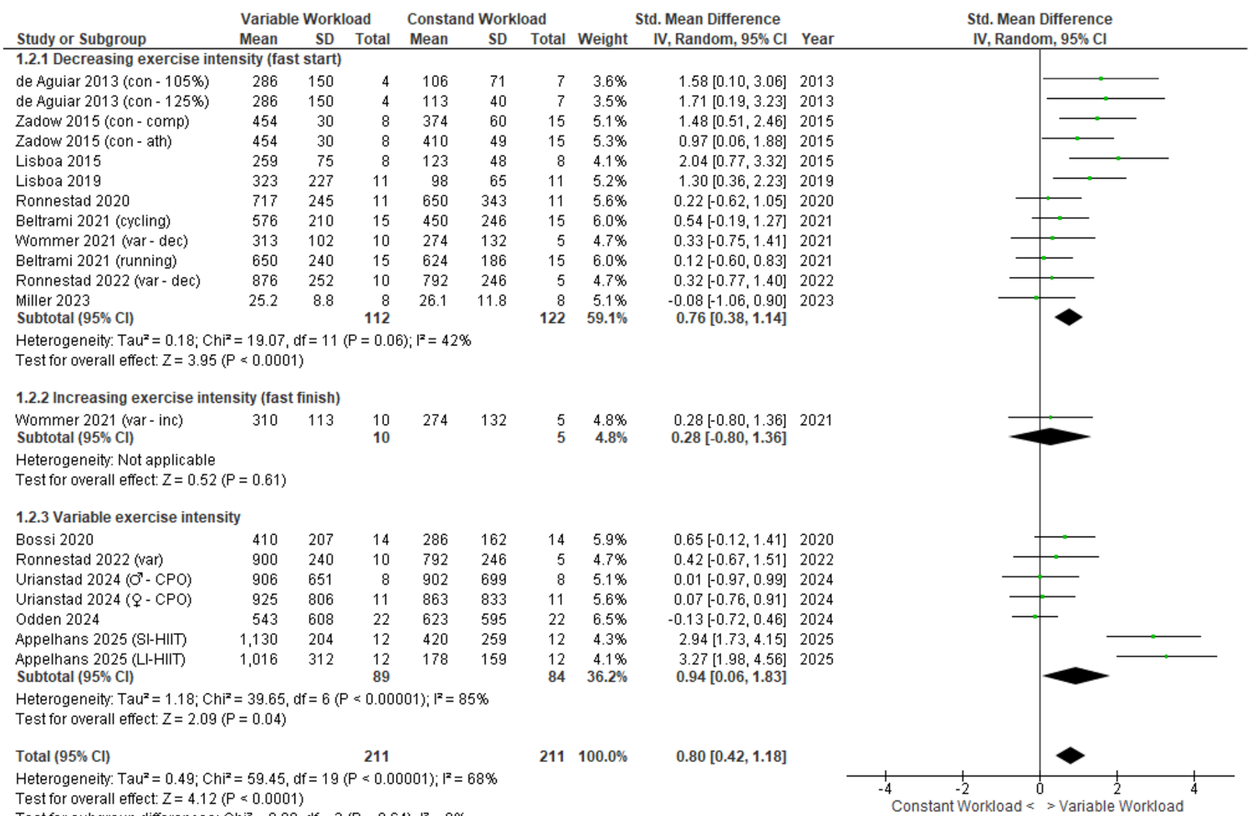

Fig. 6 Forest plot of t$\dot{V}O_2$max across HIIT protocols, comparing variable-intensity work intervals to even-paced formats

Exercise intensity distribution in work intervals

The pooled mean estimate showed a higher t$\dot{V}O_2$max when HIIT protocols used variable-intensity compared with even-paced work intervals (SMD = 0.80 [95% CI: 0.40–1.18], Z = 4.12, p <.01). The overall effect was of a moderate magnitude, with substantial heterogeneity among studies (I^2 = 68%, p <.01). Subcategory analyses suggested larger effects for variable- and decreasing-intensity work intervals (see Fig. 6); however, the test for subcategory differences was not significant ($\chi^2(2)$ = 0.90, p =.64; I^2 = 0%). Excluding results presented as unspecified fractions [67], the mean difference indicated an additional increase in t$\dot{V}O_2$max of 165 s [95% CI: 97–223 s] for protocols with variable-intensity work intervals.

Discussion

The present review summarises how much time individuals spent at, or near $\dot{V}O_2$max across a wide variety of HIIT protocols and exercise modalities. Of the 239 HIIT protocols included, 133 elicited at least 5 min at t$\dot{V}O_2$max, and 48 protocols exceeded 10 min. Our results show that time ≥ 90% and ≥ 95% $\dot{V}O_2$max are higher during HIIT protocols that incorporate long (≥ 2 min), compared with short (≤ 30 s) and moderate duration work intervals (> 30 s to 2 min). Cumulative HIIT protocol duration and work interval length accounted for approximately 6.4% and 7.2% of the variance in time ≥ 90% $\dot{V}O_2$max and time ≥ 95% $\dot{V}O_2$max, respectively. In addition, variable-intensity work intervals were found to increase t$\dot{V}O_2$max compared with even-paced work intervals, while the use of active or passive recovery between work intervals had no effect on t$\dot{V}O_2$max. Together, these findings highlight that both the structure and cumulative duration of HIIT sessions exert an influence on t$\dot{V}O_2$max, providing researchers, practitioners, and athletes with a firmer foundation for understanding how specific protocols shape the physiological demands and adaptive potential of a workout.

Midgley & McNaughton were the first to collate t$\dot{V}O_2$max from 12 HIIT running protocols [32], and recommended that both work and recovery intervals should last between 15 to 30 s to maximise t$\dot{V}O_2$max, with work intervals performed at near maximal running speeds. By expanding the scope of our review to include cycling, jumping, kayaking, rowing, swimming, and cross-country skiing, we provide updated insights into t$\dot{V}O_2$max. Midgley & McNaughton's recommendations were largely based on HIIT protocols performed to exhaustion [32], an approach considered uncommon and impractical for high-performance athletes [129]. In comparison, ~60% of the included protocols in our review incorporated a preset and fixed number of repetitions, with work interval durations ranging from 6 to 480 s (see Table 2). Our results indicate that HIIT protocols with longer work intervals yield greater time ≥ 90% and ≥ 95% $\dot{V}O_2$max compared to protocols with shorter work intervals. To elicit high $\dot{V}O_2$ during HIIT, work intervals must be long enough for these levels to be reached and maintained [3], which contrasts earlier recommendations [32]. Although SI-HIIT and, to a lesser extent, MI-HIIT are generally considered to primarily target neuromuscular adaptations [13, 23], these protocols can still produce high $\dot{V}O_2$ levels when work intensities are high and recovery intervals brief, as $\dot{V}O_2$ oscillates minimally around $\dot{V}O_2$max after an initial rise (see e.g. [52, 81, 87]). However, in line with the categorisation of HIIT protocols [3, 10], our findings reinforce that incorporating longer work intervals elicit greater durations at high oxygen uptake. Our linear mixed-effects models further confirmed a positive relationship between cumulative HIIT duration and time ≥ 90% and ≥ 95% $\dot{V}O_2$max when longer work intervals are used.

To increase t$\dot{V}O_2$max during HIIT sessions, Midgley & Naughton [32] also suggested that a 10 to 15-min warm-up should be immediately followed by the first work interval to initiate these from an elevated $\dot{V}O_2$, alongside active recovery intervals. In practice, active recovery is reported to be psychologically demanding [3, 129] and has been shown to decrease exercise time at high intensities during exhaustive HIIT protocols [37, 85, 102, 106, 110]. Our results further indicate that active recovery does not increase t$\dot{V}O_2$max. In running-based LI-HIIT [101, 103] and in square wave transitions in cycling [130], starting work intervals from a lower metabolic rate prolonged time to reach a $\dot{V}O_2$ plateau, but this delay was offset by a greater $\dot{V}O_2$ amplitude, resulting in comparable t$\dot{V}O_2$max values relative to protocols starting from a higher metabolic baseline [101, 103]. Collectively, these findings suggest that passive recovery may be equally effective for facilitating t$\dot{V}O_2$max attainment, while also helping individuals to sustain high intensities for longer. Surprisingly, few studies employed a '*priming*' warm-up, with most opting for low intensity protocols (see Supplementary Table S4). Priming, a brief bout of moderate- to heavy-intensity exercise before the main session, is thought to accelerate $\dot{V}O_2$ kinetics by elevating mitochondrial calcium and activating mitochondrial enzymes [131]. Without priming, initial work intervals may act as the priming stimulus, as shown by McKee et al. [58], who reported significantly greater time spent ≥ 90% $\dot{V}O_2$max during the second (87.8 ± 28.5 s) and third (98.6 ± 26.2 s) work intervals compared to the first (59.7 ± 28.9 s). Together, these findings suggest a complementary strategy: a priming warm-up accelerates early $\dot{V}O_2$ kinetics, while starting subsequent intervals from a lower metabolic rate maximises t$\dot{V}O_2$max. Passive or low intensity recovery during HIIT sessions following priming, may therefore combine the benefits of both approaches.

More recently, the exercise intensity distribution within work intervals was proposed to influence time spent at higher fractions of $\dot{V}O_2$max [30]. Supporting this hypothesis, our results evidence that an increase in t$\dot{V}O_2$max of 165 s [95% CI: 97–223 s] can be achieved when work intervals are performed with decreasing [43, 44, 51, 55, 64, 67, 98, 117, 118], increasing [64], or variable exercise intensities [31, 38, 71, 72, 118] compared to even-paced work intervals. Higher exercise intensities at the onset of exercise bouts initiate a quick rise in $\dot{V}O_2$ [132, 133], and may increase the oxygen cost of hyperpnoea [31]. Analysing electromyographic (EMG) activity of the vastus lateralis in cycling HIIT, Lisbôa et al. [43] reported that an initial high exercise intensity may accelerate the recruitment and activation of high-threshold type II fibres, and the effect on the O_2 cost and t$\dot{V}O_2$max becomes more evident during the later stages of HIIT sessions. In addition to manipulating work intensities within HIIT sessions, cycling-based HIIT performed on a vibration platform appeared to increase EMG activity and yield a small additional increase in t$\dot{V}O_2$max [48, 62, 66]. However, this likely depends on factors such as total vibration exposure, exercise intensity, and the specific vibration protocol used, with long-term adaptations still unclear.

Quantifying t$\dot{V}O_2$max remains a popular approach for describing the adaptive potential of HIIT protocols, yet few studies have assessed t$\dot{V}O_2$max alongside long-term adaptations or performance improvements [38, 39, 73, 97, 119]. Several studies have failed to demonstrate a clear dose–response relationship. For example, despite meaningful differences in t$\dot{V}O_2$max during a seven-week intervention comparing active and passive recovery, improvements in $\dot{V}O_2$max did not differ between groups [97]. Similarly, despite markedly lower t$\dot{V}O_2$max, Turnes et al. [39] reported greater $\dot{V}O_2$max improvements in cyclists who performed short intervals (+6.3%) compared with those who completed long intervals near their critical power (+3.3%). A comparable pattern was observed in participants who trained in cooler conditions, spending more time ≥ 90% $\dot{V}O_2$max than those in the heat, while 20-km time trial improvements remained similar. [73]. In contrast, Rønnestad et al [119] reported a moderate (non-significant) correlation between time ≥ 90% $\dot{V}O_2$max and subsequent $\dot{V}O_2$max improvements (r = 0.54). More compellingly, Odden et al. [38] continuously monitored $\dot{V}O_2$ during all HIIT sessions of a nine-week intervention and found that higher fractions of $\dot{V}O_2$max predicted greater improvements in peak power output (adjusted r^2 = 0.44, p <.01) and $\dot{V}O_2$max (adjusted r^2 = 0.54, p <.05). The above mixed findings highlight the difficulty of drawing firm conclusions from a small number of studies, with heterogeneous methodologies and participant groups, and in some cases, conclusions based on only a single assessment of t$\dot{V}O_2$max. These studies also challenge the suggestion that t$\dot{V}O_2$max per HIIT session must exceed 5 min, or even 10 min, to elicit adaptations [3], as improvements in $\dot{V}O_2$max have been observed with in t$\dot{V}O_2$max < 5 min [39], between 5 and 10 min [73, 97], and ≥ 10 min t$\dot{V}O_2$max [38, 73, 119]. Given that increases in $\dot{V}O_2$max are closely linked to central adaptations, including cardiac output, stroke volume and the maximal arteriovenous O_2 difference, protocols eliciting sustained high fractions of maximal heart rate have been associated with substantial improvements in $\dot{V}O_2$max, even with limited t$\dot{V}O_2$max [36, 60]. The magnitude of change in $\dot{V}O_2$max is likely further influenced by participant training status, and the total duration of the training interventions [13, 134].

Limitations and Future directions

This review identified several HIIT configurations that may maximise t$\dot{V}O_2$max, yet important questions remain regarding their physiological and performance relevance. The rigorous methodological approach used by Odden et al. [38] provides a valuable framework for linking acute responses to long-term adaptations. Across studies, substantial variation existed in HIIT protocols (see Table 2) and in both intra- and inter-individual t$\dot{V}O_2$max physiological responses (see Supplementary Table S2). Reflecting this, t$\dot{V}O_2$max showed poor-to-moderate reliability in HIIT performed to exhaustion [70, 87], as well as in predefined sessions [75]. Across studies, ICCs ranged between 0.57 and 0.90 [70, 75, 87]; however, ICC values in isolation can be misleading, as they are influenced by between-subject variability and session-to-session changes [135], as reflected by the large coefficients of variation reported for time ≥ 90% and ≥ 95% $\dot{V}O_2$max. Between studies, variability in t$\dot{V}O_2$max was further influenced by methodological differences, including $\dot{V}O_2$ data smoothing and time-averaging techniques, and different thresholds used to define t$\dot{V}O_2$max (see Supplementary Table S4). Short averaging intervals can inflate $\dot{V}O_2$max due to noise from irregular ventilatory patterns, artificially shifting t$\dot{V}O_2$max threshold for subsequent HIIT sessions beyond achievable levels. Notably, using short averaging intervals to determine $\dot{V}O_2$max while averaging $\dot{V}O_2$ data over longer periods to assess t$\dot{V}O_2$max in HIIT sessions can make t$\dot{V}O_2$max appear shorter, whereas the inverse combination can produce the opposite effect [88, 136]. It remains unclear whether intra- and inter-individual variability represents 'biological noise' or indeed an inconsistent training response to HIIT [70, 87, 119]. Indexing t$\dot{V}O_2$max to same-day $\dot{V}O_2$max reduced inter-individual variation in exhaustive continuous runs [85] and cycling HIIT sessions [75], although substantial variability persisted. This highlights that inter-individual variability can only be meaningfully interpreted when intra-individual variability is accounted for [70], and single measurements of t$\dot{V}O_2$max should be interpreted with caution. To improve reliability and ensure robust comparisons, future studies should acquire gas exchange data across identical HIIT sessions and report t$\dot{V}O_2$max as the mean of repeated trials [31, 63]. Additionally, ensemble averaging methods, recently applied in the field of oxygen kinetics and muscle deoxygenation research [137, 138], may offer further improvements in precision and reduce measurement noise, supporting more robust assessments of HIIT protocols and participant responses.

It is important to note that categorising HIIT protocols solely by work interval duration can lead to misclassification, potentially influencing our findings. For example, protocols with repeated short 'on'/'off' transitions were originally described as SI-HIIT [52, 139], but have since been reclassified as LI-HIIT when the series are treated as one single work interval (e.g. in [38]; 11 repetitions of 30 s 'on'/15 s 'off' is considered one 7 min 45 s work interval). In the present study, we adhered to the original categorisation as set out by Wen et al. [10], indexing protocols with the series format as SI-HIIT, consistent with their work interval duration [38, 52, 59, 63, 69, 71, 72, 76, 78, 83, 84, 86]. Many of these studies contributed to the meta-analytic estimates comparing $t\dot{V}O_2max$ between SI-HIIT, MI-HIIT and LI-HIIT, not only influencing the effect sizes, but also obscuring the true comparisons between protocols of different work interval durations (Fig. 4). Even within categories, discrepancies exist; for example, 3-min and 8-min intervals differ substantially in in physiological demands and exercise intensities yet were treated equivalently. Maintaining prior classifications ensured comparability with previous literature, despite some loss of nuance, but existing discrepancies in HIIT terminology highlight the limitations of duration-based classifications and the need for clearer, standardised criteria. Future research should therefore treat work interval duration as a continuous variable, allowing for more precise evaluation. In young swimmers [115, 116], and more recently in cyclists [74], time spent ≥ VT2 has been proposed as a novel, physiologically grounded alternative method to define time in the *'red zone'.* Adopting this individualised approach resulted in notable higher $t\dot{V}O_2max$ compared to 80%, 90% and 95% $\dot{V}O_2max$ [74, 115, 116]. Future studies are warranted to validate time spent ≥ VT2 as an alternative to fixed $\dot{V}O_2max$ fractions for quantifying the physiological stimulus of HIIT. This could be achieved using the methodological blueprint of Odden et al. [38], with continuous $\dot{V}O_2$ monitoring during HIIT sessions and subsequent analysis of the data against multiple $t\dot{V}O_2max$ thresholds, including both time ≥ VT2 and traditional fixed fractions. Such an approach would provide clear insight into which physiological metrics best capture the adaptive stimulus of HIIT and help identify more robust predictors of training responsiveness.

Practical applications

The present review provides a synthesis of responses across a wide range of HIIT protocols, which can serve as a practical reference for selecting and comparing exercise formats in applied settings. Our findings are primarily derived from laboratory-based assessments of $\dot{V}O_2$, and the monitoring of $t\dot{V}O_2max$ during HIIT sessions may not transfer as readily to applied settings compared with the widespread use of heart rate monitoring. However, heart rate and $\dot{V}O_2$ responses may not demonstrate a sufficiently strong or consistent relationship to serve as interchangeable markers of exercise intensity during intermittent exercise [103, 140].

The regression equations provide a practical means of estimating $t\dot{V}O_2max$ from commonly reported training variables, facilitating comparison and prescription of HIIT protocols. Theoretically, the application of the regression equations to standardised 30-min HIIT sessions suggests that exercise structure may meaningfully influence predicted $t\dot{V}O_2max$, despite equivalent total session duration. As illustrated in Table 5, model-derived estimates indicate higher predicted $t\dot{V}O_2max$ for LI-HIIT compared with SI- and MI-HIIT formats. Our findings further suggest that variable work intensities within intervals and passive recovery intervals are likely effective strategies for maximising $t\dot{V}O_2max$ during HIIT sessions.

Table 5 Predicted $t\dot{V}O_2max$ for standardised HIIT sessions based on regression equations

HIIT Category	HIIT Protocol	Cumulative duration (s)	Predicted time ≥ 90% $\dot{V}O_2max$ (s)
SI-HIIT	6 × 30 s Wingate sprint, 4:30 min passive rest	1800	152
MI-HIIT	15 × 1 min isoeffort, 1 min passive rest	1800	158
LI-HIIT	5 × 4 min isoeffort, 2 min passive rest	1800	319

Conclusion

This systematic review demonstrates that HIIT protocols incorporating work intervals longer than 2 min and greater total session durations elicit greater $t\dot{V}O_2max$ compared to shorter protocols. While strategies such as fast starts, variable intensities, and priming warm-ups can further enhance oxygen uptake kinetics, recovery mode (active vs. passive) appears to exert little influence on $t\dot{V}O_2max$. Although $t\dot{V}O_2max$ is widely used as an indicator of internal training load, the present synthesis highlights substantial intra- and inter-individual variability, as well as methodological diversity in how $\dot{V}O_2$ responses are quantified. Rather than detracting from its utility, this variability underscores the importance of interpreting $t\dot{V}O_2max$ within the context of protocol design, participant characteristics and complementary physiological markers. Importantly, evidence from intervention studies indicates that improvements in $\dot{V}O_2max$ are not strictly dependent on accumulating fixed durations (e.g. ≥ 5 or ≥ 10 min in *'the red zone'*), reinforcing that multiple configurations of HIIT can drive adaptations. Future research should adopt standardised reporting methods and consider individualised thresholds such as VT2 to improve the precision and applicability of training load quantification.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s13102-026-01766-x.

Supplementary Material 1.

Supplementary Material 2.

Supplementary Material 3.

Supplementary Material 4.

Supplementary Material 5.

Acknowledgements
Not applicable.

Authors' contributions

PS conceived the study and led the study design. PS developed the search strategy and conducted the literature search and initial data extraction. KM and JW independently performed study screening, data extraction, and quality assessment. PS and AB conducted the statistical analyses, with methodological input from GM and KM. All authors contributed to the interpretation of the results. PS drafted the initial manuscript, and all authors critically revised the manuscript for important intellectual content. All authors read and approved the final version of the manuscript.

Funding

The author(s) declare that no financial support was received for the research, authorship, and/or publication of this article.

Data availability

All extracted data from the included studies are reported in table 1 and 2 (and supplementary material). Data are available upon request from the corresponding author.

Declarations

Ethics approval and consent to participate

Not applicable. This study was a meta-analysis of previously published studies; therefore, ethical approval and participant consent were not required.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

Received: 28 January 2026 / Accepted: 20 May 2026
Published online: 03 June 2026

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