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SYSTEMATIC REVIEW

The Effects of Interval and Continuous Training on the Oxygen Cost of Running in Recreational Runners: A Systematic Review and Meta-analysis

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Abstract

Background Oxygen cost of running is largely influenced by endurance training strategies, including interval and continuous training. However, which training method better reduces the oxygen cost remains unknown.

Objective This study aimed to systematically review the scientific literature and performs a meta-analysis to address the effects of different endurance training modalities on the oxygen cost of running.

Methods A literature search on 3 databases (MEDLINE, SPORTDiscus and Web of Science) was conducted on February 28, 2019. After analysing 8028 resultant articles, studies were included if they met the following inclusion criteria: (a) studies were randomised controlled trials, (b) studies included trained runners without previous injuries (c) interventions lasted at least 6 weeks, with participants allocated to Interval (INT) or Continuous (CON) groups, and (d) oxygen cost was assessed pre- and post-training intervention. Six studies (seven trials) met the inclusion criteria and were included in the meta-analysis. This resulted in 295 participants ($n = 200$ INT; $n = 95$ CON training method). Standardised mean difference with 95% confidence intervals (CI) between INT and CON conditions and effect sizes were calculated. To assess the potential effects of moderator variables (such as, age, VO_{2max} of participants, number of weeks of intervention) on main outcome (oxygen cost of running), subgroup analyses were performed.

Results Comparing changes from pre- to post-intervention, oxygen cost improved to a greater extent in CON when compared to INT interventions (0.28 [95% CI 0.01, 0.54], $Z = 2.05$, $p = 0.04$, $I^2 = 30\%$). Oxygen cost improvements were larger in participants with higher VO_{2max} (≥ 52.3 ml kg^{-1} min^{-1}) (0.39 [95% CI 0.06, 0.72], $Z = 2.34$, $p = 0.02$), and in programs greater or equal to 8 weeks (0.35 [95% CI 0.03, 0.67], $Z = 2.13$, $p = 0.03$). When the total volume per week of INT was ≥ 23.2 min, there was a significant improvement favorable to CON (0.34 [95% CI 0.01, 0.61], $Z = 2.02$, $p = 0.04$).

Conclusion Continuous training seems, overall, a better strategy than interval training to reduce the oxygen cost in recreational endurance runners. However, oxygen cost reductions are influenced by several variables including the duration of the program, runners' aerobic capacity, the intervals duration and the volume of interval training per week. Practitioners and coaches should construct training programs that include both endurance training methods shown to be effective in reducing the oxygen cost of running.

1 Introduction

Endurance running performance is reliant on a complex interaction of factors, such as cardiac output, oxygen delivery to working muscles and maximal oxygen uptake (VO_{2max}) [1], that lead to efficient muscular work and result in a fast and effective running gait [2]. These factors disclose several aspects of running performance and are able to identify discrepancies between untrained and well-trained runners [3]. However, unraveling the differences between runners of matched ability has proved more challenging [4]. In this regard, the oxygen cost of running, commonly defined

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Key Points

Continuous training elicits greater reductions in the oxygen cost of running when compared with interval training for recreational endurance runners.

However, analysis of moderator variables showed that oxygen cost reductions were influenced by several variables including the duration of the program, runners' aerobic capacity, the intervals duration and the volume of interval training per week.

Practitioners and coaches should construct training programs that include both endurance training methods shown to be effective in reducing the oxygen cost of running.

as the steady-state oxygen uptake required at a given submaximal speed [1], has been reported to most appropriately discriminate between performances in homogeneous groups of runners [5, 6]. Consequently, together with $VO_{2\max}$ [7] and lactate threshold [8], the oxygen cost is considered a key factor for distance running success [9, 10].

The oxygen cost is largely determined by physiological factors [11], muscle fiber distribution [12], age [13], sex [14], anthropometric factors [15] and biomechanical variables [16]. Similarly, previous research has suggested that the oxygen cost may be influenced by different training strategies, including strength training [17] and endurance training modalities. This is because different training approaches have been reported to elicit changes in the functionality of skeletal muscle mitochondria (i.e. muscle respiratory capacity), which ultimately would imply less use of oxygen during exercise [3]. Other endurance training adaptations, including increased skeletal muscle buffer capacity and haematological changes (i.e. increased red cell mass [18]), may also improve oxygen delivery and utilisation [19].

Two of the most common endurance training strategies are interval training and continuous training methods [20]. However, despite the scientific evidence supporting the use of endurance training to reduce the oxygen cost, the effects of the training method used (interval *vs*. continuous) are still a matter of debate in the literature. On the one hand, several studies investigating the effects of interval training at intensities between 93–120% of the speed at $VO_{2\max}$ and continuous training at the onset of blood lactate accumulation speed have reported similar running economy improvements of around 1–7% [21–25]. On the other hand, previous research using similar training strategies found no significant improvements at all [26, 27], while some authors suggest that the endurance training modality used exerts a trivial effect on the oxygen cost [19, 28]. At the same time, the effects of exercise intensity, frequency and duration of interval and continuous training on the oxygen cost are yet to be explored.

It is against this apparently contradictory background that this study systematically reviews the body of scientific literature of original research and performs a meta-analysis to assess the effects of different endurance training modalities on the oxygen cost. In addition, the study also analyses how other variables, including age, $VO_{2\max}$, and duration of effort and duration of intervention, may affect the incidence of interval and continuous training on running economy. We hypothesise that continuous training modalities will elicit greater oxygen cost reductions than interval training methods.

2 Methods

This meta-analysis followed the PRISMA statement for improved reporting of meta-analyses [21].

2.1 Search Strategy

A literature search was conducted on February 28, 2019 by two independent reviewers for the following databases: MEDLINE, SPORTDiscus and Web of Science. The keywords used in the search were: *running economy, energy cost, metabolic cost, continuous training, interval training* and *runners*. Abstracts and citations from scientific conferences were excluded.

Title, abstract and keyword search fields were searched using the following search strategy:

Running economy* OR energy cost* OR metabolic cost* AND continuous training* AND/OR interval training* AND runners.

Searches were limited to human trained participants and English language only publications. Identification, screening, eligibility assessments and inclusion of studies were performed independently by two reviewers (FGM and IY) with disagreement settled by consensus. All records of literature search were examined by title and abstract to exclude irrelevant records. Studies were selected following the eligibility criteria. Data including the publication details, participant characteristics (recreational runners), testing procedures, study design, description of intervention and results of the oxygen cost of running outcome were extracted from all eligible studies. If insufficient information was reported (e.g. $VO_{2\max}$ of participants), the authors were contacted to confirm additional information about the included studies.

2.2 Inclusion Criteria

The summary of eligibility criteria is shown in Table 1.

2.2.1 Type of Study

Our meta-analysis included randomised controlled trials, written in English and published previous to February 28, 2019.

2.2.2 Type of Participants

The participants included in our meta-analysis were recreational runners without previous injuries or chronic diseases. No exclusion criteria were used for participant sex or baseline fitness. The classification of participants followed the criteria previously reported by De Pauw et al. 2013 [30], in terms of $VO_{2\max}$. The range established for recreational runners was 45–54.9 mL kg^{-1} min^{-1} of $VO_{2\max}$ [30], which was similar to that of our participants (range 47.3–56.7 mL kg^{-1} min^{-1}, Table 3).

2.2.3 Type of Interventions

Endurance training studies usually last between 6 and 12 weeks [31–33]. Therefore, to be included in our meta-analysis, training programs had to last at least a minimum of 6 weeks, with participants allocated to *Interval* (INT) and *Continuous* (CON) groups. Training programs were detailed in the corresponding *Methods* section, with duration, intensity and volume of each session recorded. Studies were excluded if experimental training programs were combined with other extra-training sessions.

2.2.4 Type of Outcome Measure

The outcome measure for this meta-analysis was the oxygen cost of running, which was measured on a treadmill.

2.3 Data Extraction

Two of the authors (FGM and IY) independently extracted characteristics of participants and training protocols using a standardised form. Results were compared and discrepancies were resolved by consensus or by consulting the senior author (JMG).

2.4 Final Study Selection

8028 potential manuscripts were identified following database examination (Fig. 1). References list of selected manuscripts were also examined for any other potentially eligible manuscripts. Following this examination, 3 potential manuscripts were added. After removal of duplicates and elimination of papers based on title and abstract screening, 101 studies remained. Only 6 out of 101 studies met the inclusion criteria and were, therefore, included in the meta-analysis (Fig. 1).

2.5 Quality assessment

The methodological quality of the studies was rated using the PEDro scale [34] and Oxford's levels of quality [35] (Table 2). The PEDro scale consists of 11 items related to scientific rigor. Item 1 is rated as Yes/No, while Items 2–11 are rated using 0 (absent) or 1 (present), and a score out of 10 is obtained by summation. A score of ≥ 6 represents the threshold for studies with low risk of bias [36]. Given that the assessors are rarely blinded, and that is impossible to blind the participants and investigators in supervised exercise interventions the items related to blinding (5–7) were removed from the scale [37]. For this reason, the maximum result on the modified PEDro 8-point scale was 7 (highest score), as the first item is not included in the total score. The qualitative ratings were adjusted to that used in previous exercise-related systematic reviews [37, 38] as follows: 6–7 = "excellent"; 5 = "good"; 4 = "moderate"; and, 0–3 = "poor".

2.6 Statistical Considerations

Meta-analytical procedures were applied to evaluate possible effects of INT and CON training on the oxygen cost of running. Standardised mean difference (SMD) with 95%

Table 1 Summary of eligibility criteria

Criterion	Description
Type of participant	Endurance runners. Eligible studies had to describe participants as recreational runners
Type of intervention	Endurance training: interval and continuous training
Type of outcome measure	
Running economy	Measured using steady-state oxygen consumption or energy cost calculated using indirect calorimetry
Type of study	Experimental studies
Publication status	Peer-reviewed journal publication
Publication date	Publicate date did not form part of the eligibility criteria
Language of publication	English language publication

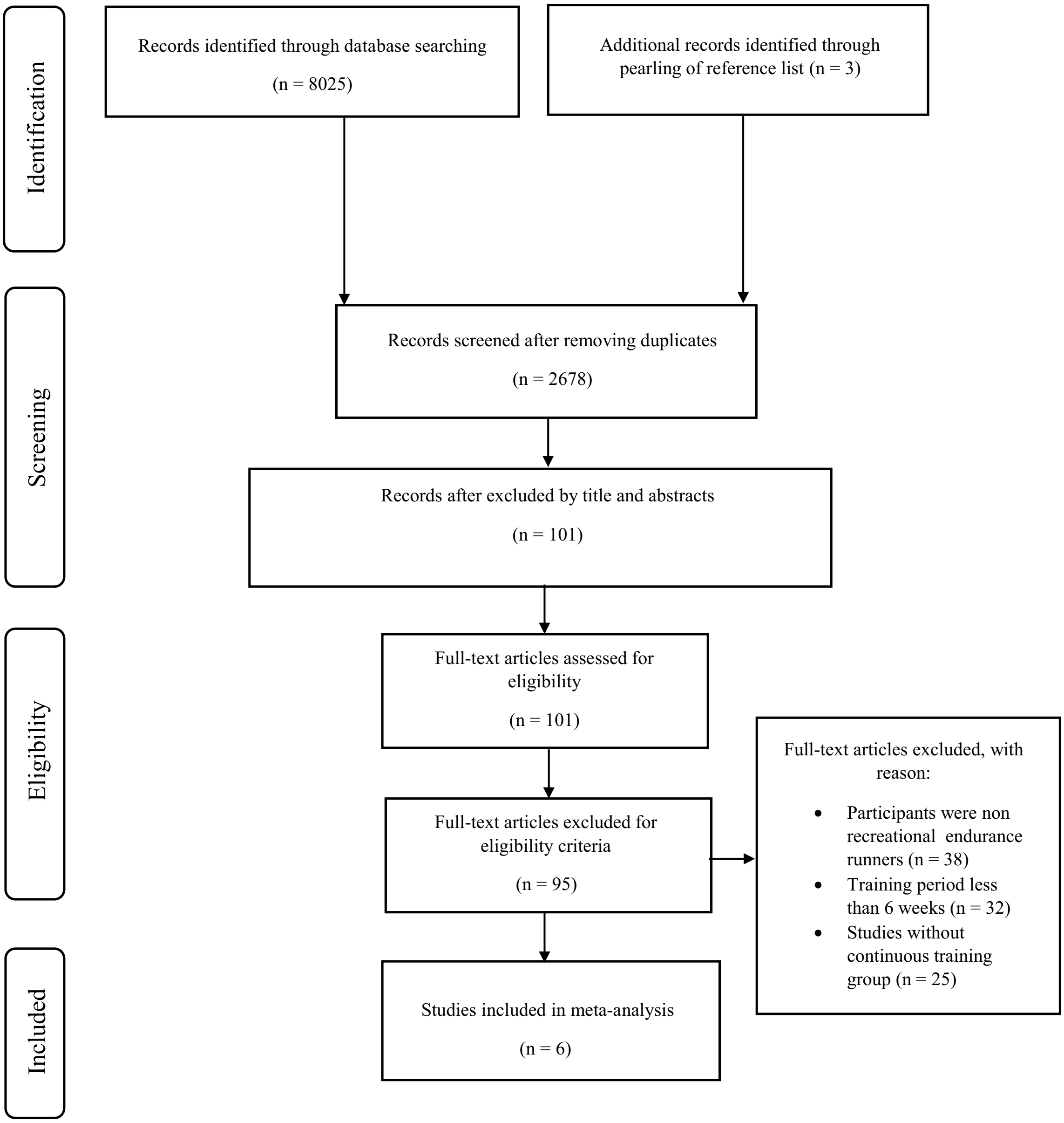


Fig. 1 Flow diagram of the study selection process

Confidence Intervals (CI) between INT and CON conditions was calculated with RevMan 5.3.5 for Windows using a fixed effects model. During the screening of the selected studies, mean and standard deviations for the outcome measures were extracted. It was not necessary to contact the authors for further data. Significance for overall effect was set at $p < 0.05$. Heterogeneity of the analysed studies was assessed using an *I*-squared (I^2) test. Significance level of I^2 test was set at $p < 0.05$. I^2 represents the proportion of effects that are due to heterogeneity as opposed to chance [39]. Thresholds for low, moderate and high levels of heterogeneity correspond to I^2 values of 25, 50, and 75%, respectively. Within the controlled trial studies, a positive effect indicates a larger oxygen cost improvement in the CON group when compared to the INT group, while a negative effect means the opposite. For a clearer interpretation of the results, it is important to highlight that oxygen cost of running improvements means a reduced oxygen cost, thereby giving rise to the negative change. The calculated effect sizes (ES) were interpreted using the conventions outlined for SMD by Hopkins et al. [40] (small (> 0.2 and < 0.6); moderate (≥ 0.6 and < 1.2); large (≥ 1.2 and < 2) and very large (≥ 2 and < 4)).

Table 2 PEDro ratings* and Oxford's evidence levels of the included studies

References	PEDro ratings									Oxford's Evidence levels
	1	2	3	4	5	6	7	8	Total	
Franch et al. [14]	Yes			1	1	1	1	1	5	2b
Gliemann et al. [29]	Yes			1	1	1	1	1	5	2b
González-Mohíno et al. [12]	Yes	1		1	1	1	1	1	6	2b
Gunnarsson et al. [28]	Yes			1	1	1	1	1	5	2b
Pugliese et al. [30]	Yes	1		1	1	1	1	1	6	1b
Schaun et al. [31]	Yes	1		1	1	1	1	1	6	2b

*Items in the PEDro scale: 1 = eligibility criteria were specified; 2 = subjects were randomly allocated to groups; 3 = allocation was concealed; 4 = the groups were similar at baseline regarding the most important prognostic indicators; 5 = measures of 1 key outcome were obtained from 95% of subjects initially allocated to groups; 6 = all subjects for whom outcome measures were available received the treatment or control condition as allocated or, where this was not the case, data for at least 1 key outcome were analysed by "intention to treat"; 7 = the results of between-group statistical comparison are reported for at least 1 key outcome; 8 = the study provides both point measures and measures of variability for at least 1 key outcome

2.6.1 Analysis of Moderator Variables

To assess the potential effects of moderator variables on main outcome (oxygen cost of running), subgroup analyses were performed. We used a random-effects model and selected potential moderators likely to influence the effects of training. Studies were divided into the following variables: age (Group 1, 23.7–33.1 years and Group 2, 33.1–49.2 years), $VO_{2\max}$ of participants (Group 1, 47.3–52.2 ml kg^{-1} min^{-1} and Group 2, 52.3–56.7 ml kg^{-1} min^{-1}) and number of weeks of intervention (Group 1, 6–7 weeks and Group 2, 8–16 weeks). At the same time, for the INT intervention, studies were divided for the duration of the interval (Group 1, 15 s^{-1} min and Group 2, 4–5 min) and the total exercise time per week (Group 1, 7.2–23.2 min and Group 2, 35.2–156 min). For the CON intervention, studies were divided by total exercise time per week (Group 1, 62.5–105 min and Group 2, 125.8–177 min). The division of the moderator variables was established to obtain a similar number of studies to those of subgroup analyses.

3 Results

3.1 Level of Evidence and Quality of the Studies

All the studies selected achieved the required standard to be considered to have a low risk of bias (PEDro score ≥ 6; Table 2) following the previous systematic reviews [37, 38]. Based on the Oxford Level of Evidence, 5 of the studies selected had an evidence of 2b. This was because confidence intervals were not reported. Only the study of Pugliese et al. [41] achieved an evidence level 1b (high-quality randomised controlled trial).

3.2 Characteristics of the Participants

Table 3 shows the participant characteristics of the six studies included in this meta-analysis (total sample size of 295 participants, 27.12% women). The total participants were randomised to either INT ($n = 200$) or CON ($n = 95$). Only two of the studies [42, 43] included men and women, while the rest of studies included only male participants [20, 22, 41, 44].

3.3 Characteristics of the Studies Selected

The outcome for this meta-analysis was the change in the oxygen cost of running measured during a steady-state run on a treadmill. Mean intervention duration was 8.5 weeks (range 6–16), with only one study having a duration longer than 8.5 weeks [44]. Mean training frequency was three times a week (range 2–3 times a week). Mean duration of the total training session was 45.6 min for INT (range 8.6–156 min) and 112 min for CON (range 62.5–177 min).

The intensity of the interventions of INT was prescribed as percentage of HR_{max} in one study [14], as a percentage of maximal aerobic speed (MAS) in two studies [20, 44], as a percentage of gas exchange threshold (GET) in one study [41], and as a percentage of maximal speed test [42, 43]. Regarding CON interventions, the intensity was prescribed as percentage of HR_{max} in two studies [22, 43], as a percentage of MAS [20], as a percentage of GET [41], and as a percentage of HR at intensity of second ventilatory threshold [44]. The study by Gunnarsson et al. [42] does not report the intensity of CON.

3.4 Oxygen Cost Assessment (Main Effect)

The oxygen cost reduced to a greater extent in CON when compared to INT interventions (SMD = 0.28 [95% CI 0.01,

Table 3 Characteristics of interval and continuous training interventions of included studies

References	*n* (M/F)	Age (years)	VO_2max (ml kg^{-1} min^{-1})	Training protocol						Running economy		
				Interval training		Continuous training		Weeks	Session/week	Unit of measure	Speed/Relative intensity	% change
				Training characteristics	Exercise time (min/week)	Training characteristics	Exercise time (min/week)					
Franch et al. [14]	36 (36/0)	30.4 ± 4.8	54.8 ± 3.0	Group 1: 4 × 4 min at 94% HR_{max}/2 min recovery Group 2: 30–40 × 15 s (92% HR_{max})/15 s recovery	Group 1: 35.2; Group 2: 23.2	20–30 min at 93% HR_{max} (15 km h^{-1})	62.5	6	2–3	ml kg^{-1} min^{-1}	3.41, 3.72, 4.00 m s^{-1}	CON:– 2.5% INT 1:– 4.4% INT 2: – 2.5%
González-Mohíno et al. [12]	11 (11/0)	33.1 ± 11.3	56.7 ± 8.4	Session 1: 10–15 × 1 min at 110% MAS/1 min at 55% MAS active; session 2: 5–10 × 2 min at 100% MAS/2 min at 50% MAS active recovery; session 3: 3–8 × 3 min at 95% MAS/3 min at 45% MAS active recovery	81	22–48 min at 70–75% MAS	105	6	3	ml kg^{-1} min^{-1}	60, 80 and 90% of MAS	CON: – 15% INT: 2.7%

Table 3 (continued)

References	*n* (M/F)	Age (years)	VO_2max (ml kg^{-1} min^{-1})	Training protocol						Running economy		
				Interval training		Continuous training		Weeks	Session/ week	Unit of measure	Speed/Relative intensity	% change
				Training characteristics	Exercise time (min/ week)	Training characteristics	Exercise time (min/ week)					
Pugliese et al. [30]	22 (22/0)	47.2 ± 7.4	48.27 ± 0.61	Session 1: 18 × 1 min at 120% GET/2 min at 65% GET recovery; session 2: 18 × 1 min at 130% GET/2 min at 65% GET recovery; session 3: 18 × 1 min at 140% GET/2 min at 65% GET recovery	156	Session 1: 64.5 min at 70% GET; session 2: 58.5 min at 80% GET; session 3: 54 min at 90% GET	177	8	3	ml kg^{-1} min^{-1}	60% of VO_2 peak (10 km h^{-1})	CON: – 3.8% INT: – 4.2%
Schaun et al. [31]	36 (36/0)	23.7 ± 0.7	47.3 ± 0.21	8 × 20 s at 130% MAS/10 s recovery	7.2	30 min at 90–95% HR VT_2	90	16	3	ml kg^{-1} min^{-1}	12 km h^{-1}	CON:3.9% INT: 6.4%
Gunnarsson et al. [28]	18 (12/6)	33.8 ± 1.6	52.2 ± 1.5	3–4 × 5 min (each period consisted of 5 consecutive 1 min interval divided into 30, 20, 10 s at intensities of 30%, 60% and 90–100% of maximal intensity.	8.6	~ 8 km in 132.4 and 119.2 min during the intervention period	125.8	7	3	ml kg^{-1} km^{-1}	9.9 and 12.4 km h^{-1}	CON:1.9% INT: 1.4%

Table 3 (continued)

References	*n* (M/F)	Age (years)	VO_2max (ml kg^{-1} min^{-1})	Training protocol						Running economy		
				Interval training		Continuous training		Weeks	Session/week	Unit of measure	Speed/Relative intensity	% change
				Training characteristics	Exercise time (min/week)	Training characteristics	Exercise time (min/week)					
Gliemann et al. [29]	160 (58/74)	49.2 ± 0.8	52.3 ± 0.28	3–4 × 5 min (each period consisted of 5 consecutive 1 min interval divided into 30, 20, 10 s at intensities of 30%, 60% and 90–100% of maximal intensity.	8.6	9 km between 75 and 85% HR$_{max}$	–	8	3	ml kg^{-1} km^{-1}	9–13 km h^{-1} depending of runners	CON:1.4% INT: 2.9%

Data are mean ± SD

GET gas exchange threshold, *MAS* maximal aerobic speed, HR_{max} maximum heart rate, VT_2 second ventilatory threshold, VO_2max maximal oxygen uptake

0.54], $Z=2.05$, $p=0.04$). The I^2 test showed a non-significant heterogeneity among the included studies ($I^2=30\%$, $p=0.20$). These results are displayed in Figure 2.

3.5 Effect of Moderator Variables

Between-group heterogeneity was found to be insignificant ($p>0.05$) in the subgroup analysis. Table 4 shows the effect of moderator variables on oxygen cost of running. Oxygen cost reductions were larger in participants with higher VO_{2max} (≥ 52.3 ml kg^{-1} min^{-1}) (SMD = 0.39 [95% CI 0.06, 0.72], $Z=2.34$, $p=0.02$),in programs greater or equal to 8 weeks (SMD = 0.35 [95% CI 0.03, 0.67], $Z=2.13$, $p=0.03$) and in participants greater or equal to 33.8 years (SMD = 0.29 [95% CI − 0.05, 0.64], $Z=1.67$, $p=0.09$) favorable to CON interventions.

For INT interventions, studies prescribing intervals duration ≤ 1 min revealed no significant subgroup oxygen cost differences when compared to CON interventions (test for subgroup differences, $p=0.49$, $I^2=0\%$). For studies prescribing intervals duration > 1 min, there was a significant reduction in oxygen cost favorable to INT compared to CON (SMD = − 0.59 [95% CI − 0.91,− 0.24], $Z=3.35$, $p=0.0008$, $I^2=80\%$, $p=0.002$). However, when the total exercise time per week was ≥ 23.2 min in INT interventions, there was a significant reduction in oxygen cost favorable to CON (SMD = 0.34 [95% CI 0.01, 0.61], $Z=2.02$, $p=0.04$). The I^2 test showed a non-significant heterogeneity among the included studies ($I^2=0\%$, $p=0.37$).

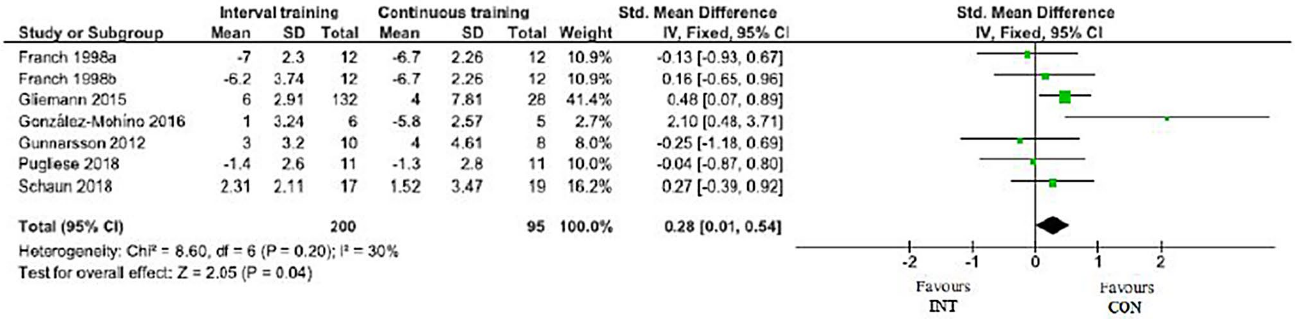
For CON interventions, subgroup analyses revealed no significant subgroup differences (test for subgroup differences, $p=0.78$, $I^2=0\%$) on oxygen cost when the total exercise time per week was divided into two groups (≤ 105 min or ≥ 106 min).

4 Discussion

The main finding of this systematic review was that continuous training (CON) improved the oxygen cost of running to a greater extent than interval training (INT) in recreational endurance runners. However, we found that oxygen cost reductions were influenced by several variables including the duration of the program, runners' aerobic capacity, the intervals duration and the volume of interval training per week.

These results agree with the conclusions of previous studies reporting that continuous endurance training is an effective method to improve the oxygen cost in trained endurance runners [20, 21]. González-Mohíno et al. [20] suggest that the reduced oxygen cost observed after a CON training intervention may be due to an improved intracellular oxidative capacity (which implies an increased rate of lactate oxidation), and changes in the morphology and function of mitochondria [45]. However, it is known that oxygen cost reductions are greater at the intensities close to what runners routinely reach during training [46]. Therefore, part of the results may be explained by the fact that CON interventions imply higher volume of work (~ 80%) at intensities closer to the speed at which the oxygen cost is commonly assessed [8].

There are contradictory findings regarding INT training programs and its effects on the oxygen cost. Some researchers have reported no running economy improvements after an INT intervention [25, 47], whereas others have found the opposite [48]. Others, such as Billat et al. [23] have reported oxygen cost improvements when adding high intensity training to baseline running, although this effect seems to be lost when that high intensity training is performed too often. Similarly, Franch et al. [22] found that the oxygen cost significantly reduced after a training intervention using high intensity interval training at intensities of 94% and 106% of VO_{2max}, but not when the intensity was 132% of VO_{2max}. All this suggests that there must be an optimal amount of interval training volume and intensity in order to produce training adaptations below and above in which there are no further oxygen cost reductions. According to our results, that



Study or Subgroup	Interval training Mean	SD	Total	Continuous training Mean	SD	Total	Weight	Std. Mean Difference IV, Fixed, 95% CI
Franch 1998a	-7	2.3	12	-6.7	2.26	12	10.9%	-0.13 [-0.93, 0.67]
Franch 1998b	-6.2	3.74	12	-6.7	2.26	12	10.9%	0.16 [-0.65, 0.96]
Gliemann 2015	6	2.91	132	4	7.81	28	41.4%	0.48 [0.07, 0.89]
González-Mohíno 2016	1	3.24	6	-5.8	2.57	5	2.7%	2.10 [0.48, 3.71]
Gunnarsson 2012	3	3.2	10	4	4.61	8	8.0%	-0.25 [-1.18, 0.69]
Puglese 2018	-1.4	2.6	11	-1.3	2.8	11	10.0%	-0.04 [-0.87, 0.80]
Schaun 2018	2.31	2.11	17	1.52	3.47	19	16.2%	0.27 [-0.39, 0.92]
Total (95% CI)			**200**			**95**	**100.0%**	**0.28 [0.01, 0.54]**

Heterogeneity: $Chi^2 = 8.60$, $df = 6$ ($P = 0.20$); $I^2 = 30\%$
Test for overall effect: $Z = 2.05$ ($P = 0.04$)

Fig. 2 Forest plot of the effects of *INT* and *CON* training on oxygen cost of running. *INT* interval training, *CON* continuous training, *CI* confidence interval, *SD* standard deviation, *IV* weighted mean difference

Table 4 Effect of moderator variables on the oxygen cost of running

Moderator variables	Studies (n)	Participants	Effect estimate [95% CI]	Heterogeinity I^2 (%)	Heterogeinity p	Test for overall effect Z	Test for overall effect p
Age of participants (years)							
≤ 33.7	4	95	0.25 [− 0.16, 0.67]	50	0.11	1.19	0.23
≥ 33.8	3	200	0.29 [− 0.05, 0.64]	24	0.27	1.67	0.09
VO_2max of participants (ml kg^{-1} min^{-1})							
≤ 52.2	3	76	0.06 [− 0.39, 0.51]	0	0.66	0.25	0.80
≥ 52.3	4	219	0.39 [0.06, 0.72]	53	0.09	2.34	0.02
Training intervention (weeks)							
≤ 7	4	77	0.12 [− 0.34, 0.59]	55	0.08	0.52	0.60
≥ 8	3	218	0.35 [0.03, 0.67]	0	0.54	2.13	0.03
INT duration per week (min)							
≤ 23.1	3	214	− 0.35 [− 1.18, 0.48]	80	0.007	0.82	0.41
≥ 23.2	4	81	0.34 [0.01, 0.66]	0	0.37	2.02	0.04
INT intervals duration (min)							
≤ 1	3	82	0.15 [− 0.28, 0.59]	0	0.86	0.69	0.49
> 1	4	213	− 0.59 [− 0.91, − 0.24]	80	0.002	3.35	0.0008
CON duration per week (min)							
≤ 105	4	95	0.25 [− 0.15, 0.67]	50	0.11	1.19	0.23
≥ 106	2	40	− 0.13 [− 0.75, 0.49]	0	0.74	0.41	0.69

A positive effect indicates a larger oxygen cost improvement in the CON group when compared to the INT group, while a negative effect means the opposite

INT interval training, *CON* continuous training, *CI* confidence interval, I^2 I-square, *Z* z score, *p* p value optimal amount lies somewhere below ~ 23 min per week, as greater volumes seem to have detrimental effects.

Similarly, we found that training programs greater or equal to 8 weeks elicited greater oxygen cost improvements than shorter interventions in both CON and INT. This result may be due to the higher volume of work completed in longer programs. Previous research has suggested that training volume is important to generate physiological adaptations [22], although whether the same running economy improvements would exist in programs of matched volume of work but different duration is debatable.

To the authors' best knowledge, no research has yet investigated the effects of endurance training on the oxygen cost taking into account runners' VO_{2max}. Together with the oxygen cost and lactate threshold, VO_{2max} is considered one of the factors that sets the upper limit for performance in endurance events [1, 28, 49, 50]. It has been suggested that exercise economy and VO_{2max} are inversely related, as better oxygen cost values are usually related to lower values of VO_{2max} and vice versa [51–53]. Interestingly, we found that athletes with VO_{2max} values above 52.3 ml kg^{-1} min^{-1} showed greater oxygen cost reductions after a training intervention than runners with smaller values. One of the possible explanations may be that, due to the known inverse relationship between VO_{2max} and oxygen cost [51, 52], runners with higher VO_{2max} values present greater inefficiency values at baseline; thus, they have greater potential for improvement.

However, the relationships between VO_{2max} and the oxygen cost and how they change after CON and INT training interventions are still a matter of debate in the scientific literature. For example, whereas Pugliese et al. [41] found that the oxygen cost decreased in CON and INT interventions (while VO_{2peak} decreased only in the INT group), Gunnarsson et al. [42] found an improvement of VO_{2max} after an INT intervention (with no oxygen cost changes). Similarly, Schaun et al. [44] found an improvement of VO_{2max} in both CON and INT intervention while the oxygen cost worsened in both groups. Lastly, González-Mohíno et al. [20] found that the oxygen cost reduced and the VO_{2max} decreased after a CON intervention. Since a typical endurance training program is a combination of both interval and continuous training, longitudinal data of studies lasting several years where different training methods are combined are needed to properly assess the effects of different approaches on the oxygen cost and $VO_{2max.}$

It is necessary to acknowledge several limitations to the present study. These include the wide variety of different protocols for both INT and CON training interventions, since this prevented us from drawing a definitive conclusion from the results. Another important limitation was the lack of statistical power of some of the studies that resulted in equivocal findings in relation to INT interventions [54].

5 Conclusion

This is the first review to analyse the effects of different endurance training modalities on the oxygen cost of running. We found that continuous training is, overall, a better strategy than interval training to reduce the oxygen cost in recreational endurance runners. However, there are a number of variables that seem to influence oxygen cost reductions. As such, we found that oxygen cost improvements were larger in participants with higher VO_{2max} ($\geq$ 52.3 ml kg^{-1} min^{-1}) than in those with lower values. Similarly, training programs lasting 8 or more weeks had greater effects on oxygen cost improvements than shorter ones. We also found that when prescribing intervals duration > 1 min, INT was more effective than CON for reducing the oxygen cost. However, when the total exercise time per week of the INT interventions was ≥ 23.2 min, CON interventions implied greater oxygen cost improvements.

5.1 Practical Applications

Endurance training methods (CON and INT) are effective in reducing oxygen cost in recreational endurance runners. For future research purposes, we recommend that researchers carry out studies in find the optimal load amounts of both endurance training methods that lead to substantial reduction of oxygen cost. In addition to these endurance training methods, other training strategies have been shown to be effective in the oxygen cost reduction. For example, exercises in strength training, including low to high intensity resistance exercises and plyometric exercises, are an appropriate means of reducing the oxygen cost of running [17, 55]. Therefore, due to their ability to reduce the oxygen cost of running and improve endurance performance, we recommend incorporating the above-mentioned strategies into the training programs of recreational endurance runners.

Compliance with Ethical Standards

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Conflict of interest Fernando González-Mohíno, Jordan Santos-Concejero, Inmaculada Yustres and José María González-Ravé declare that they have no conflicts of interest relevant to the content of this review.

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