Journal of Sports Sciences

The dose-response relationship between interval-training and V̇O2max in well-trained endurance runners: A systematic review

--Manuscript Draft--

Full Title:	The dose-response relationship between interval-training and V̇O2max in well-trained endurance runners: A systematic review
Manuscript Number:	RJSP-2020-2691R1
Article Type:	Systematic Review
Keywords:	Running; endurance; Training-impulse; Training-load; High-intensity
Abstract:	Success in endurance running is primarily determined by maximal aerobic power (V̇O2max), fractional utilisation, and running economy (RE). Within the literature, two training modalities have been identified to improve V̇O2max; continuous training (CT) and interval-training (IT). The efficacy of IT to improve V̇O2max in well-trained runners remains equivocal, as does whether a dose-response relationship exists between the IT training load performed and changes in V̇O2max. A keyword search was performed in 5 electronic databases. Seven studies met the inclusion criteria for this systematic review. The training impulse (TRIMP) was calculated to analyse relationships between training load and changes in V̇O2max. Non-significant (P >0.05) improvements in V̇O2max were reported in 6 studies, with only one study reporting a significant (P <0.05) improvement in V̇O2max following the IT interventions. A relationship between the training session impulse of the interval-training performed (IT STRIMP)and V̇O2max improvements was observed. The efficacy of IT to improve V̇O2max in well-trained runners remains equivocal due to a lack research. Nevertheless, the novel method of training-load analysis demonstrates a relationship between the IT STRIMP and V̇O2max improvements; providing practical application for the periodisation of IT within the training regime of well-trained distance runners.
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Response to Reviewers:	Response to Reviewers' comments RE: Ms. No. RJSP-2020-2691 " The dose-response relationship between interval-training and V̇O2max in well-trained endurance runners: A systematic review" Dear Michalis G Nikolaidis, Firstly, we would like to thank the reviewers for the constructive feedback provided on the submitted manuscript. All amendments have been highlighted within the manuscript in red text. An itemised, point-by-point response to the comments of the reviewers follows: Reviewer 1 comments General comments The aim of the present review manuscript was to compare continuous and interval training in regards to their efficacy to improve VO2max in well-trained runners. The authors concluded that the positive effects of interval training on well-trained runners' VO2max remains equivocal. The review is well designed and well written. Moreover, in the present review, was introduced a novel method to evaluate training load. However, the authors should respond in a couple of major comments listed below. Response: We would like to thank the reviewer for their comments. We are pleased the reviewer found the present review, and the novel method of training-load analysis in particular, to add to the current body of knowledge, and appreciate the suggestions provided to

improve the manuscript.

Abstract
The authors conclude (lines 34-35) that in the present review they propose a novel method of training-load analysis "the training impulse". The authors should include some information regarding the proposed new method for calculating training load.
Response:
We thank the reviewer for this suggestion. A brief explanation of how the training load was calculated has been provided earlier in the abstract by stating: "… by calculating the time accumulated in certain intensity domains throughout a training intervention." (Lines 31-32).

Introduction, lines 67-88
The authors should consider re-writing this section because it is not clear which methodology was adopted in each presented review-manuscript. For instance, the study of Midgley et al. (25) was included both continuous and interval training? Additionally, in line 72, the near identical interval training in which research was adopted?
Response: We thank the reviewer for this suggestion. This section of the introduction has been restructured to improve clarity when comparing the implemented interval-training interventions in the research studies referenced (Lines 70-82).

Materials and Methods, Training load quantification, line 197
In the present review, the authors are using a novel method for quantifying the load of a training intervention. Due to the originality of the method (i.e., training impulse), the authors should present the method giving more details and highlighting it throughout the review.
Response:
We thank the reviewer for highlighting this. Within this section, further details of how training load was quantified and used for subsequent analyses have been provided (Lines 212-221).

Reviewer 2 comments

General comments
This is an interesting paper that compared the effects of continuous and interval training on maximal aerobic power (VO2max) in well-trained athletes. This systematic review is well designed and provides a novel method for quantifying training load. I believe this study is within the scope of the journal and provides useful practical recommendations for other researchers, as well as for coaches. Please find next some comments about the manuscript that may be useful
Response: We are pleased the reviewer found this study of interest and appreciate the suggestions provided to improve the manuscript.

Specific comments
1) Throughout the manuscript the authors state that high intensity training would induce positive effects only in short-term interventions (for example Line 390) and that periodising training intensity is necessary. I think that these comments should be moderated because this systematic review was only consisted of studies with a duration of 4 to 8 weeks. Therefore, based on the available data, we do not know if the short-term interventions are superior to longer intervention durations. Moreover, I am not aware of any studies with a strong methodology (randomized controlled trials and crossover designs) proving that periodising training intensity is safer and offers greater adaptations than longer intervention durations of sustained training intensity. If I am missing such studies please add them in the Discussion, otherwise I think that the comments about periodization should be moderated too.
Response:
We thank the reviewer for this suggestion. We acknowledge that the results and conclusions drawn within this review are based on studies with interventions of only 4-8 weeks, as such this has been stated in the limitations section (Lines 585-589).
The periodisation of training intensity, specifically with reference to a polarised model, has been included as this model has been shown to be used most commonly in elite endurance populations (these have been referenced in the discussion) along with one experimental study (also referenced) showing greater adaptations following an interval-

training intervention using polarised training intensity distribution compared to other distribution models.

2) I believe it would be helpful for the reader if you defined the differences between elite, highly trained and well-trained runners.
Response:
The use of the terms “elite”, “highly trained”, and “well-trained” represent the same level of training status in this review and were only included due to previous studies using different terminology. To improve clarity and reduce confusion, all instances where terms other than “well-trained” have been used have been changed to “well-trained” throughout the manuscript for consistency.

3) Since this systematic review included only runners, caution should be advised when it comes to interpreting the results in other sports and endurance athletes (e.g., swimming, cycling). Maybe it could be added in the Limitations section.
Response:
We thank the reviewer for highlighting this point. This review does include only runners, and throughout the manuscript all interpretations and recommendations have been directed towards runners (and their coaches) with no reference that these findings could be applied to other endurance sporting disciplines. This has been acknowledged in the limitations section as per the reviewer’s recommendations. (Lines 581-583)

4) Figure 1. I believe the "records after duplicates removed" is confusing since the number of manuscripts is the same as in "Title and abstract analysis". I recommend that it should be changed to something like "Duplicate records removed n = 577". And the number of studies after removal of duplicates (n = 1018) could be added in the Study selection section too (Lines 152-162).
Response:
We agree that this could cause confusion. This has been amended as per the reviewer’s recommendations, along with the number of studies remaining after the removal of duplicates stated in-text in the Study selection section. (Lines 164-165)
5) Line 239: Table 2 I believe is a typo. Please change to Table 3.YWe thank the reviewer for bringing this to our attention. This is a typo and has been amended to state Table 3 (Line 258).

Reviewer 3 comments

General comments
This is an interesting manuscript entitled: "The dose-response relationship between interval-training and VO2max in well-trained endurance runners: A systematic review". There are two central findings that can be emphasized: i) 6 out of the 7 studies included in the systematic review reported no significant effect of IT on VO2max improvements in well-trained athletes; ii) however, a dose-response relationship seems to exist and based on the analysis conducted, the authors suggest that performing 2 to 3 interval-training sessions per week, at a work intensity of 100% sVO2max for repetitions > 2 min, accumulating > 15 min of total work per session at this intensity is suitable to optimally accumulate a high IT STRIMP. I believe that the study is of particular interest to the readers of the journal, with practical application in real-life conditions. The methods are adequately described in detail and limitations fairly acknowledged. Please find next some comments on the paper that could be useful:
Response:
My co-authors and I are pleased the reviewer found this study of interest and appreciate the suggestions provided to improve the manuscript.

Specific comments
Title: Since only runners were included in the final analysis, I think that this should be clearly stated in the title. The general term "endurance athletes" cannot be supported from this specifically designed systematic review on runners.
Response:
We agree with the reviewer’s comments, as such, the title does specify “endurance runners” and not endurance athletes, however, if this requires further clarity we can amend the title.

Third paragraph, second line: The authors state that "…athletes, with the initial training

	status known to contribute to the magnitude of V̇O2max improvements (6,10,14,15)". A large debate exists in the literature about the effect of the regression to the mean statistical artifact on such outcomes (effect of baseline measurement on the response to a training intervention) (see for instance PubMedID: 25823596, 27596985, 12797839). Response: We thank the reviewer for bringing this to our attention. To negate such debates, this statement has been removed from the paragraph (Lines 69-70). I think that it is necessary to define "elite", "highly trained", "well-trained" athletes even from the intro, because it becomes confusing to follow previous studies.YThe use of the terms “elite”, “highly trained”, and “well-trained” represent the same level of training status in this review and were only included due to previous studies using different terminology. To improve clarity and reduce confusion, all instances where terms other than “well-trained” have been used have been changed to “well-trained” throughout the manuscript for consistency. The authors state: "The IT interventions used within the abovementioned studies might not have provided the T@V̇O2max required to stimulate improvements…". How much is this stimulus? It should be somehow be clarified (even in general terms), otherwise it looks highly speculative. Response: We thank the reviewer for this suggestion. Previous work suggesting a stimulus accumulating >15 mins of T@VO2max per session has been referenced to improve clarity (Lines 82-86). Since 6/7 of the included studies also conducted Continuous Training protocols, it would be interesting to know what these protocols generally showed. I mean that we would more safely conclude if the lack of an effect is a matter of the training protocol or the training status of the participants. Response: We agree that this would help provide a stronger conclusion, however, the use of the TRIMP dose-relationship for the total training and interval-training performed aimed to provide this interpretation, specifically as it pertains to the interval training interventions performed which is the primary focus of the review. The continuous training protocols performed in 6/7 studies were very similar meaning the training effects observed can be attributed primarily to the interval training protocols performed. Participants: The authors state that runners exhibiting a V̇O2max greater than 60 mL/kg-1/min-1 were included. However, in the study by Ferley et al. (2013) the participants exhibited a lower baseline value. Response: The study by Ferley (2013) was included as the average VO2max and SD were marginally lower than 60 ml·kg-1·min-1 along with this value displaying no significant difference to the other training group in the study with a VO2max higher than 60. This has been acknowledged in the participant characteristics and quality assessment section of the results. (Lines 250-253). Figure 1: please check the n value of studies in the excluded ones under the title "records after duplicates removed". Response: We thank the reviewer for bringing this to our attention. The n value presented in the figure is correct, however, this has been amended to state the number of duplicate records removed, along with the number of studies remaining after the removal of duplicates stated in-text in the Study selection section. (Lines 164-165). Figure 3: please enlarge the legend boxes of the three intensities. Response: The figure legend has been amended as per the reviewer’s recommendations.

Title: The dose-response relationship between interval-training and $\dot{V}O_{2max}$ in well-trained endurance runners: A systematic review

Running Head: Dose-response relationship between interval-training and $\dot{V}O_{2max}$

Word Count: 7758

Abstract

Success in endurance running is primarily determined by maximal aerobic power ($\dot{V}O_{2max}$), fractional utilisation, and running economy (RE). Within the literature, two training modalities have been identified to improve $\dot{V}O_{2max}$; continuous training (CT) and interval-training (IT). The efficacy of IT to improve $\dot{V}O_{2max}$ in well-trained runners remains equivocal, as does whether a dose-response relationship exists between the IT training load performed and changes in $\dot{V}O_{2max}$. A keyword search was performed in 5 electronic databases. Seven studies met the inclusion criteria for this systematic review. The training impulse (TRIMP) was calculated to analyse relationships between training load and changes in $\dot{V}O_{2max}$, by calculating the time accumulated in certain intensity domains throughout a training intervention. Non-significant ($P > 0.05$) improvements in $\dot{V}O_{2max}$ were reported in 6 studies, with only one study reporting a significant ($P < 0.05$) improvement in $\dot{V}O_{2max}$ following the IT interventions. A relationship between the training session impulse of the interval-training performed (IT S_{TRIMP}) and $\dot{V}O_{2max}$ improvements was observed. The efficacy of IT to improve $\dot{V}O_{2max}$ in well-trained runners remains equivocal due to a lack research. Nevertheless, the novel method of training-load analysis demonstrates a relationship between the IT S_{TRIMP} and $\dot{V}O_{2max}$ improvements; providing practical application for the periodisation of IT within the training regime of well-trained distance runners.

Keywords: Running, Endurance, Training-impulse, Training-load, High-intensity

Introduction

Maximal aerobic power ($\dot{V}O_{2max}$) is an established determinant of endurance performance (1–5). Training methods to improve $\dot{V}O_{2max}$ are characterised in two modes: continuous training (CT) and interval training (IT) methods (6,7). CT methods consist of long durations of sub-maximal intensity exercise typically eliciting adaptations associated with oxygen utilisation (8). By contrast, IT methods consist of repeated higher intensity work durations (above or equal to the maximal steady state) interspersed with periods of recovery (light exercise or rest) typically eliciting adaptations associated with oxygen delivery (9–12).

The use of IT methods to improve $\dot{V}O_{2max}$ has increased in popularity with evidence showing the same if not greater improvements compared to CT methods (10,13,14). Training intensities at or close to $\dot{V}O_{2max}$ have been suggested to be optimal in improving $\dot{V}O_{2max}$ (15), with the total time spent at this intensity proportional to the increase in $\dot{V}O_{2max}$. Further supporting this, numerous studies and reviews have shown greater improvements in $\dot{V}O_{2max}$ utilising IT methods close to, or at an intensity eliciting $\dot{V}O_{2max}$ compared to CT methods matched for load (10,13,14,16–19). Interestingly, longer duration work intervals have been shown to elicit greater increases in $\dot{V}O_{2max}$ (10,14,20), as such work intervals maximally stress cardiorespiratory parameters by increasing the time spent at, or close to $\dot{V}O_{2max}$ (T@$\dot{V}O_{2max}$) to a greater extent than shorter work intervals, leading to greater adaptations (10,13,14,21–24). This suggests a dose-response relationship exists between T@$\dot{V}O_{2max}$ and improvements in $\dot{V}O_{2max}$, hence IT methods maximising T@$\dot{V}O_{2max}$ might elicit the greatest improvements in $\dot{V}O_{2max}$. The vast majority of evidence supporting this has primarily been reported in lesser-trained populations, meaning the efficacy of IT methods in well-trained populations is unclear.

A lack of conclusive evidence exists to support the efficacy of IT methods to improve $\dot{V}O_{2max}$ in well-trained endurance athletes. Midgley et al. (25) reviewed 23 studies for improvements in $\dot{V}O_{2max}$, RE, and lactate threshold (LT) in response to training interventions consisting of plyometric training, interval training, resistance training, and continuous training, of which, 14 included well-trained runners ($\dot{V}O_{2max}$ > 60 mL·kg^{-1}·min^{-1}). Only one study included in the review utilised IT in well-trained runners (*n* = 8; $\dot{V}O_{2max}$ = 71.2 ± 5 mL·kg^{-1}·min^{-1}), with runners performing 1 IT session per week for 4 weeks increasing to 3 IT sessions per week for another 4 weeks, consisting of 5 repetitions at 100% vVO_{2max} for 3 minutes separated by 3 minutes of rest at 50% vVO_{2max}, however no improvements in $\dot{V}O_{2max}$ were reported (26). In contrast, a study utilising a near identical IT intervention in well-trained runners ($\dot{V}O_{2max}$ = 61.5 ± 2.9 mL·kg^{-1}·min^{-1}) reported significant increases in $\dot{V}O_{2max}$, however, the sample size was low (*n* = 5) and therefore potentially underpowered (27). In a follow up study utilising this near identical IT intervention of 2 IT sessions per week for 4 weeks consisting of 5-6 repetitions at 100% vVO_{2max} for approximately 2-3 minutes at a work: rest ratio of 1: 2 in a larger sample size of well-trained runners (two groups: *n* = 9 in each group; $\dot{V}O_{2max}$ ≥ 60.1 mL·kg^{-1}·min^{-1}), no significant improvements in $\dot{V}O_{2max}$ were reported (28). The IT interventions used within the abovementioned studies might not have provided the T@$\dot{V}O_{2max}$ required to stimulate improvements in $\dot{V}O_{2max}$, with previous work in lesser-trained populations suggesting >15 mins of T@VO_{2max} accumulated per session to be effective in maximising VO_{2max} improvements (14,20), supporting the notion of a dose-response relationship. In well-trained endurance athletes a minimum training dose combining volume and intensity might need to be exceeded to elicit chronic adaptations in the cardiorespiratory parameters mediating $\dot{V}O_{2max}$ (25). In support of this, a 10-week IT intervention similar to that used previously (26,28) resulted in improvements in $\dot{V}O_{2max}$, albeit in lesser-trained runners ($\dot{V}O_{2max}$ = 51.6 ± 2.7 mL·kg^{-1}·min^{-1}) (29). The longer training intervention (10-weeks (29) vs 4-weeks (28) vs 8-weeks (26)) perhaps provided the accumulated T@$\dot{V}O_{2max}$ and training dose required to stimulate improvements in $\dot{V}O_{2max}$. Had the previous studies with similar IT protocols used longer interventions (26,28), improvements in $\dot{V}O_{2max}$ could have been observed due to the greater accumulated training load exceeding the minimum training dose required for improvements in $\dot{V}O_{2max}$ in these well-trained runners, however this remains speculative.

The efficacy of IT methods is well-established in lesser-trained populations (10,14), however, inconclusive evidence exists to support the effectiveness of IT methods to improve cardiorespiratory and metabolic factors in well-trained runners (6,25). The apparent dose-response relationship between training load and improvements in $\dot{V}O_{2max}$, perhaps offers a method of training load analysis that could be effective for well-trained runners aiming to improve $\dot{V}O_{2max}$. Therefore, this review aimed to analyse the volume and quality of the current evidence pertaining to the chronic effects of IT methods in well-trained runners on improving $\dot{V}O_{2max}$. A further aim was to analyse the dose-response relationship associated with the total load of IT and changes in $\dot{V}O_{2max}$.

Materials and methods

This systematic review was conducted according to the 'Preferred Reporting Items for Systematic Reviews and Meta-Analyses' (PRISMA) guidelines (30). All the following steps were implemented by three independent raters (AP, PH, TJ), with discrepancies and conflicts resolved by discussion.

Literature Search Strategy

Electronic database searches were carried out in PubMed, MEDLine, SPORTDiscus, CINAHL, and Web of Science. All searches were conducted between the 24th January 2019 and 12th April 2019. Searches were limited to papers published in English and from 1st January 1960 to 12th April 2019. Further searches on authors known by the investigators to have published papers using interval-training interventions in well-trained distance runners were conducted. Additionally, reference lists of all eligible studies were reviewed to identify potentially eligible studies that may have been missed. The following strategy using Boolean search terms and operators were used in each electronic database: ("Runners" OR "Endurance Runners" OR "Running" OR "Middle Distance" OR "Long Distance" OR "Marathon" OR "Well Trained" OR "Competitive" OR "Athlete" OR "Endurance Athlete" OR "Elite" OR "High Level") AND ("Interval Training" OR "High Intensity Interval Training" OR "High Intensity Interval Exercise" OR "HIIT" OR "HIIE" OR "Sprint Interval Training" OR "SIT" OR "Aerobic Interval Training" OR "Maximum Intensity Interval" OR Intermittent") AND ("VO2" OR "VO2 Max" OR "VO2 Peak" OR "Maximal Oxygen Uptake" OR "Aerobic Fitness" OR "Maximum Aerobic Capacity" OR "Maximum Oxygen Consumption" OR "Peak Oxygen Uptake" OR "Peak Oxygen Consumption" OR "Maximum Aerobic Power") NOT ("Cycling" OR "Swimming" OR "Rowing" OR "Skiing" OR "Soccer" OR "Football" OR "Basketball" OR "Untrained" OR "Recreational" OR "Clinical" OR "Obese" OR "Youth" OR "Adolescent" OR "Older").

Inclusion and Exclusion Criteria

To be eligible for inclusion, studies met each of the following inclusion criteria:

- Participants were adult well-trained runners
  - Well trained was defined as runners exhibiting a $\dot{V}O_{2max}$ greater than 60 $mL \cdot kg^{-1} \cdot min^{-1}$ or a performance score greater than 600 in the Mercier Scoring Tables (31). (Triathletes were included if they constituted a small proportion [less than 20%] of the population sample).
- The interval-training intervention lasted 4 weeks or longer, with a minimum of two interval sessions performed per week.
- Interval-training interventions consisted of running only.
- Interval-training interventions reported the intensity, volume and duration of the work and relief periods used throughout the intervention.
- The intensity of the work interval was greater than the lactate turn point / second ventilatory threshold (VT_2) / maximal lactate steady state (MLSS).
- Continuous training during the intervention was below the LT / first ventilatory threshold (VT_1) with the intensity, volume and duration reported.
- Data on $\dot{V}O_{2max}$ values pre- and post-training intervention were reported in addition to one or more of the following physiological variables: speed at $\dot{V}O_{2max}$ ($s\dot{V}O_{2max}$) speed at LT (sLT), running economy (RE), peak treadmill speed, time-trial performance, time to exhaustion (TTE).
- Published in an indexed peer-reviewed journal.

Studies were excluded if any of the following criteria applied:

- Not published in English
- Participants were non-runners (e.g. students, cyclists, recreationally trained, team-sport athletes etc.)
- Participants were reported to be in poor health and/or suffering from any kind of acute or chronic diseases.
- Strength training and/or continuous training above LT / VT_1 was included.
- Interval-training interventions were performed using an incline and / or hypoxic conditions.

- The characteristics of the interval-training interventions implemented (e.g. repetition number, intensity used, relief durations etc.) were not reported in enough detail to calculate the training load for comparisons between studies to be made.
- Ergogenic aids were used as part of the intervention.

Figure 1

Study Selection

Figure 1 provides a schematic overview of the study identification, screening approach and selection process. Search results were imported into a published software for systematic reviews (32), allowing a blinded screening process to be performed by the three independent reviewers (AP, PH and TJ). Conflicted decisions were resolved through discussion of the full-text until a consensus was reached. The initial search yielded 1588 results which increased to 1595 following addition of records identified through authors and reviewing references known to be relevant. The publication titles and abstracts remaining after the removal of duplicates (n = 1018) were screened independently by the reviewers for eligibility [inter-rater reliability (IRR): 98.4%, Fleiss' k = 0.48]. Following this screening, 29 potentially eligible studies were given full consideration, with the full-texts of each reviewed for inclusion. Of the 29 potentially eligible studies (Figure 1), a total of 7 studies meeting the criteria remained for further analysis.

Analysis of Results

A quality checklist for Randomised Controlled Trials (RCT) and Observational Studies modified by Kennelly (33) based on the Downs and Black Methodological Quality checklist (34) was used to assess quality of the 7 remaining studies. This modified version was used due to the inclusion of non-randomized and observational studies, as many of the items relating to the blinding of studies within the original Downs and Black checklist were therefore not appropriate. When scoring the quality of the study, the checklist is split into 5 sections with a total score provided from each: Reporting (items 1-12), External Validity (items 13-16), Internal Validity – bias (items 17-25), Internal Validity –

confounding (items 26-32), and Power (item 33). Studies are able to attain a total score of 32 with the total score indicating the quality (≥20 = good, 15-19 = fair, ≤14 = poor) (33).

Data Extraction

Data Extraction was performed by one investigator (AP) using a standardized form to allow the extraction of relevant study characteristics. The data extracted from each study were:

- Study characteristics (author(s), title, year of publication).
- Participant characteristics (number of participants, age, stature, body mass, training level). Training intervention characteristics (duration, frequency, total training time, IT work intensity, IT work duration, IT relief intensity, IT relief duration, total number of intervals, CT intensity, CT duration.
- Total time spent in intensity domains and as a percentage of the total training time (below VT_1/2mmol·L^{-1} BLa^-, between VT_1/2mmol·L^{-1} and VT_2/4mmol·L^{1} BLa^-, between VT_2/4mmol·L^{-1} BLa^- and s$\dot{V}O_{2max}$, and above s$\dot{V}O_{2max}$).
- Training load characteristics (Total intervention training impulse overall [TOT_{TRIMP}], per week [W_{TRIMP}] and per session [S_{TRIMP}]. Interval-training impulse overall [IT TOT_{TRIMP}], per week [IT W_{TRIMP}] and per session [IT S_{TRIMP}]).
- Average intervention training intensity scaled to the s$\dot{V}O_{2max}$, interval-training intensity scaled to the s$\dot{V}O_{2max}$.
- Training response (initial $\dot{V}O_{2max}$, post-training $\dot{V}O_{2max}$, change in $\dot{V}O_{2max}$, total TRIMP units to change $\dot{V}O_{2max}$ by 1 mL·kg^{-1}·min^{-1}, IT TRIMP units to change $\dot{V}O_{2max}$ by 1 mL·kg^{-1}·min^{-1}, significance of change).

$\dot{V}O_{2max}$ values were reported as mL·kg^{-1}·min^{-1} in all cases, along with the standard deviation of all variables reported. Where standard errors were reported, these were converted into standard deviation. The total training time and time spent in each intensity domain was reported in hours, minutes and seconds (h:min:s).

Training load quantification

Training load in each intervention was estimated by calculating a modified version of the training impulse (TRIMP), commonly referred to as Lucia's' TRIMP (35,36). This method of calculating TRIMP has also been previously used to estimate training load in well-trained endurance runners (37,38). The TRIMP score was calculated by multiplying the accumulated training duration spent in each intensity domain by an intensity-weighted multiplier. For example; 1 min in the first intensity domain [$<VT_1$] is given a score of 1 arbitrary unit (AU), 1 min in the second intensity domain [$>VT_1$ $<VT_2$] is given a score of 2 AU, and 1 min in the third intensity domain [$>VT_2$] is given a score of 3 AU. The total TRIMP score is then obtained by summing the results of the three intensity domains. The total TRIMP was calculated for the total duration of a training intervention (TOT_{TRIMP}), the weekly TRIMP of a training intervention (W_{TRIMP}), and the TRIMP of a training session (S_{TRIMP}). To further investigate the effects of only the interval-training interventions, the TRIMP of only the interval-training performed in each study was calculated for the total training intervention duration (IT TOT_{TRIMP}), the weekly interval-training performed (W_{TRIMP}), and the TRIMP of an interval-training session (IT S_{TRIMP}). The calculated TRIMP scores were then expressed relative to changes in VO_{2max} to examine if a dose-response relationship exists between training load and changes in VO_{2max} for all training performed throughout an intervention and the effects of only the interval-training performed throughout an intervention.

To determine the training intensity in each study and to allow comparisons to be made between studies, intensity was scaled to the reported average $s\dot{V}O_{2max}$, with $s\dot{V}O_{2max}$ being 1. For example, if the reported training intensity for the interval work duration was 90% of $s\dot{V}O_{2max}$, then the intensity was calculated as 0.9. These scaled intensities were subsequently used to examine relationships between the training intensities used in each study and changes in $\dot{V}O_{2max}$.

Main Analysis

Effect sizes (Hedges' g) were calculated for pre- and post-training $\dot{V}O_{2max}$ values for each study individually without an overall pooled effect. Hedges' g was used to bias correct for the typically small sample sizes, as observational studies were primarily included with no control groups. The pooled standard deviation for Hedges' g was calculated using the root mean square of the pre- and post-group standard deviations. This version does not specifically include the sample size (*n*), preventing any complications that could arise from inflating *n* when both group's means are from the same sample. This statistical approach was chosen due to data being from the same sample rather than a separate intervention and control group, thus making a traditional weighted effects meta-analysis pooling inappropriate. Traditional meta-analysis assumes two different sets of individuals in each group (39) meaning a violation of underlying assumptions would have occurred if applied to this review. 95% confidence intervals were calculated for individual Hedges' g effect sizes. A forest plot of the individual effect sizes with 95% confidence intervals was created to display the pre-post $\dot{V}O_{2max}$ responses to the training intervention (Figure 2). The qualitative inferences associated with the calculated effect sizes were defined as *trivial* (<0.2), *small* (0.2-0.6), *moderate* (0.6-1.2), *large* (1.2-2.0), *very large* (2.0-4.0), and *nearly perfect* (>4.0) (40). As the data extracted from the included studies were from the same sample rather than a separate intervention and control group, it was deemed unsuitable to amalgamate the results for a meta-analysis. The results in this review were therefore analysed narratively.

Figure 2

Results

Participant Characteristics and Quality Assessment

A summary of the participant characteristics and the quality assessment results for the studies included in this review are displayed in Table 1. Seven studies with a total of 62 participants met the inclusion criteria for this review. One study included runners with an average VO_{2max} and SD marginally lower than 60 $ml \cdot kg^{-1} \cdot min^{-1}$ (44) as this group (VO_{2max} = 59.4 ± 8.9 $ml \cdot kg^{-1} \cdot min^{-1}$) displayed no significant difference to the other training group with a VO_{2max} value greater than 60 $ml \cdot kg^{-1} \cdot min^{-1}$ (63.3 ± 8.0 $ml \cdot kg^{-1} \cdot min^{-1}$). Differences in the quality assessment scores were mainly in the external validity and confounding sections of the assessment. All studies scored 0 as it relates to the calculation of statistical power.

Table 1

Training Intervention

A summary of the training characteristics implemented in the 7 studies are displayed in Table 3. In all studies, interval-training interventions lasted between 4- and 8-weeks, with sessions performed 2 to 3 times per week (27,28,41–45). Supplementary continuous training sessions were included in 6 studies 1 to 3 times per week (27,28,41–44), with one study not including any continuous training (45).

Maximal Aerobic Power

Only one study (27) reported a *large*, significant increase of 4.9% in $\dot{V}O_{2max}$ in response to the training intervention (ES: 1.86, P = 0.007). Non-significant, *trivial* changes in $\dot{V}O_{2max}$ of less than 0.7% (ES: 0.02 - 0.06) were reported in 4 studies (42–45). Smith et al. (28) reported *nearly perfect*, non-significant increases in $\dot{V}O_{2max}$ of 5.9% (ES: 5.33) and 4.2% (ES: 7.02) in the 60% of the time to exhaustion (TTE) and 70% TTE experimental groups, respectively. Only one study (41) reported a non-significant, *trivial* decrease in $\dot{V}O_{2max}$ of -0.9% (ES: 0.14) (Table 2).

Table 2

Continuous Training

In all studies including supplementary continuous training, sessions were performed at 60-75% s$\dot{V}O_{2max}$ for 0:30:00 – 1:00:00, 1 to 3 times per week (Table 3).

Interval Training characteristics

Work Intensity

The lowest intensity for the work period was prescribed as the median speed between the sLT and s$\dot{V}O_{2max}$ (sΔ50) (41–43). The s$\dot{V}O_{2max}$ was prescribed as the work intensity in 3 studies (27,28,44). The highest work intensity was prescribed as 90-100% maximum effort sprints in 1 study (45) (Table 3).

Work Duration

The longest work durations were prescribed as 50% TTE at sΔ50 (41–43). Work durations were prescribed as 60-75% TTE at s$\dot{V}O_{2max}$ in studies using s$\dot{V}O_{2max}$ as the intensity (27,28,44). The shortest work durations were prescribed as 5-15 s, 90-100% maximum effort sprints over 40-100m (45) (Table 3).

Relief Intensity

Static rest was prescribed as the relief intensity in 3 studies using s$\dot{V}O_{2max}$ as the work intensity (27,28,44). Active relief periods were prescribed as 50% s$\dot{V}O_{2max}$ in the 3 studies using sΔ50 as the work intensity (41–43), and walking or jogging back to the start of a sprint effort in one study (45) (Table 3).

Relief Duration

The shortest relief durations of 25% TTE at sΔ50 were prescribed in 3 studies using sΔ50 as the work intensity (41–43). Relief durations prescribed as the time taken to recover to 65% HR_{max} were almost equal to the work durations in one study using s$\dot{V}O_{2max}$ as the work intensity (44). The relief duration was prescribed as a 1: 2 work: rest ratio in 2 studies using s$\dot{V}O_{2max}$ as the work intensity (27,28). In the one study using sprint efforts (45), relief durations were prescribed as progressively declining work: rest ratios throughout the training intervention of 1: 5, 1: 4, and 1: 3 (Table 3).

Interval-Training Duration

Repetitions

The higher the work intensity the greater number of repetitions performed per training session and throughout the study intervention. In the only study using sprint efforts (45) the highest repetitions per training session (n = 22) and in total (n = 412) were performed over the 6-week intervention. The lowest repetitions per training session (n = 2-4) and in total (n = 37-64) were performed in the 3 studies using the lowest work intensity of sΔ50 (41–43). In the 3 studies using s$\dot{V}O_{2max}$ as the work intensity (27,28,44), repetitions performed per training session (n = 5-6) and in total (n = 40-60) were similar (Table 3).

Table 3

Duration

The average training session durations were longest (0:33:00 – 0:40:00) in the two 4-week studies using $s\dot{V}O_{2max}$ as the work intensity (27,28), along with the highest average time spent at the work intensity per session (0:13:00 – 0:15:00). Two studies using $s\Delta50$ (41,42) and the 6-week study using $s\dot{V}O_{2max}$ as the work intensities (44) had the shortest average training session durations (0:12:00 – 0:20:00), with equal average time spent at the work intensity per session (0:11:00). The shortest average time spent at the work intensity per session (0:04:00) was in the only study using sprint efforts as the work intensity (45), despite a relatively long average training session duration of 0:33:00 (Figure 3A).

The total time at the work intensity increased as the prescribed intensity decreased over the duration of the training intervention. In the 8-week studies using the lowest work intensity of $s\Delta50$ (41–43) the total time at the work intensity was highest (3:00:00 – 4:20:00). The total time spent at the work intensity was lowest (1:10:00) in the 1 study using the highest work intensity of sprint efforts for 6-weeks (45) (Figure 3A).

The total training volume was highest (25:30:00 – 30:30:00) in the 8-week interventions using $s\Delta50$ as the work intensity (41–43) and lowest (3:40:00 – 4:00:00) in the 4-week studies using $s\dot{V}O_{2max}$ as the work intensity (27,28) (Figure 3A).

Training Load

Total Training Impulse per week (W_{TRIMP})

The total W_{TRIMP} increased as the work intensity prescribed decreased, with the 3 studies using the lowest work intensity of $s\Delta50$ over the 8-week intervention (41–43) having the highest total W_{TRIMP} (237-294 $AU \cdot wk^{-1}$). In contrast, the 6-week study with the highest work intensity of sprint efforts (45) had the lowest total W_{TRIMP} of 123 $AU \cdot wk^{-1}$ (Figure 3B).

Interval Training Impulse per week (IT W_{TRIMP})

The training impulse score per week for only the interval-training performed (IT W_{TRIMP}) was lowest (67-80 $AU \cdot wk^{-1}$) in two of the 8-week intervention studies using sΔ50 for the work intensity (41,43), accounting for 30% of the total W_{TRIMP}. In the two 4-week studies using $s\dot{V}O_{2max}$ for the work intensity (27,28) the IT W_{TRIMP} (118-140 $AU \cdot wk^{-1}$) was highest, accounting for 80% of the total W_{TRIMP}. The only study to use sprint efforts for the work intensity (45) had an IT W_{TRIMP} of 123 $AU \cdot wk^{-1}$ accounting for 100% of the total W_{TRIMP} as no continuous training was prescribed as part of the training intervention (Figure 3B).

Continuous Training Impulse per week (CT W_{TRIMP})

The training impulse score per week for the continuous training only (CT W_{TRIMP}) was lowest and identical (30 $AU \cdot wk^{-1}$) in the two 4-week studies using $s\dot{V}O_{2max}$ for the work intensity (27,28), with a CT TRIMP: IT TRIMP ratio of approximately 1: 4. The 8-week studies using sΔ50 for the work intensity (41–43) had the highest CT W_{TRIMP} (157-180 $AU \cdot wk^{-1}$), with a CT TRIMP: IT TRIMP ratio of approximately 2: 1 (Figure 3B).

Figure 3

Dose-response relationship

Training distribution and change in $\dot{V}O_{2max}$

Improvements in $\dot{V}O_{2max}$ decreased as the percentage of total training time spent $<VT_1$ increased (Figure 4A). In contrast, improvements in $\dot{V}O_{2max}$ increased as the percentage of total training time spent $>VT_2$ increased (Figure 4B). The greatest improvements in $\dot{V}O_{2max}$ (2.5-3.6 $mL \cdot kg^{-1} \cdot min^{-1}$) were reported in 2 studies (27,28) with the highest percentage of total training time $>VT_2$ (46.1% - 49.9%). By contrast, a decrease in $\dot{V}O_{2max}$ of -0.6 $mL \cdot kg^{-1} \cdot min^{-1}$ was reported in one study (41) with the lowest percentage of total training time $>VT_2$ (10.2%).

Figure 4

Training intensity and change in $\dot{V}O_{2max}$

Improvements in $\dot{V}O_{2max}$ decreased as the average total training intensity increased (Figure 5A1); however, if the sprint interval study is removed (45) (the only study to prescribe a work intensity above s$\dot{V}O_{2max}$), improvements in $\dot{V}O_{2max}$ increased as the average total training intensity increased (Figure 5A2). Similarly, improvements in $\dot{V}O_{2max}$ decreased as the work intensity prescribed increased (Figure 5B1). After removing the sprint interval study (45), improvements in $\dot{V}O_{2max}$ increased as the work intensity increased (Figure 5B2). When using aerobic intensities ≤s$\dot{V}O_{2max}$, greater improvements in $\dot{V}O_{2max}$ are shown with higher average total training intensities and higher interval-training intensities up to s$\dot{V}O_{2max}$ (Figures 5A2 & 5B2).

Figure 5

Total Training Load and change in $\dot{V}O_{2max}$

As the TOT_{TRIMP} and total W_{TRIMP} performed during the training interventions increased, improvements in $\dot{V}O_{2max}$ decreased (Figures 6A & 6C). By contrast, when displayed as the total TRIMP per training session (S_{TRIMP}), improvements in $\dot{V}O_{2max}$ increased as the total S_{TRIMP} increased (Figure 6D). The total TRIMP required to change $\dot{V}O_{2max}$ by 1 $mL \cdot kg^{-1} \cdot min^{-1}$ ($TRIMP \cdot mL \cdot kg^{-1} \cdot min^{-1}$) showed no clear relationship with the average total training intensity used throughout the training interventions (Figure 6B).

Figure 6

Interval-Training Load and change in $\dot{V}O_{2max}$

As the IT TRIMP performed during the training interventions increased, improvements in $\dot{V}O_{2max}$ decreased (Figure 7A). When displayed as the IT W_{TRIMP} and IT TRIMP per training session (IT S_{TRIMP}) however, improvements in $\dot{V}O_{2max}$ increased as the IT W_{TRIMP} and IT S_{TRIMP} increased (Figures 7C & 7D). The IT TRIMP required to change $\dot{V}O_{2max}$ by 1 $mL \cdot kg^{-1} \cdot min^{-1}$ (IT $TRIMP \cdot mL \cdot kg^{-1} \cdot min^{-1}$) increased with higher interval-training intensities (Figure 7B).

Figure 7

Discussion

This systematic review aimed to provide an updated evaluation of current evidence investigating the efficacy of interval-training interventions to improve $\dot{V}O_{2max}$ in well-trained, middle- and long-distance runners. A further aim was to examine if a dose-response relationship existed between the interval-training load and changes in $\dot{V}O_{2max}$ in a well-trained population. Empirical evidence to support the efficacy of interval-training to improve $\dot{V}O_{2max}$ in well-trained runners remains in the same inconclusive state as the review previously conducted by Midgley (25). A dose-response relationship might be evident, with a higher total load and individual session load correlating with greater increases in $\dot{V}O_{2max}$. Furthermore, intensities up to, but not exceeding s$\dot{V}O_{2max}$, performed for long durations (>2 min) provide the greatest stimulus for improvements in $\dot{V}O_{2max}$. These findings however, should be interpreted with caution due to the limited number of included studies with small sample sizes and relatively short training interventions (4-8 weeks). This might be due to the difficulties associated with overcoming the reluctance of this population to alter their training regime for extended periods (46). The quality of the studies included within this review are considered acceptable based on the quality checklist for RCT and Observational studies modified by Kennelly (33), with all studies displaying fair to good quality assessment scores (n = 19-26).

Training Intensity Distribution

The data analysed here indicate that interval-training interventions have little effect on changes in $\dot{V}O_{2max}$ in well-trained runners, contrary to previous findings reporting significant improvements in $\dot{V}O_{2max}$, albeit in lesser-trained populations (10,14,20). Nevertheless, the available data suggests increasing the percentage of total training time performed above VT_2 in comparison to the percentage of training time performed below VT_1 elicits greater improvements in $\dot{V}O_{2max}$, but only in short-term training interventions (< 8 weeks). Supporting the inclusion of high proportions of training performed at high intensities within a micro-cycle, top-class marathon runners have been shown to train at relatively higher velocities for more total kilometres per week than lower-level competitors, and exhibit significantly higher $\dot{V}O_{2max}$ values (47). Recent analyses have also reported the volume of training performed above VT_2 to be a predictor of world-class endurance running performance, with well-trained endurance runners performing high volumes of long intervals slightly above VT_2 (48,49). This conflicts the training intensity distribution (TID) of well-trained, elite-level endurance athletes who reportedly perform the majority of their training below VT_1 (approximately 80%), in comparison to the training performed above VT_2 (7,9,47,50–53). Previous observations of TID have been reported over longer training durations (8 weeks to a season) (7,50–53) than the study interventions presented here (4-8 weeks) (27,28,41–44) therefore, increased training time above VT_2 might be indicative of greater $\dot{V}O_{2max}$ improvements, but only in short-term training interventions (< 8 weeks). It is likely sustained durations of increased training intensity (> 8 weeks) are not conducive to performance improvements, particularly due to the high mechanical and neuromuscular demands associated with running at high velocities (50,54). Appropriately periodising training intensity is therefore necessary, with polarised TID models shown to elicit greater performance improvements without inducing signs of overtraining, even with an equal TRIMP, than other TID models (38,50,55–58).

Interval Intensity and Duration

The results of this review suggest short-term training interventions (4-6 weeks) with work intervals at $s\dot{V}O_{2max}$, sustained for long durations (>2 min) are the most effective in improving $\dot{V}O_{2max}$ in well-trained runners, so long as the intensity allows a sustained $T@\dot{V}O_{2max}$ to create a strong enough stimulus to elicit $\dot{V}O_{2max}$ improvements. Accumulating $T@\dot{V}O_{2max}$ in well-trained runners appears necessary as the studies that accumulated 13-16 min of running at $s\dot{V}O_{2max}$ per training session reported the greatest $\dot{V}O_{2max}$ improvements (27,28). In contrast, lesser $\dot{V}O_{2max}$ improvements were reported in the studies that accumulated running times per session of 10-16 min at $s\Delta50$ (41–43), 9-12 min at $s\dot{V}O_{2max}$ (44), and 4-min as 90-100% maximum sprint efforts (45). This supports previous recommendations that interval-training protocols accumulating ≥ 15 min of $T@\dot{V}O_{2max}$ per session are optimal to maximally stress cardiorespiratory parameters for $\dot{V}O_{2max}$ improvements in well-trained runners (20,23,59). Selecting appropriate intensities and durations to maximise $T@\dot{V}O_{2max}$ is highlighted by the contrasting improvements in $\dot{V}O_{2max}$ shown in the studies using $s\dot{V}O_{2max}$ as the work intensity (27,28,44). Greater improvements in $\dot{V}O_{2max}$ were reported in the two studies that accumulated more time (13-16 min) running at $s\dot{V}O_{2max}$ per training session (27,28) than the study accumulating less time per training session (9-12 min) (44), despite using the same work intensity of sVO_{2max}.

The lack of improvements in $\dot{V}O_{2max}$ reported in the studies using sΔ50 as the work intensity (41–43) suggests the duration and intensity might have been too low to evoke a maximal $\dot{V}O_2$ response and in turn stimulate improvements in $\dot{V}O_{2max}$. The use of sΔ50 to elicit a maximal $\dot{V}O_2$ response relies on the presence of a $\dot{V}O_2$ slow component (60), with Billat et al. (61) previously showing the time to reach $\dot{V}O_{2max}$ to be approximately 5-min when running at sΔ50. Moreover, well-trained runners have been shown to maintain a plateau in $\dot{V}O_2$ below $\dot{V}O_{2max}$ during exhaustive runs at sΔ50 (60). These data indicate sΔ50 is insufficient to provide the T@$\dot{V}O_{2max}$ required to maximally stress cardiorespiratory parameters in well-trained runners and in turn improve $\dot{V}O_{2max}$ (23,25,59). Conversely, the one study using maximal sprint efforts reported a *trivial* increase in $\dot{V}O_{2max}$ (45), indicating this to be too high an intensity to allow a maximal $\dot{V}O_2$ response to be sustained to stimulate improvements in $\dot{V}O_{2max}$. Such high intensities above s$\dot{V}O_{2max}$ limit the duration of the interval and in turn the ability to attain and sustain a maximal $\dot{V}O_2$ response, due to the greater contribution from anaerobic metabolism increasing the intramuscular accumulation of lactate and hydrogen ion production associated with fatigue (15,23).

The use of long duration interval repetitions (≥ 2 min) performed at 100% s$\dot{V}O_{2max}$, accumulating ≥ 15 min T@$\dot{V}O_{2max}$ per training session is therefore suggested to be optimal to maximally stress cardiorespiratory parameters in well-trained endurance runners. It should be noted that despite the data suggesting this to be optimal, $\dot{V}O_{2max}$ improvements were non-significant in the included studies; perhaps due to the small sample sizes increasing the probability of type 2 errors when using probability based statistics (62). Nevertheless, based on current evidence the efficacy of interval-training to improve $\dot{V}O_{2max}$ in well-trained runners remains equivocal.

Dose – response relationship

Total Training Load and changes in $\dot{V}O_{2max}$

In this study, data from the original studies have been used to calculate a TRIMP to evaluate the relationship between the TOT_{TRIMP} and changes in $\dot{V}O_{2max}$. This novel approach provides a different interpretation of this relationship that has not been presented in previous reviews. The present data show diminishing increases in $\dot{V}O_{2max}$ as the TOT_{TRIMP} increases, both throughout the duration of an intervention and when expressed as the total TRIMP per week (W_{TRIMP}). However, when the TOT_{TRIMP} is expressed per training session (S_{TRIMP}), greater S_{TRIMP} elicited greater increases in $\dot{V}O_{2max}$.

The diminishing increases in $\dot{V}O_{2max}$ with increasing TOT_{TRIMP} and W_{TRIMP} follow the relationship displayed between the total training time $<VT_1$ and changes in $\dot{V}O_{2max}$. This suggests the high TOT_{TRIMP} values and decreasing $\dot{V}O_{2max}$ improvements displayed are a result of the inclusion of high proportions of CT $<VT_1$. Performing such high proportions of CT $<VT_1$ reduces the average intervention intensity due to a potentially excessive accumulation of fatigue affecting the ability to perform and recover from IT sessions for improvements in cardiorespiratory parameters mediating $\dot{V}O_{2max}$ to occur. This contrasts previous observations and reports on TID in elite endurance athletes showing greater volumes of training performed $<VT_1$, with very little performed $>VT_2$; however, these observations have been reported over much longer training durations (7,38,50,51,53,63).

The greater increases in $\dot{V}O_{2max}$ with increasing S_{TRIMP} displayed here is in line with the reportedly rapid effects of interval training on physiology and performance, albeit with rapid plateau effects as well (53). This perhaps indicates improvements in $\dot{V}O_{2max}$ are elicited in the initial 4-8 weeks of interval-training interventions but only with high S_{TRIMP} in well-trained runners, supporting suggestions that intensities greater than sΔ50 are required to improve $\dot{V}O_{2max}$ in well-trained populations (6,23,25,64). Extending to longer training interventions might require lower S_{TRIMP} due to the accumulated load of repeatedly performing high-intensity interval-training sessions, in addition to the potential de-training of other aspects of performance (65,66), especially in well-trained runners performing high volumes of training (47,48,63). In support of this, the inclusion of 10% of the weekly running volume constituting intense interval training at 3km and 10km race pace over an 8-week period significantly improved $\dot{V}O_{2max}$ in well-trained marathon runners (67). The inclusion of this interval-training however, was accompanied with a decrease in the total weekly running volume to 90% of that performed previously. This indicates that in well-trained runners, increases in training intensity can potentially elicit improvements in $\dot{V}O_{2max}$ using short-term interventions. The total volume of training might need to be reduced to allow high intensities to be reached and to recover from the demands of these sessions, thereby reducing the TOT_{TRIMP} but maintaining or even increasing the S_{TRIMP}, as indicated by the present findings.

Periodising short-term, higher intensity training blocks into the training regime is therefore recommended to ensure continued performance improvements without compromising recovery and performance in the long-term.

Interestingly, the TRIMP units required to change $\dot{V}O_{2max}$ ($TRIMP \cdot mL \cdot kg^{-1} \cdot min^{-1}$) displayed little relationship with the average intervention intensity. This might be due to methodological differences of the interventions implemented in the included studies (total duration and inclusion of continuous training); with longer interventions displaying higher TOT_{TRIMP}, along with high volumes of CT increasing TOT_{TRIMP} further without improvements in $\dot{V}O_{2max}$. Despite this, it appears increases in average intervention training intensity reduce $TRIMP \cdot mL \cdot kg^{-1} \cdot min^{-1}$, but only up to $s\dot{V}O_{2max}$. This supports previous recommendations regarding increasing $T@\dot{V}O_{2max}$ by using 100% $s\dot{V}O_{2max}$ as the interval intensity for long durations (≥ 2-min) as this also maximises the total S_{TRIMP} (20,23,59). In addition, decreasing the total volume of training performed as CT below VT_1 reduces the TOT_{TRIMP} and the $TRIMP \cdot mL \cdot kg^{-1} \cdot min^{-1}$ in the short-term, perhaps providing greater recovery from IT sessions. This might therefore allow higher intensities to be sustained for longer durations during IT sessions, increasing the total average intervention intensity, $T@\dot{V}O_{2max}$, and in turn improvements in $\dot{V}O_{2max}$.

Interval-Training Load and changes in $\dot{V}O_{2max}$

The IT TIRIMP (IT TOT_{TRIMP}) performed throughout the study interventions shows diminishing improvements in $\dot{V}O_{2max}$ as the IT TOT_{TRIMP} increased. This is likely the result of the shorter interventions being more intense with less CT, whereas the longer interventions were less intense with more CT. To overcome this, the IT TRIMP per week (IT W_{TRIMP}) and the IT TRIMP per session (IT S_{TRIMP}) were calculated, both showing greater improvements in $\dot{V}O_{2max}$ as the IT W_{TRIMP} and IT S_{TRIMP} increased. This further supports the notion that high training loads accumulated through high-intensity interval-training sessions are required to improve $\dot{V}O_{2max}$ in well-trained runners. This is due to the ability to increase $T@\dot{V}O_{2max}$ and thereby maximally stress cardiorespiratory parameters (6,15,23,59). In line with this, the present data indicates the IT W_{TRIMP} and IT S_{TRIMP} are of greater importance in eliciting $\dot{V}O_{2max}$ improvements than the total W_{TRIMP} and S_{TRIMP}. This suggests the intensity during interval sessions to be the likely key driver of $\dot{V}O_{2max}$ adaptations, more so than the overall training load in short-term training interventions. It is recognised that $\dot{V}O_{2max}$ is predominantly limited by maximal cardiac output ($\dot{Q}_{max}$) (5,68). Changes in $\dot{Q}_{max}$ are primarily due to increases in stroke volume (SV), as HR_{max} displays little change in response to training, along with previous observations even reporting small decreases in HR_{max} (69–72). Increases in SV occur due to a mechanical overload of the ventricles through the filling and ejection of blood stimulating hypertrophy of the myocardium, with maximum filling pressure, and therefore maximum mechanical overload, occurring at $\dot{V}O_{2max}$ (69,70,73). This further supports the use of intensities at, or close to, $\dot{V}O_{2max}$ to provide the mechanical overload necessary to elicit improvements in $\dot{Q}_{max}$, and in turn $\dot{V}O_{2max}$.

Greater improvements in $\dot{V}O_{2max}$ with greater IT S_{TRIMP} were observed here, in well-trained runners. Studies using 100% s$\dot{V}O_{2max}$ as the interval intensity displayed greater IT S_{TRIMP} and improvements in $\dot{V}O_{2max}$ than studies using sΔ50 as the intensity. This suggests short-term training interventions aiming to improve $\dot{V}O_{2max}$ should increase the IT TOT_{TRIMP} by increasing the time spent running at 100% s$\dot{V}O_{2max}$ during IT sessions to provide the optimal stimulus for adaptation. This should be incorporated into the training regime however, by increasing both IT S_{TRIMP} rather than increasing the weekly volume of IT, and reducing the total running volume to allow recovery and reduce the risk of overtraining. While the importance of high total running volumes in well-trained distance runners is not to be dismissed (48,63), when the focus of training is to improve $\dot{V}O_{2max}$, the intensity of training is the predominant factor regulating improvements that can be optimised through interval-training. Supporting this, in well-trained endurance athletes, maximal (and near maximal) intensities (90-100% $\dot{V}O_{2max}$) have been suggested to be optimal in eliciting maximal SV values, increasing the time spent at $\dot{Q}_{max}$ (T@$\dot{Q}_{max}$) and therefore the cardiopulmonary stress (23,59). This is in line with the optimal intensity suggested to increase T@$\dot{V}O_{2max}$ during interval-training sessions; however, Seiler et al. (22) showed that an interval protocol enabling 90% HR_{max} to be sustained for 32-min induced greater increases in cardiorespiratory parameters than an interval protocol enabling 95% HR_{max} to be sustained for 16-min. While SV and $\dot{Q}$ were not measured, this raises the question as to whether slightly lower intensities may be optimal in increasing T@$\dot{Q}_{max}$, rather than higher intensities that increase T@$\dot{V}O_{2max}$. These findings were reported in recreational cyclists, therefore the intensity and mode of exercise might differ in well-trained runners (22). By contrast, maximal SV and $\dot{Q}$ values were elicited following an exhaustive exercise bout at 100% power at $\dot{V}O_{2max}$ (p$\dot{V}O_{2max}$), whereas an exhaustive bout at the power at Δ50 (pΔ50) was unable to elicit maximal SV and $\dot{Q}$ values in well-trained triathletes ($\dot{V}O_{2max}$ = 64 mL·kg^{-1}·min^{-1}) (74). Even though this was shown during exhaustive cycling, it is speculated that higher intensities are able to elicit maximal SV and $\dot{Q}$ responses in well-trained runners; thereby increasing T@$\dot{Q}_{max}$ and in turn T@$\dot{V}O_{2max}$, optimising the overall stimulus for $\dot{V}O_{2max}$ improvements. The use of IT methods appear to be effective in enabling intensities eliciting $\dot{Q}_{max}$ to be attained and sustained; thus providing the stimulus required to further improve $\dot{V}O_{2max}$ in well-trained runners.

In the studies using work intensities at 100% s$\dot{V}O_{2max}$ performed for long durations (> 2 mins), increases in $\dot{V}O_{2max}$ per IT TRIMP unit are greater than in studies using work intensities above (sprint efforts) and below (Δ50) s$\dot{V}O_{2max}$. This suggests interval intensities of 100% s$\dot{V}O_{2max}$ performed for long durations (> 2 mins) to be an optimal protocol to increase $\dot{V}O_{2max}$ in well-trained runners, with the lowest IT TRIMP units required to improve $\dot{V}O_{2max}$ (IT TRIMP·mL·kg^{-1}·min^{-1}). In contrast, the current data show work intensities below (sΔ50) and above (sprint efforts) s$\dot{V}O_{2max}$ would require more IT TRIMP·mL·kg^{-1}·min^{-1} for the same increase in $\dot{V}O_{2max}$. This indicates that higher volumes of interval-training would need to be performed either during individual training sessions or by including a greater frequency of interval-training sessions. Increasing the IT TRIMP by increasing the volume of running however, increases the risk of overtraining and injury, particularly due to high frequencies of running at high velocities limiting the recovery time available between training bouts (55,57). Furthermore, as evidence suggests sΔ50 to be an intensity unable to evoke maximal $\dot{V}O_2$ and $\dot{Q}$ responses in well-trained runners (60,74), it is speculated these sessions may be more characteristic of 'threshold' training where long durations of running are performed close to, or slightly above the maximal steady state, accumulating blood lactate concentrations of approximately 2-4 mmol·L^{-1} (7,52). Well-trained runners typically exhibit high fractional utilisation in addition to a high $\dot{V}O_{2max}$ allowing high but sub-maximal velocities, such as sΔ50, to be sustained (47,60,75,76); with well-trained endurance runners running at sΔ50 reportedly sustaining blood lactate concentrations comparable to that achieved during a 10-km race (9,60,75). Greater volumes of running at sΔ50 to increase the IT TRIMP would lead to well-trained runners performing higher volumes of 'threshold' training; however, this exerts a greater demand on the autonomic nervous system (55,77), endocrine system (63,78), and carbohydrate fuelling (50,79). This in turn restricts training time due to an increased recovery time and limited glycogen storing, increasing the risk of overtraining without offering further $\dot{V}O_{2max}$ improvements. This further supports the need to maximise the cardiorespiratory demand during training interventions to provide the optimal stimulus required to improve $\dot{V}O_{2max}$ in well-trained runners, without increasing the risk of overtraining and injury during such short-term interventions. It is therefore suggested to utilise 100% s$\dot{V}O_{2max}$ for repetition durations >2-min, accumulating >15-min of total work at this intensity to provide the greatest IT S_{TRIMP}, thereby maximising T@$\dot{V}O_{2max}$ and T@$\dot{Q}_{max}$ whilst reducing the IT TRIMP·mL·kg^{-1}·min^{-1} in well-trained runners.

Limitations

The limited number of studies included in this review highlights the lack of training studies in well-trained runners to establish the efficacy of interval-training, making it difficult to provide valid training recommendations in this population. This is likely due to the reluctance of well-trained runners to modify their training programmes for a significant period (46). Nevertheless, conclusions based on a systematic analysis of the literature can be made, but interpretations should be made within the limitations of this review. Furthermore, all recommendations and analyses presented within this review are only applicable to endurance running therefore caution is advised if these results are attempted to be applied to other endurance disciplines. For all studies included in the review, interpretations of the data are based predominantly upon probability values, however, these can be misleading due to the low sample sizes and the heterogeneity in the pool of participants studied. In addition, the recommendations and conclusions presented on how to periodise interval-training into the training regime are limited to the results and analyses of the short-term interventions (4-8 weeks) of the studies included in this review, with the absence of longer-term intervention studies not allowing comparisons to be made as to whether longer intervention durations elicit inferior or superior adaptations. A further limitation is related to the calculation of the training load within the included studies as no studies reported HR data during training sessions. Previous work supports the approach used here to calculate training load (80), however it is acknowledged that the calculation of training load and demarcation of training zones is based upon the intended prescription of the training interventions, which might differ to the actual physiological response evoked during the sessions. Arguably, the greatest limitation when interpreting the conclusions made is the lack of studies including more than one experimental group. This makes evaluating the efficacy of interval-training to improve $\dot{V}O_{2max}$ difficult due to the lack of a control group to compare training effects. It is acknowledged however, that including control groups within this population presents challenges due to well-trained runners potentially being unwilling to participate in a reduced training volume or intensity for a training block. Finally, the ecological validity of the training interventions implemented within the included studies is debateable, with evidence from a survey under review showing the interval sessions completed by runners differ to those implemented in study interventions (81). Consequently, the lack of research conducted on well-trained runners along with the questionable ecological validity, mean the conclusions drawn as it pertains to the efficacy of interval-training to improve $\dot{V}O_{2max}$ might be misleading. This is due to the interval-training methods prescribed in practice potentially resulting in different physiological responses compared to those reported in research.

Practical Applications

The novel TRIMP quantification presented in this review displays a relationship between a high IT TRIMP per session (IT S_{TRIMP}) and $\dot{V}O_{2max}$ improvements that coaches of well-trained runners can implement to optimise training adaptations during focussed interval-training blocks aiming to improve $\dot{V}O_{2max}$. The data presented herein suggests performing 2 to 3 interval-training sessions per week, at a work intensity of 100% $s\dot{V}O_{2max}$ for repetitions > 2 min, accumulating > 15 min of total work per session at this intensity to optimally accumulate a high IT S_{TRIMP}. Such protocols appear to maximise the $T@\dot{V}O_{2max}$ and $T@\dot{Q}_{max}$, thereby reducing the total interval-training TRIMP required to improve $\dot{V}O_{2max}$. The total running volume performed below VT_1 should be decreased in already well-trained runners during such periods of training intensification in the short-term (≤ 8 weeks) to appropriately balance training stress, recovery and adaptation. When the aim is to improve $\dot{V}O_{2max}$, the current data indicate short-term training blocks (≤ 8 weeks) prioritising the intensity of interval-training sessions and reducing the total volume of running are an effective means of improving $\dot{V}O_{2max}$. High-intensity training focussed on improving $\dot{V}O_{2max}$ should be periodised appropriately into the training regime over prolonged periods (> 8 weeks) due to the stress associated with high-intensity training, with a polarised TID model appearing to be effective in eliciting training adaptations without inducing signs of overtraining. Such short-term blocks of training intensification might not display the typical polarised TID observed in the long term, however, the reduction in running volume to accommodate the increase in intensity appears to be optimal for interval-training sessions to be performed at the necessary intensity, whilst also allowing for appropriate recovery and adaptation.

Conclusions and Future Research

In conclusion, the available evidence is insufficient to unequivocally support the efficacy of interval-training to improve $\dot{V}O_{2max}$ in well-trained runners. The novel method of analysis used here for the first time has quantified the IT across different studies and has shown that a dose-response relationship appears to be evident, perhaps providing a guide as to the minimal dose required to improve $\dot{V}O_{2max}$. The lack of research supporting the use of interval-training in well-trained runners warrants further research to elucidate the effectiveness of these training methods, with particular reference to the training intensity and total training load required to improve $\dot{V}O_{2max}$. Furthermore, future research should aim to include interval-training protocols performed by well-trained runners with more than one experimental group to allow confident conclusions to be drawn, and in turn provide worthwhile recommendations to researchers and practitioners alike.

This review provides an updated systematic analysis of the literature to date regarding the use of interval-training methods to improve $\dot{V}O_{2max}$ in well-trained middle- to long-distance runners. The dose-response relationship evident between the IT S_{TRIMP} and changes in $\dot{V}O_{2max}$ suggest this novel method to be a useful metric coaches can implement to optimise the interval-training protocols prescribed. Evidence from this review suggests interval-training interventions performed at 100% $s\dot{V}O_{2max}$ for repetitions >2 min, accumulating >15 min of total work per session at this intensity maximise the T@$\dot{V}O_{2max}$ and T@$\dot{Q}_{max}$, reducing the interval-training load required to improve $\dot{V}O_{2max}$ in well-trained runners.

Acknowledgements

Not applicable

Disclosure of Interest

The authors report no conflicts of interest

Funding

Not applicable

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Tables

Table 1 – Participant characteristics (Mean ± SD) and quality assessment results of each study.

Study	Participant Characteristics						Quality Assessment						
	n	**Sex**	**Age (years)**	**Stature (cm)**	**Mass (kg)**	**Training level**	**Reporting**	**External Validity**	**Internal Validity - Bias**	**Internal Validity - Confounding**	**Power**	**Total Quality Score**	**Qualitative Inference**
Demarle et al. 2001	6	Not Reported	27 ± 5.1	174.2 ± 2.9	68.5 ± 5.4	Endurance trained, middle- and long-distance runners	9	1	7	2	0	19	Fair
Slawinski et al. 2001	6	Not Reported	27 ± 4	175 ± 6	72 ± 9	Well-trained runners	9	1	7	2	0	19	Fair
Ferley et al. 2013	12	M&F	27.4 ± 3.8	173.6 ± 6.4	66 ± 7.1	Well-trained club runners	12	4	5	5	0	26	Good
Garcin et al. 2002	8	M	20.1 ± 4	176 ± 5.1	62.5 ± 5.1	High-level endurance-trained runners	11	1	7	3	0	22	Good
Bickham et al. 2004	7	M	27 ± 6.9	Not Reported	77.1 ± 9.8	Endurance trained distance runners	10	2	7	2	0	21	Good
Smith et al. 1999	5	M	22.8 ± 4.5	181 ± 4.7	74.1 ± 3.2	Well-trained middle-distance state-level runners	9	1	7	2	0	19	Fair
Smith et al. 2003	60% TTE: 9 70% TTE: 9	Not Reported	25.2 ± 0.2	178.8 ± 0.3	72.2 ± 0.3	Well-trained competitive middle-distance, triathlete, 10km runners	12	2	5	4	0	23	Good

TTE Time to exhaustion

Table 2 – The $\dot{V}O_{2max}$ response to the training intervention used along with statistical interpretation is displayed (Mean ± SD).

Study	Training response						
	Initial VO_{2max} (ml·kg^{-1}·min^{-1})	**Post VO_{2max} (ml·kg^{-1}·min^{-1})**	**% change**	**Sig**	**Effect Size (Hedges' g)**	**95% CI for Effect Size**	**Qualitative inference**
Demarle et al. 2001	61.2 ± 6.6	61.6 ± 5.4	+0.65%	NS	0.05	-1.08 to 1.18	Trivial
Slawinski et al. 2001	61.2 ± 6	61.6 ± 4.9	+0.65%	NS	0.06	-1.07 to 1.19	Trivial
Ferley et al. 2013	59.4 ± 8.9	59.6 ± 7.6	+0.34%	NS	0.02	-0.78 to 0.82	Trivial
Garcin et al. 2002	64.8 ± 3.6	64.2 ± 3.8	-0.92%	NS	-0.14	-1.12 to 0.84	Trivial
Bickham et al. 2004	60.1 ± 3.2	60.3 ± 5.3	+0.33%	NS	0.04	-1.01 to 1.09	Trivial
Smith et al. 1999	61.46 ± 1.3	64.45 ± 0.9	+4.86%	0.007	1.86	0.38 to 3.35	Large
Smith et al. 2003 60% TTE group	60.5 ± 0.6	64.1 ± 0.6	+5.95%	NS	5.33	3.36 to 7.3	Nearly Perfect
Smith et al. 2003 70% TTE group	60.1 ± 0.2	62.6 ± 0.4	+4.16%	NS	7.02	4.55 to 9.49	Nearly Perfect

Sig Significance; *NS* Not Significant (*P*>0.05); *95% CI* 95% Confidence Interval

Table 3 – Training intervention characteristics of each study (Mean ± SD).

Study	Total Training Characteristics		Interval Training characteristics					Continuous Training characteristics	
	Duration	Frequency	Work Intensity (km·h^{-1})	Work Duration (s)	Relief Intensity (km·h^{-1})	Relief Duration (s)	Total Intervals	Intensity (km·h^{-1})	Duration (mins)
Demarle et al. 2001	8 weeks	2 IT/wk 3 CT/wk	sΔ50: 17 ± 0.9	50% TTE sΔ50: 294 ± 49	50% sVO_{2max}: 9.1 ± 0.2	25% TTE sΔ50: 147 ± 24	37.2 ± 7.8	60-70% sVO2max: 11.8 ± 0.5	45 – 60
Slawinski et al. 2001	8 weeks	2 IT/wk 3 CT/wk	sΔ50: 17 ± 0.7	50% TTE sΔ50: 294 ± 45.5	50% sVO_{2max}: 9.1 ± 0.3	25% TTE sΔ50: 147 ± 22.7	53.2 ± 7.9	60-70% sVO2max: 11.8 ± 0.4	60
Ferley et al. 2013	6 weeks	2 IT/wk 2 CT/wk	100% sVO_{2max}: 17.3 ± 2.1	60% TTE sVO_{2max}: 136 ± 36.7	Rest	HRR to 65% HRmax: 142 ± 45.4	60	75% sVO_{2max}: 12.9 ± 1.6	45 – 60
Garcin et al. 2002	8 weeks	2 IT/wk 3 CT/wk	sΔ50: 19.5 ± 1.0	50% TTE sΔ50: 162.5 ± 52	50% sVO_{2max}: 10.3 ± 1.0	25% TTE sΔ50: 81.2 ± 26	64	65-75% sVO_{2max}: 14.4 ± 1.0	60
Bickham et al. 2004	6 weeks	3 IT/wk	90-100% max effort sprints	5-15s, 40-100m	Walk or jog	Work:Rest - 1:5, 1:4, 1:3 5 mins between sets	412	None performed	None performed
Smith et al. 1999	4 weeks	2 IT/wk 1 CT/wk	100% sVO_{2max}: 20.5 ± 0.39	60-75% TTE sVO_{2max}: 135.3 ± 9.96 to 169.1 ± 12.45	Rest	Work:Rest - 1:2 60-75% TTE: 270.6 ± 19.92 to 338.2 ± 24.9	48	60% sVO_{2max}: 12.3 ± 0.23	30
Smith et al. 2003 60% TTE group	4 weeks	2 IT/wk 1 CT/wk	100% sVO_{2max}: 19.1 ± 0.13	60% TTE sVO_{2max}: 133.4 ± 1.4	Rest	Work:Rest - 1:2 266.8 ± 2.8	48	60% sVO_{2max}: 11.46 ± 0.13	30
Smith et al. 2003 70% TTE group	4 weeks	2 IT/wk 1 CT/wk	100% sVO_{2max}: 19.9 ± 0.4	70% TTE sVO_{2max}: 154 ± 4.5	Rest	Work:Rest = 1:2 308 ± 9	40	60% sVO_{2max}: 11.94 ± 0.4	30

wk week; *IT* Interval training; *CT* Continuous training; $s\dot{V}O_{2max}$ speed at $\dot{V}O_{2max}$; *sΔ50* median speed between the sLT and $s\dot{V}O_{2max}$; *TTE* Time to exhaustion; *HRR* Heart rate recovery; HR_{max} age predicted maximum heart rate.

Figure Legends

Figure 1 – Schematic overview of search, screening approach and selection process for suitable studies

Figure 2 – Forest plot of the pre- to post-$\dot{V}O2max$ scores in response to the training intervention implemented in each study, displayed as the bias corrected hedge's effect size with 95% confidence intervals.

Figure 3 - Panel A: Total duration of training performed in the interventions implemented by each study and the distribution of training within each intensity domain. Total training duration is displayed at the end of each stacked column in h, min and s (h:min:s). The time spent in each intensity domain is displayed above each respective section of the stacked column (h:min:s). $<VT_1$: Domain 1 – Below the first ventilatory threshold; $> VT_2 < sVO_{2max}$: Domain 3 - between the second ventilatory threshold and the velocity at maximal aerobic power; $> sVO_{2max}$: Domain 4 - above the velocity at maximal aerobic power. **Panel B**: Total training impulse per week (W_{TRIMP}) of the training interventions implemented by each study with the total W_{TRIMP} split into the interval training (IT) TRIMP and continuous training (CT) TRIMP per week. Total W_{TRIMP} is displayed at the end of each stacked column. The IT W_{TRIMP} and CT W_{TRIMP} is displayed above each respective section of the stacked column.

Figure 4 – **Panel A**: The relationship between the percentage of total training time spent below VT_1 and the change in $\dot{V}O_{2max}$ (Δ $\dot{V}O_{2max}$) in the training intervention implemented in each study. Linear regression line, regression equation and R^2 value displayed for the relationship between the percentage of training time below VT_1 and the Δ $\dot{V}O_{2max}$. *denotes statistically significant change in $\dot{V}O_{2max}$. **Panel B**: The relationship between the percentage of total training time spent above VT_2 and the change in $\dot{V}O_{2max}$ (Δ $\dot{V}O_{2max}$) in the training intervention implemented in each study. Linear regression line, regression equation and R^2 value displayed for the relationship between the percentage of training time

above VT_2. *denotes statistically significant change in $\dot{V}O_{2max}$. Legend with coloured boxes relates to all panels to signify each study.

Figure 5 - Panel A1: The relationship between the average intensity of the total training intervention implemented in each study and the change in $\dot{V}O_{2max}$ (Δ $\dot{V}O_{2max}$). Average intervention intensity is calculated scaled to the speed at $\dot{V}O_{2max}$ ($s\dot{V}O_{2max}$) with $s\dot{V}O_{2max}$ being 1. Linear regression line, regression equation and R^2 value displayed for the relationship between the average intervention intensity and the Δ $\dot{V}O_{2max}$. *denotes statistically significant change in $\dot{V}O_{2max}$. **Panel B1**: The relationship between the prescribed intensity of the interval training work period implemented in each study and the change in $\dot{V}O_{2max}$ (Δ $\dot{V}O_{2max}$). Interval intensity is calculated scaled to the speed at $\dot{V}O_{2max}$ ($s\dot{V}O_{2max}$) with $s\dot{V}O_{2max}$ being 1. Linear regression line, regression equation and R^2 value displayed for the relationship between the interval intensity and the Δ $\dot{V}O_{2max}$. *denotes statistically significant change in $\dot{V}O_{2max}$. **Panel A2**: The relationship between the average intensity of the total training intervention implemented in each study and the change in $\dot{V}O_{2max}$ (Δ $\dot{V}O_{2max}$) excluding data from Bickham & Le Rossignol (2004). Average intervention intensity is calculated scaled to the speed at $\dot{V}O_{2max}$ ($s\dot{V}O_{2max}$) with $s\dot{V}O_{2max}$ being 1. Linear regression line, regression equation and R^2 value displayed for the relationship between the average intervention intensity and the Δ $\dot{V}O_{2max}$. *denotes statistically significant change in $\dot{V}O_{2max}$. **Panel B2**: The relationship between the prescribed intensity of the interval training work period implemented in each study and the change in $\dot{V}O_{2max}$ (Δ $\dot{V}O_{2max}$) excluding data from Bickham & Le Rossignol (2004). Interval intensity is calculated scaled to the speed at $\dot{V}O_{2max}$ ($s\dot{V}O_{2max}$) with $s\dot{V}O_{2max}$ being 1. Linear regression line, regression equation and R^2 value displayed for the relationship between the interval intensity and the Δ $\dot{V}O_{2max}$. *denotes statistically significant change in $\dot{V}O_{2max}$. Legend with coloured boxes relates to all panels to signify each study.

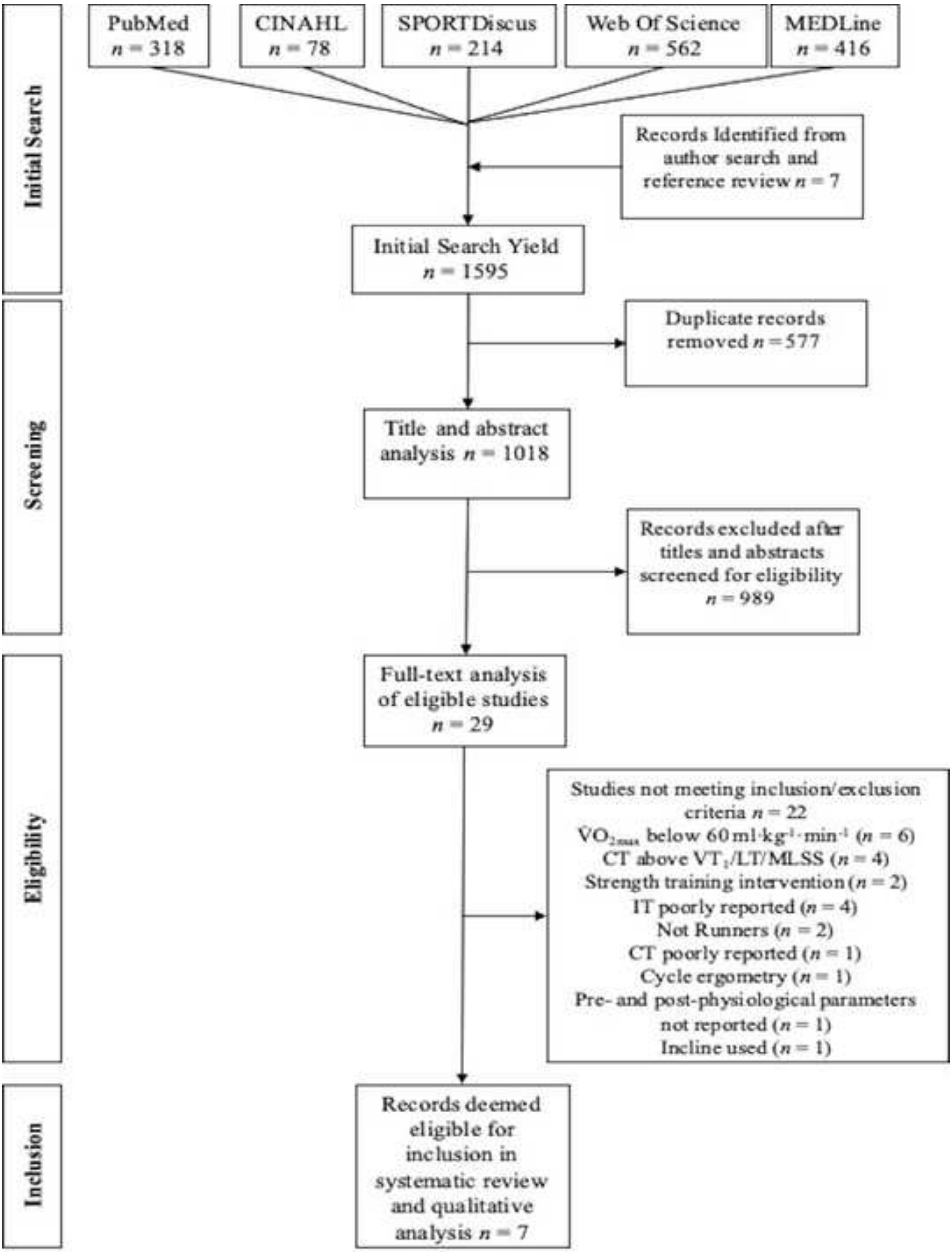
Figure 6 – **Panel A**: The relationship between the total training impulse (TRIMP) of the training intervention implemented in each study and the change in $\dot{V}O_{2max}$ (Δ $\dot{V}O_{2max}$). The total TRIMP is the

accumulated TRIMP of both interval and continuous training sessions completed throughout the training intervention. Linear regression line, regression equation and R^2 value displayed for the relationship between the TRIMP and the change in $\dot{V}O_{2max}$. *denotes statistically significant change in $\dot{V}O_{2max}$. **Panel B**: The relationship between the average intensity of the total training intervention implemented in each study and the total training impulse units required to change $\dot{V}O_{2max}$ by 1 $ml^{-1}\cdot kg^{-1}\cdot min^{-1}$ ($TRIMP\cdot mL\cdot kg^{-1}\cdot min^{-1}$). Average intervention intensity is calculated scaled to the speed at $\dot{V}O_{2max}$ (s$\dot{V}O_{2max}$) with s$\dot{V}O_{2max}$ being 1. Linear regression line, regression equation and R^2 value displayed for the relationship between the average intervention intensity and the $TRIMP\cdot ml^{-1}\cdot kg^{-1}\cdot min^{-1}$. *denotes statistically significant change in $\dot{V}O_{2max}$. **Panel C**: The relationship between the total training impulse per week (Total W_{TRIMP}) and the change in $\dot{V}O_{2max}$ (Δ $\dot{V}O_{2max}$). Total W_{TRIMP} is the accumulated TRIMP of both interval and continuous training sessions completed per week. Linear regression line, regression equation and R^2 value displayed for the relationship between the W_{TRIMP} and the change in $\dot{V}O_{2max}$. *denotes statistically significant change in $\dot{V}O_{2max}$. **Panel D**: The relationship between the total training impulse per session (Total S_{TRIMP}) and the change in $\dot{V}O_{2max}$ (Δ $\dot{V}O_{2max}$). Linear regression line, regression equation and R^2 value displayed for the relationship between the S_{TRIMP} and the change in $\dot{V}O_{2max}$. *denotes statistically significant change in $\dot{V}O_{2max}$. Legend with coloured boxes relates to all panels to signify each study.

Figure 7 - Panel A: The relationship between the interval training impulse (IT TRIMP) implemented in each study and the change in $\dot{V}O_{2max}$ (Δ $\dot{V}O_{2max}$). The IT TRIMP is the TRIMP of only the interval training sessions completed throughout the training intervention. Linear regression line, regression equation and R^2 value displayed for the relationship between the IT TRIMP and the change in $\dot{V}O_{2max}$. *denotes statistically significant change in $\dot{V}O_{2max}$. **Panel B**: The relationship between the prescribed intensity of the interval training work period implemented in each study and the interval training impulse units required to change $\dot{V}O_{2max}$ by 1 $ml^{-1}\cdot kg^{-1}\cdot min^{-1}$ (IT $TRIMP\cdot mL\cdot kg^{-1}\cdot min^{-1}$). Interval intensity is calculated scaled to the speed at $\dot{V}O_{2max}$ (s$\dot{V}O_{2max}$) with s$\dot{V}O_{2max}$ being 1. Linear regression line, regression equation and R^2 value displayed for the relationship between the interval intensity and

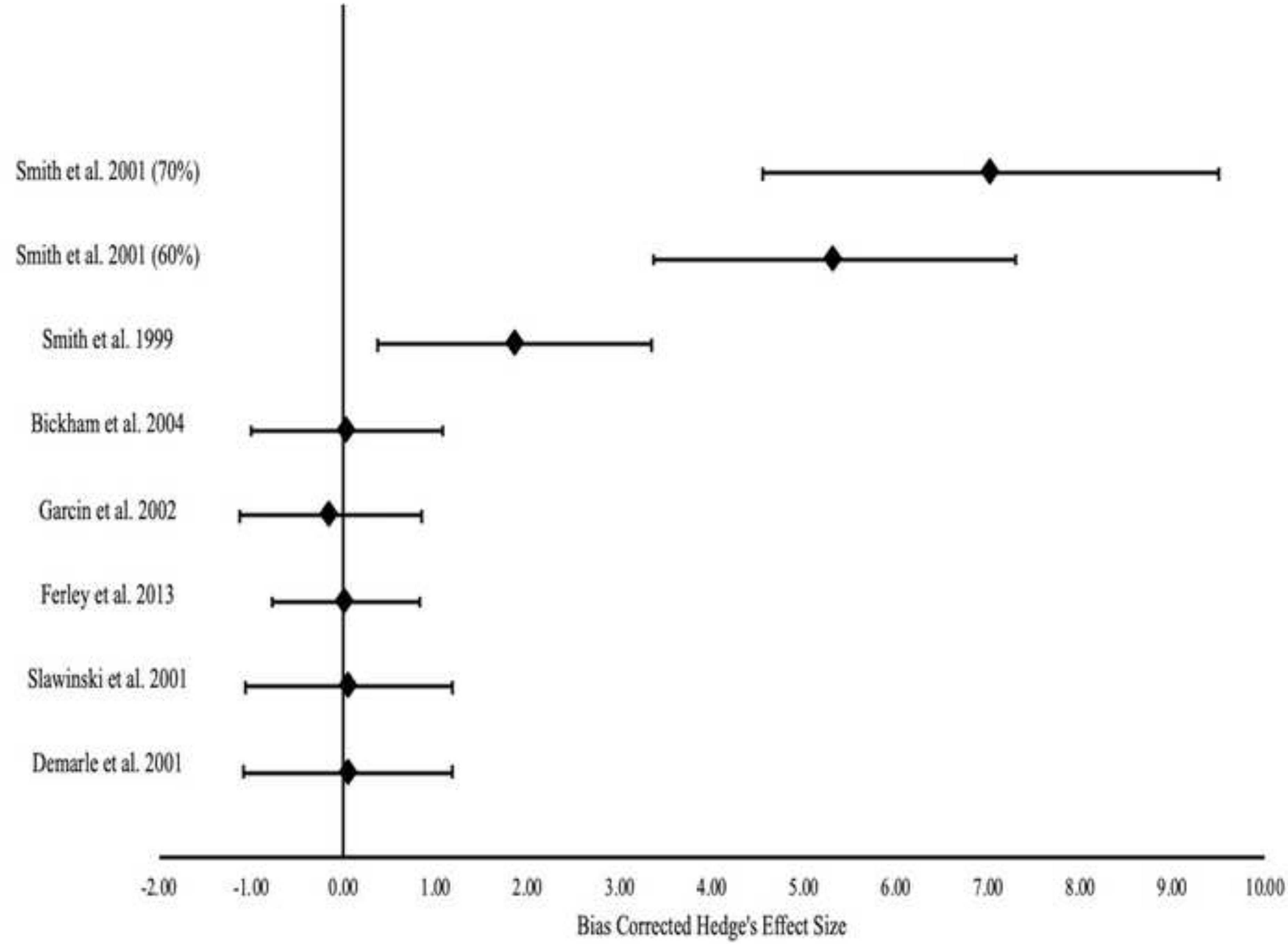
the IT TRIMP·mL·kg^{-1}·min^{-1}. *denotes statistically significant change in $\dot{V}O_{2max}$. **Panel C**: The relationship between the interval training impulse per week (IT W_{TRIMP}) and the change in $\dot{V}O_{2max}$ (Δ $\dot{V}O_{2max}$). IT W_{TRIMP} is the TRIMP of only the interval training sessions completed per week. Linear regression line, regression equation and R^2 value displayed for the relationship between the IT W_{TRIMP} and the change in $\dot{V}O_{2max}$. *denotes statistically significant change in $\dot{V}O_{2max}$. **Panel D**: The relationship between the interval training impulse per session (IT S_{TRIMP}) and the change in $\dot{V}O_{2max}$ (Δ $\dot{V}O_{2max}$). Linear regression line, regression equation and R^2 value displayed for the relationship between the IT S_{TRIMP} and the change in $\dot{V}O_{2max}$. *denotes statistically significant change in $\dot{V}O_{2max}$. Legend with coloured boxes relates to all panels to signify each study

Figure 1



Initial Search
Screening
Eligibility
Inclusion
PubMed n = 318
CINAHL n = 78
SPORTDiscus n = 214
Web Of Science n = 562
MEDLine n = 416
Records Identified from author search and reference review n = 7
Initial Search Yield n = 1595
Duplicate records removed n = 577
Title and abstract analysis n = 1018
Records excluded after titles and abstracts screened for eligibility n = 989
Full-text analysis of eligible studies n = 29
Studies not meeting inclusion/exclusion criteria n = 22
$\dot{V}O_{2max}$ below 60 ml·kg^{-1}·min^{-1} (n = 6)
CT above VT_1/LT/MLSS (n = 4)
Strength training intervention (n = 2)
IT poorly reported (n = 4)
Not Runners (n = 2)
CT poorly reported (n = 1)
Cycle ergometry (n = 1)
Pre- and post-physiological parameters not reported (n = 1)
Incline used (n = 1)
Records deemed eligible for inclusion in systematic review and qualitative analysis n = 7

Figure 2



Smith et al. 2001 (70%)
Smith et al. 2001 (60%)
Smith et al. 1999
Bickham et al. 2004
Garcin et al. 2002
Ferley et al. 2013
Slawinski et al. 2001
Demarle et al. 2001
-2.00
-1.00
0.00
1.00
2.00
3.00
4.00
5.00
6.00
7.00
8.00
9.00
10.00
Bias Corrected Hedge's Effect Size

Figure 3

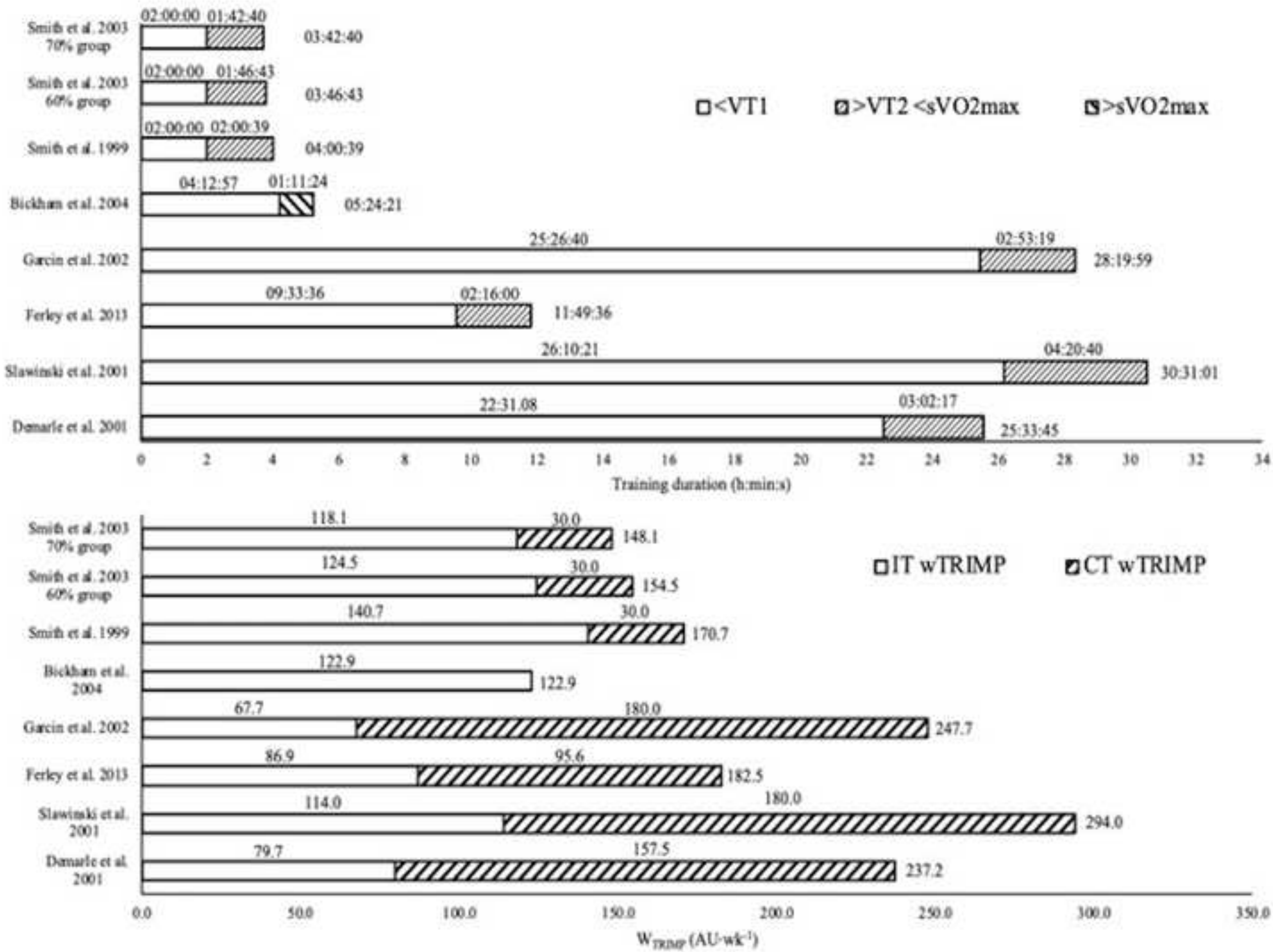
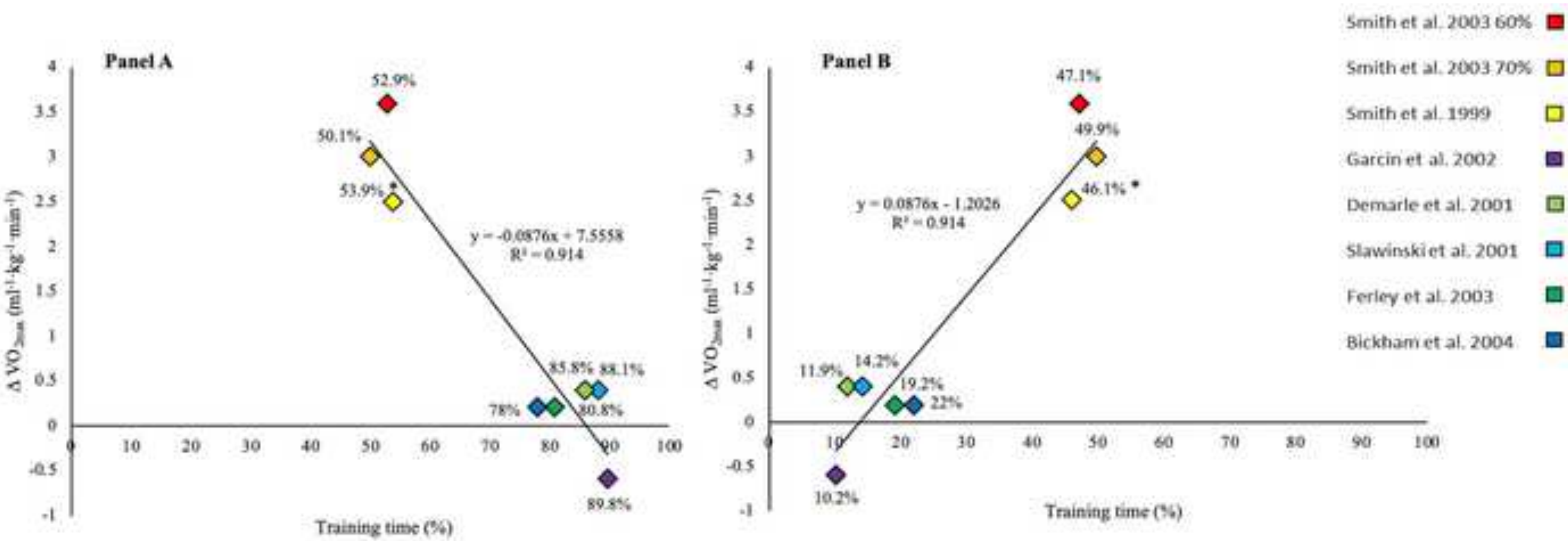
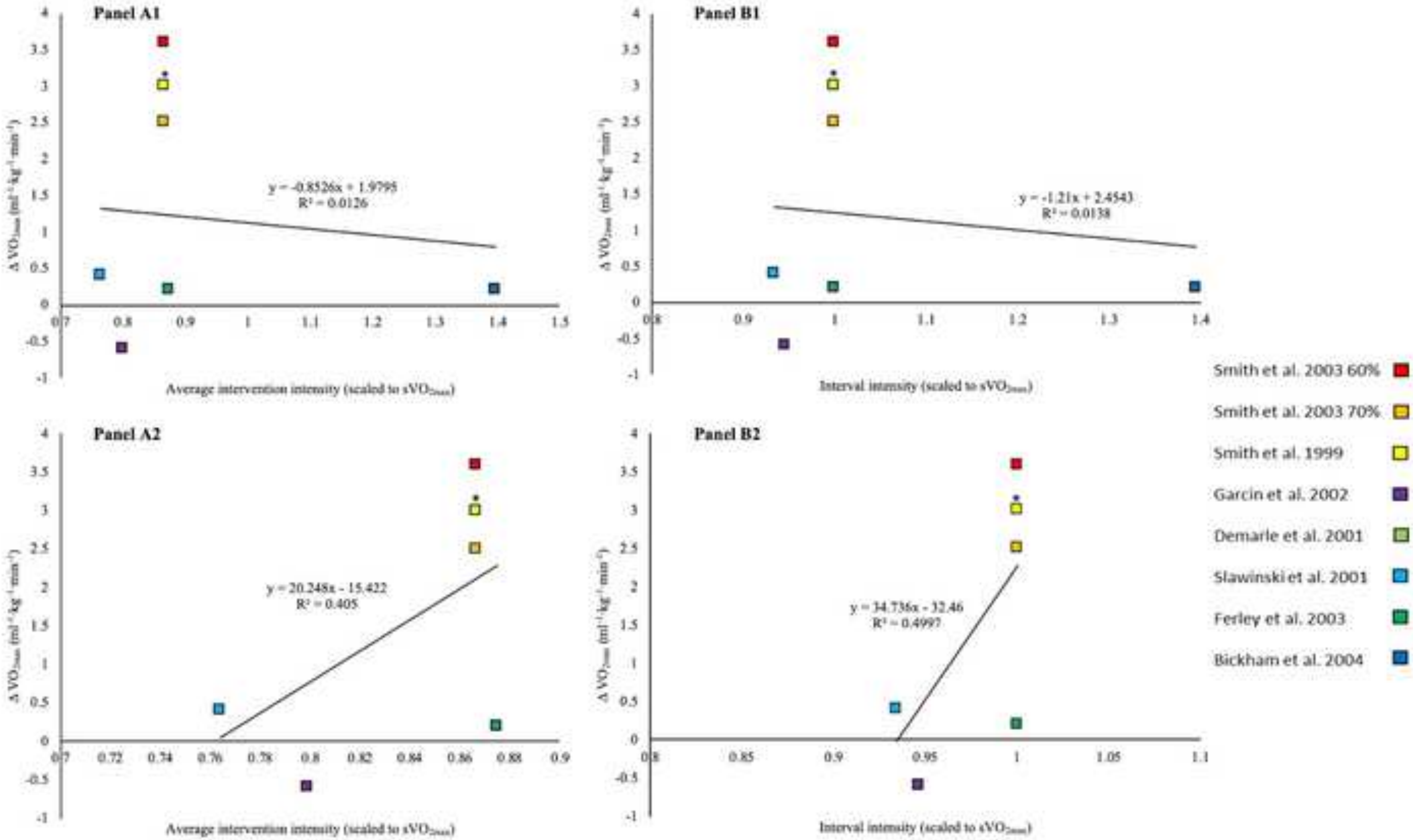

Smith et al. 2003 70% group
02:00:00 01:42:40 03:42:40
Smith et al. 2003 60% group
02:00:00 01:46:43 03:46:43
Smith et al. 1999
02:00:00 02:00:39 04:00:39
Bickham et al. 2004
04:12:57 01:11:24 05:24:21
Garcin et al. 2002
25:26:40 02:53:19 28:19:59
Ferley et al. 2013
09:33:36 02:16:00 11:49:36
Slawinski et al. 2001
26:10:21 04:20:40 30:31:01
Demarle et al. 2001
22:31.08 03:02:17 25:33:45
<VT1
>VT2 <sVO2max
>sVO2max
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34
Training duration (h:min:s)
Smith et al. 2003 70% group
118.1 30.0 148.1
Smith et al. 2003 60% group
124.5 30.0 154.5
Smith et al. 1999
140.7 30.0 170.7
Bickham et al. 2004
122.9 122.9
Garcin et al. 2002
67.7 180.0 247.7
Ferley et al. 2013
86.9 95.6 182.5
Slawinski et al. 2001
114.0 180.0 294.0
Demarle et al. 2001
79.7 157.5 237.2
IT wTRIMP
CT wTRIMP
0.0 50.0 100.0 150.0 200.0 250.0 300.0 350.0
W_{TRIMP} (AU·wk⁻¹)

Figure 4



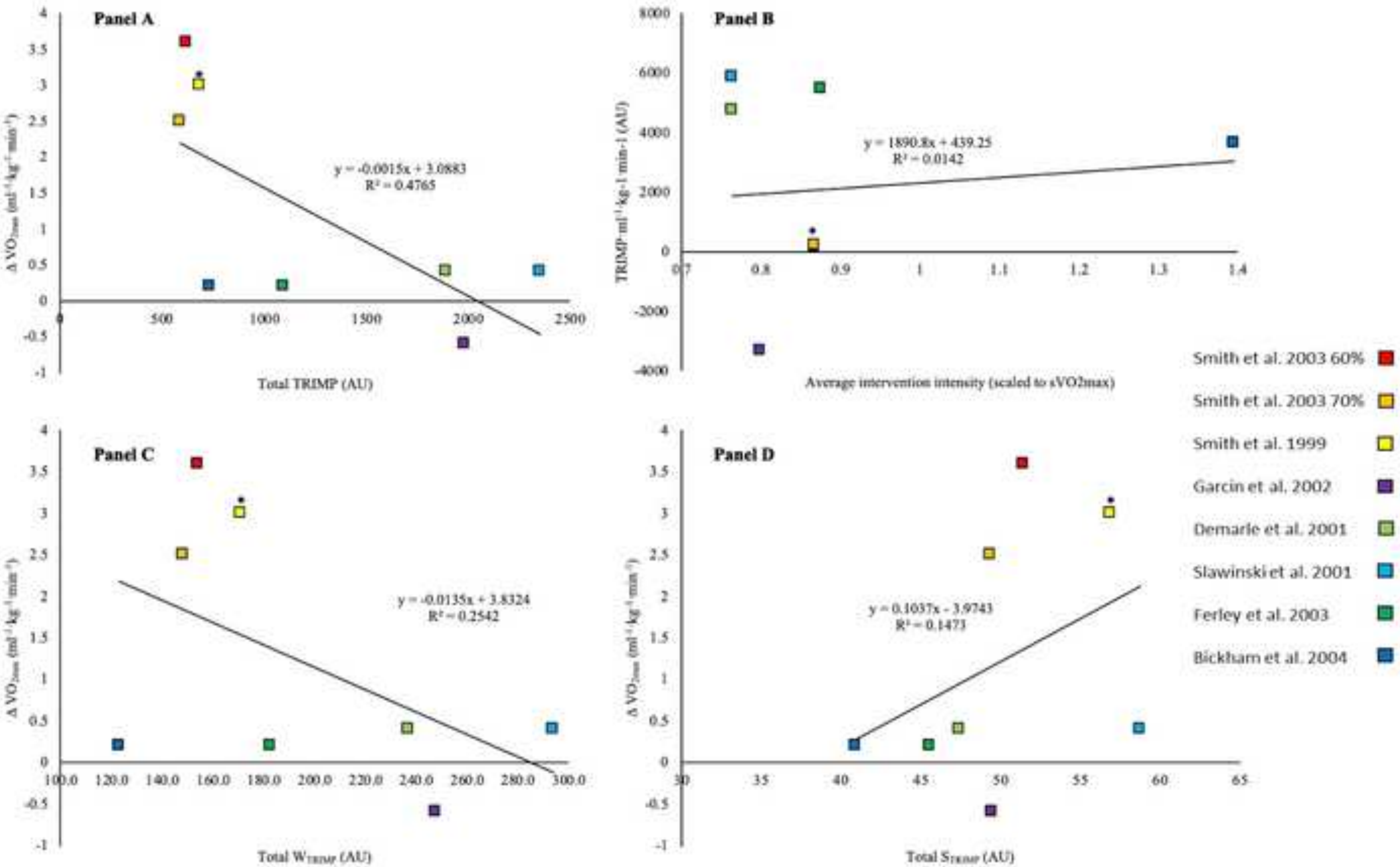
Panel A
52.9%
50.1%
53.9%
y = -0.0876x + 7.5558
R² = 0.914
85.8%
88.1%
78%
80.8%
89.8%
Training time (%)
Panel B
47.1%
49.9%
46.1%
y = 0.0876x - 1.2026
R² = 0.914
11.9%
14.2%
19.2%
22%
10.2%
Training time (%)
Smith et al. 2003 60%
Smith et al. 2003 70%
Smith et al. 1999
Garcin et al. 2002
Demarle et al. 2001
Slawinski et al. 2001
Ferley et al. 2003
Bickham et al. 2004

Figure 5



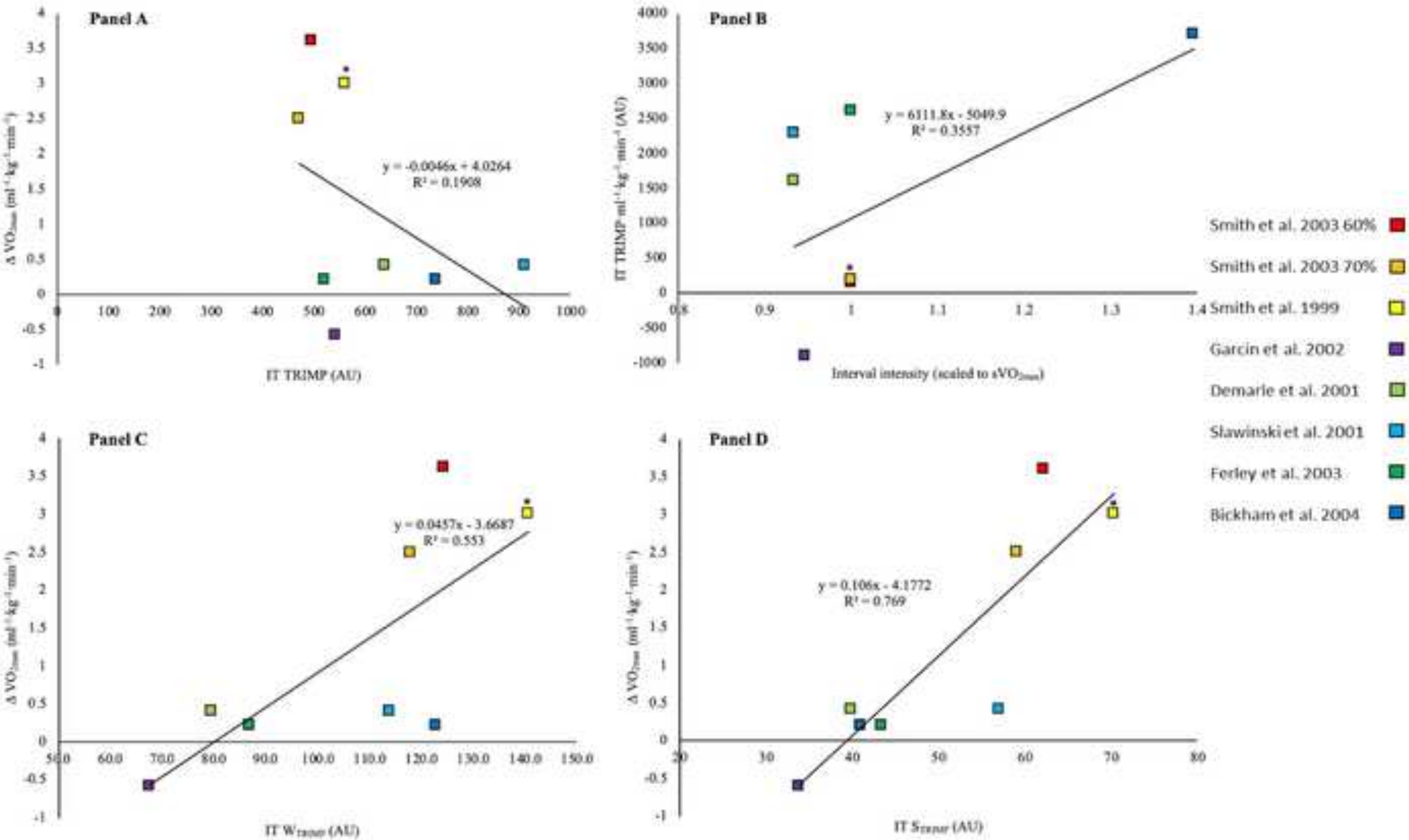
Panel A1
y = -0.8526x + 1.9795
R² = 0.0126
Average intervention intensity (scaled to sVO2max)
Panel B1
y = -1.21x + 2.4543
R² = 0.0138
Interval intensity (scaled to sVO2max)
Panel A2
y = 20.248x - 15.422
R² = 0.405
Average intervention intensity (scaled to sVO2max)
Panel B2
y = 34.736x - 32.46
R² = 0.4997
Interval intensity (scaled to sVO2max)
Δ VO2max (ml⁻¹·kg⁻¹·min⁻¹)
Smith et al. 2003 60%
Smith et al. 2003 70%
Smith et al. 1999
Garcin et al. 2002
Demarle et al. 2001
Slawinski et al. 2001
Ferley et al. 2003
Bickham et al. 2004

Figure 6



Panel A
y = -0.0015x + 3.0883
R² = 0.4765
Total TRIMP (AU)
Panel B
y = 1890.8x + 439.25
R² = 0.0142
Average intervention intensity (scaled to sVO2max)
Panel C
y = -0.0135x + 3.8324
R² = 0.2542
Panel D
y = 0.1037x - 3.9743
R² = 0.1473
Smith et al. 2003 60%
Smith et al. 2003 70%
Smith et al. 1999
Garcin et al. 2002
Demarle et al. 2001
Slawinski et al. 2001
Ferley et al. 2003
Bickham et al. 2004

Figure 7



Panel A
y = -0.0046x + 4.0264
R² = 0.1908
Δ VO2max (ml⁻¹·kg⁻¹·min⁻¹)
IT TRIMP (AU)
Panel B
y = 6111.8x - 5049.9
R² = 0.3557
IT TRIMP ml⁻¹·kg⁻¹·min⁻¹ (AU)
Interval intensity (scaled to sVO2max)
Panel C
y = 0.0457x - 3.6687
R² = 0.553
IT WTRIMP (AU)
Panel D
y = 0.106x - 4.1772
R² = 0.769
IT STRIMP (AU)
Smith et al. 2003 60%
Smith et al. 2003 70%
Smith et al. 1999
Garcin et al. 2002
Demarle et al. 2001
Slawinski et al. 2001
Ferley et al. 2003
Bickham et al. 2004

Title: The dose-response relationship between interval-training and $\dot{V}O_{2max}$ in well-trained endurance runners: A systematic review

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Running Head: Dose-response relationship between interval-training and $\dot{V}O_{2max}$

Word Count: 7758

Abstract

Success in endurance running is primarily determined by maximal aerobic power ($\dot{V}O_{2max}$), fractional utilisation, and running economy (RE). Within the literature, two training modalities have been identified to improve $\dot{V}O_{2max}$; continuous training (CT) and interval-training (IT). The efficacy of IT to improve $\dot{V}O_{2max}$ in well-trained runners remains equivocal, as does whether a dose-response relationship exists between the IT training load performed and changes in $\dot{V}O_{2max}$. A keyword search was performed in 5 electronic databases. Seven studies met the inclusion criteria for this systematic review. The training impulse (TRIMP) was calculated to analyse relationships between training load and changes in $\dot{V}O_{2max}$, by calculating the time accumulated in certain intensity domains throughout a training intervention. Non-significant ($P > 0.05$) improvements in $\dot{V}O_{2max}$ were reported in 6 studies, with only one study reporting a significant ($P < 0.05$) improvement in $\dot{V}O_{2max}$ following the IT interventions. A relationship between the training session impulse of the interval-training performed (IT S_{TRIMP}) and $\dot{V}O_{2max}$ improvements was observed. The efficacy of IT to improve $\dot{V}O_{2max}$ in well-trained runners remains equivocal due to a lack research. Nevertheless, the novel method of training-load analysis demonstrates a relationship between the IT S_{TRIMP} and $\dot{V}O_{2max}$ improvements; providing practical application for the periodisation of IT within the training regime of well-trained distance runners.

Keywords: Running, Endurance, Training-impulse, Training-load, High-intensity

Introduction

Maximal aerobic power ($\dot{V}O_{2max}$) is an established determinant of endurance performance (1–5). Training methods to improve $\dot{V}O_{2max}$ are characterised in two modes: continuous training (CT) and interval training (IT) methods (6,7). CT methods consist of long durations of sub-maximal intensity exercise typically eliciting adaptations associated with oxygen utilisation (8). By contrast, IT methods consist of repeated higher intensity work durations (above or equal to the maximal steady state) interspersed with periods of recovery (light exercise or rest) typically eliciting adaptations associated with oxygen delivery (9–12).

The use of IT methods to improve $\dot{V}O_{2max}$ has increased in popularity with evidence showing the same if not greater improvements compared to CT methods (10,13,14). Training intensities at or close to $\dot{V}O_{2max}$ have been suggested to be optimal in improving $\dot{V}O_{2max}$ (15)**,** with the total time spent at this intensity proportional to the increase in $\dot{V}O_{2max}$. Further supporting this, numerous studies and reviews have shown greater improvements in $\dot{V}O_{2max}$ utilising IT methods close to, or at an intensity eliciting $\dot{V}O_{2max}$ compared to CT methods matched for load (10,13,14,16–19). Interestingly, longer duration work intervals have been shown to elicit greater increases in $\dot{V}O_{2max}$ (10,14,20), as such work intervals maximally stress cardiorespiratory parameters by increasing the time spent at, or close to $\dot{V}O_{2max}$ (T@$\dot{V}O_{2max}$) to a greater extent than shorter work intervals, leading to greater adaptations (10,13,14,21–24). This suggests a dose-response relationship exists between T@$\dot{V}O_{2max}$ and improvements in $\dot{V}O_{2max}$, hence IT methods maximising T@$\dot{V}O_{2max}$ might elicit the greatest improvements in $\dot{V}O_{2max}$. The vast majority of evidence supporting this has primarily been reported in lesser-trained populations, meaning the efficacy of IT methods in well-trained populations is unclear.

A lack of conclusive evidence exists to support the efficacy of IT methods to improve $\dot{V}O_{2max}$ in well-trained endurance athletes. Midgley et al. (25) reviewed 23 studies for improvements in $\dot{V}O_{2max}$, RE, and lactate threshold (LT) in response to training interventions consisting of plyometric training, interval training, resistance training, and continuous training, of which, 14 included well-trained runners ($\dot{V}O_{2max}$ > 60 mL·kg^{-1}·min^{-1}). Only one study included in the review utilised IT in well-trained runners (*n* = 8; $\dot{V}O_{2max}$ = 71.2 ± 5 mL·kg^{-1}·min^{-1}), with runners performing 1 IT session per week for 4 weeks increasing to 3 IT sessions per week for another 4 weeks, consisting of 5 repetitions at 100% vVO_{2max} for 3 minutes separated by 3 minutes of rest at 50% vVO_{2max}, however no improvements in $\dot{V}O_{2max}$ were reported (26). In contrast, a study utilising a near identical IT intervention in well-trained runners ($\dot{V}O_{2max}$ = 61.5 ± 2.9 mL·kg^{-1}·min^{-1}) reported significant increases in $\dot{V}O_{2max}$, however, the sample size was low (n = 5) and therefore potentially underpowered (27). In a follow up study utilising this near identical IT intervention of 2 IT sessions per week for 4 weeks consisting of 5-6 repetitions at 100% vVO_{2max} for approximately 2-3 minutes at a work: rest ratio of 1: 2 in a larger sample size of well-trained runners (two groups: n = 9 in each group; $\dot{V}O_{2max}$ ≥ 60.1 mL·kg^{-1}·min^{-1}), no significant improvements in $\dot{V}O_{2max}$ were reported (28). The IT interventions used within the abovementioned studies might not have provided the T@$\dot{V}O_{2max}$ required to stimulate improvements in $\dot{V}O_{2max}$, with previous work in lesser-trained populations suggesting >15 mins of T@VO_{2max} accumulated per session to be effective in maximising VO_{2max} improvements (14,20), supporting the notion of a dose-response relationship. In well-trained endurance athletes a minimum training dose combining volume and intensity might need to be exceeded to elicit chronic adaptations in the cardiorespiratory parameters mediating $\dot{V}O_{2max}$ (25). In support of this, a 10-week IT intervention similar to that used previously (26,28) resulted in improvements in $\dot{V}O_{2max}$, albeit in lesser-trained runners ($\dot{V}O_{2max}$ = 51.6 ± 2.7 mL·kg^{-1}·min^{-1}) (29). The longer training intervention (10-weeks (29) vs 4-weeks (28) vs 8-weeks (26)) perhaps provided the accumulated T@$\dot{V}O_{2max}$ and training dose required to stimulate improvements in $\dot{V}O_{2max}$. Had the previous studies with similar IT protocols used longer interventions (26,28), improvements in $\dot{V}O_{2max}$ could have been observed due to the greater accumulated training load exceeding the minimum training dose required for improvements in $\dot{V}O_{2max}$ in these well-trained runners, however this remains speculative.

The efficacy of IT methods is well-established in lesser-trained populations (10,14), however, inconclusive evidence exists to support the effectiveness of IT methods to improve cardiorespiratory and metabolic factors in well-trained runners (6,25). The apparent dose-response relationship between training load and improvements in $\dot{V}O_{2max}$, perhaps offers a method of training load analysis that could be effective for well-trained runners aiming to improve $\dot{V}O_{2max}$. Therefore, this review aimed to analyse the volume and quality of the current evidence pertaining to the chronic effects of IT methods in well-trained runners on improving $\dot{V}O_{2max}$. A further aim was to analyse the dose-response relationship associated with the total load of IT and changes in $\dot{V}O_{2max}$.

Materials and methods

This systematic review was conducted according to the 'Preferred Reporting Items for Systematic Reviews and Meta-Analyses' (PRISMA) guidelines (30). All the following steps were implemented by three independent raters (AP, PH, TJ), with discrepancies and conflicts resolved by discussion.

Literature Search Strategy

Electronic database searches were carried out in PubMed, MEDLine, SPORTDiscus, CINAHL, and Web of Science. All searches were conducted between the 24th January 2019 and 12th April 2019. Searches were limited to papers published in English and from 1st January 1960 to 12th April 2019. Further searches on authors known by the investigators to have published papers using interval-training interventions in well-trained distance runners were conducted. Additionally, reference lists of all eligible studies were reviewed to identify potentially eligible studies that may have been missed. The following strategy using Boolean search terms and operators were used in each electronic database: ("Runners" OR "Endurance Runners" OR "Running" OR "Middle Distance" OR "Long Distance" OR "Marathon" OR "Well Trained" OR "Competitive" OR "Athlete" OR "Endurance Athlete" OR "Elite" OR "High Level") AND ("Interval Training" OR "High Intensity Interval Training" OR "High Intensity Interval Exercise" OR "HIIT" OR "HIIE" OR "Sprint Interval Training" OR "SIT" OR "Aerobic Interval Training" OR "Maximum Intensity Interval" OR Intermittent") AND ("VO2" OR "VO2 Max" OR "VO2 Peak" OR "Maximal Oxygen Uptake" OR "Aerobic Fitness" OR "Maximum Aerobic Capacity" OR "Maximum Oxygen Consumption" OR "Peak Oxygen Uptake" OR "Peak Oxygen Consumption" OR "Maximum Aerobic Power") NOT ("Cycling" OR "Swimming" OR "Rowing" OR "Skiing" OR "Soccer" OR "Football" OR "Basketball" OR "Untrained" OR "Recreational" OR "Clinical" OR "Obese" OR "Youth" OR "Adolescent" OR "Older").

Inclusion and Exclusion Criteria

To be eligible for inclusion, studies met each of the following inclusion criteria:

- Participants were adult well-trained runners

  - Well trained was defined as runners exhibiting a $\dot{V}O_{2max}$ greater than 60 $mL \cdot kg^{-1} \cdot min^{-1}$ or a performance score greater than 600 in the Mercier Scoring Tables (31). (Triathletes were included if they constituted a small proportion [less than 20%] of the population sample).
- The interval-training intervention lasted 4 weeks or longer, with a minimum of two interval sessions performed per week.
- Interval-training interventions consisted of running only.
- Interval-training interventions reported the intensity, volume and duration of the work and relief periods used throughout the intervention.
- The intensity of the work interval was greater than the lactate turn point / second ventilatory threshold (VT_2) / maximal lactate steady state (MLSS).
- Continuous training during the intervention was below the LT / first ventilatory threshold (VT_1) with the intensity, volume and duration reported.
- Data on $\dot{V}O_{2max}$ values pre- and post-training intervention were reported in addition to one or more of the following physiological variables: speed at $\dot{V}O_{2max}$ ($s\dot{V}O_{2max}$) speed at LT (sLT), running economy (RE), peak treadmill speed, time-trial performance, time to exhaustion (TTE).
- Published in an indexed peer-reviewed journal.

Studies were excluded if any of the following criteria applied:

- Not published in English
- Participants were non-runners (e.g. students, cyclists, recreationally trained, team-sport athletes etc.)
- Participants were reported to be in poor health and/or suffering from any kind of acute or chronic diseases.
- Strength training and/or continuous training above LT / VT_1 was included.
- Interval-training interventions were performed using an incline and / or hypoxic conditions.

- The characteristics of the interval-training interventions implemented (e.g. repetition number, intensity used, relief durations etc.) were not reported in enough detail to calculate the training load for comparisons between studies to be made.
- Ergogenic aids were used as part of the intervention.

Figure 1

Study Selection

Figure 1 provides a schematic overview of the study identification, screening approach and selection process. Search results were imported into a published software for systematic reviews (32), allowing a blinded screening process to be performed by the three independent reviewers (AP, PH and TJ). Conflicted decisions were resolved through discussion of the full-text until a consensus was reached. The initial search yielded 1588 results which increased to 1595 following addition of records identified through authors and reviewing references known to be relevant. The publication titles and abstracts remaining after the removal of duplicates (n = 1018) were screened independently by the reviewers for eligibility [inter-rater reliability (IRR): 98.4%, Fleiss' k = 0.48]. Following this screening, 29 potentially eligible studies were given full consideration, with the full-texts of each reviewed for inclusion. Of the 29 potentially eligible studies (Figure 1), a total of 7 studies meeting the criteria remained for further analysis.

Analysis of Results

A quality checklist for Randomised Controlled Trials (RCT) and Observational Studies modified by Kennelly (33) based on the Downs and Black Methodological Quality checklist (34) was used to assess quality of the 7 remaining studies. This modified version was used due to the inclusion of non-randomized and observational studies, as many of the items relating to the blinding of studies within the original Downs and Black checklist were therefore not appropriate. When scoring the quality of the study, the checklist is split into 5 sections with a total score provided from each: Reporting (items 1-12), External Validity (items 13-16), Internal Validity – bias (items 17-25), Internal Validity –

confounding (items 26-32), and Power (item 33). Studies are able to attain a total score of 32 with the total score indicating the quality (≥20 = good, 15-19 = fair, ≤14 = poor) (33).

Data Extraction

Data Extraction was performed by one investigator (AP) using a standardized form to allow the extraction of relevant study characteristics. The data extracted from each study were:

- Study characteristics (author(s), title, year of publication).
- Participant characteristics (number of participants, age, stature, body mass, training level). Training intervention characteristics (duration, frequency, total training time, IT work intensity, IT work duration, IT relief intensity, IT relief duration, total number of intervals, CT intensity, CT duration.
- Total time spent in intensity domains and as a percentage of the total training time (below VT_1/2mmol·L^{-1} BLa^-, between VT_1/2mmol·L^{-1} and VT_2/4mmol·L^{1} BLa^-, between VT_2/4mmol·L^{-1} BLa^- and s$\dot{V}O_{2max}$, and above s$\dot{V}O_{2max}$).
- Training load characteristics (Total intervention training impulse overall [TOT_{TRIMP}], per week [W_{TRIMP}] and per session [S_{TRIMP}]. Interval-training impulse overall [IT TOT_{TRIMP}], per week [IT W_{TRIMP}] and per session [IT S_{TRIMP}]).
- Average intervention training intensity scaled to the s$\dot{V}O_{2max}$, interval-training intensity scaled to the s$\dot{V}O_{2max}$.
- Training response (initial $\dot{V}O_{2max}$, post-training $\dot{V}O_{2max}$, change in $\dot{V}O_{2max}$, total TRIMP units to change $\dot{V}O_{2max}$ by 1 mL·kg^{-1}·min^{-1}, IT TRIMP units to change $\dot{V}O_{2max}$ by 1 mL·kg^{-1}·min^{-1}, significance of change).

$\dot{V}O_{2max}$ values were reported as mL·kg^{-1}·min^{-1} in all cases, along with the standard deviation of all variables reported. Where standard errors were reported, these were converted into standard deviation. The total training time and time spent in each intensity domain was reported in hours, minutes and seconds (h:min:s).

Training load quantification

Training load in each intervention was estimated by calculating a modified version of the training impulse (TRIMP), commonly referred to as Lucia's' TRIMP (35,36). This method of calculating TRIMP has also been previously used to estimate training load in well-trained endurance runners (37,38). The TRIMP score was calculated by multiplying the accumulated training duration spent in each intensity domain by an intensity-weighted multiplier. For example; 1 min in the first intensity domain [$<VT_1$] is given a score of 1 arbitrary unit (AU), 1 min in the second intensity domain [$>VT_1$ $<VT_2$] is given a score of 2 AU, and 1 min in the third intensity domain [$>VT_2$] is given a score of 3 AU. The total TRIMP score is then obtained by summing the results of the three intensity domains. The total TRIMP was calculated for the total duration of a training intervention (TOT_{TRIMP}), the weekly TRIMP of a training intervention (W_{TRIMP}), and the TRIMP of a training session (S_{TRIMP}). To further investigate the effects of only the interval-training interventions, the TRIMP of only the interval-training performed in each study was calculated for the total training intervention duration (IT TOT_{TRIMP}), the weekly interval-training performed (W_{TRIMP}), and the TRIMP of an interval-training session (IT S_{TRIMP}). The calculated TRIMP scores were then expressed relative to changes in VO_{2max} to examine if a dose-response relationship exists between training load and changes in VO_{2max} for all training performed throughout an intervention and the effects of only the interval-training performed throughout an intervention.

To determine the training intensity in each study and to allow comparisons to be made between studies, intensity was scaled to the reported average $s\dot{V}O_{2max}$, with $s\dot{V}O_{2max}$ being 1. For example, if the reported training intensity for the interval work duration was 90% of $s\dot{V}O_{2max}$, then the intensity was calculated as 0.9. These scaled intensities were subsequently used to examine relationships between the training intensities used in each study and changes in $\dot{V}O_{2max}$.

Main Analysis

Effect sizes (Hedges' g) were calculated for pre- and post-training $\dot{V}O_{2max}$ values for each study individually without an overall pooled effect. Hedges' g was used to bias correct for the typically small sample sizes, as observational studies were primarily included with no control groups. The pooled standard deviation for Hedges' g was calculated using the root mean square of the pre- and post-group standard deviations. This version does not specifically include the sample size (*n*), preventing any complications that could arise from inflating *n* when both group's means are from the same sample. This statistical approach was chosen due to data being from the same sample rather than a separate intervention and control group, thus making a traditional weighted effects meta-analysis pooling inappropriate. Traditional meta-analysis assumes two different sets of individuals in each group (39) meaning a violation of underlying assumptions would have occurred if applied to this review. 95% confidence intervals were calculated for individual Hedges' g effect sizes. A forest plot of the individual effect sizes with 95% confidence intervals was created to display the pre-post $\dot{V}O_{2max}$ responses to the training intervention (Figure 2). The qualitative inferences associated with the calculated effect sizes were defined as *trivial* (<0.2), *small* (0.2-0.6), *moderate* (0.6-1.2), *large* (1.2-2.0), *very large* (2.0-4.0), and *nearly perfect* (>4.0) (40). As the data extracted from the included studies were from the same sample rather than a separate intervention and control group, it was deemed unsuitable to amalgamate the results for a meta-analysis. The results in this review were therefore analysed narratively.

Figure 2

Results

Participant Characteristics and Quality Assessment

A summary of the participant characteristics and the quality assessment results for the studies included in this review are displayed in Table 1. Seven studies with a total of 62 participants met the inclusion criteria for this review. One study included runners with an average VO_{2max} and SD marginally lower than 60 $ml \cdot kg^{-1} \cdot min^{-1}$ (44) as this group (VO_{2max} = 59.4 ± 8.9 $ml \cdot kg^{-1} \cdot min^{-1}$) displayed no significant difference to the other training group with a VO_{2max} value greater than 60 $ml \cdot kg^{-1} \cdot min^{-1}$ (63.3 ± 8.0 $ml \cdot kg^{-1} \cdot min^{-1}$). Differences in the quality assessment scores were mainly in the external validity and confounding sections of the assessment. All studies scored 0 as it relates to the calculation of statistical power.

Table 1

Training Intervention

A summary of the training characteristics implemented in the 7 studies are displayed in Table 3. In all studies, interval-training interventions lasted between 4- and 8-weeks, with sessions performed 2 to 3 times per week (27,28,41–45). Supplementary continuous training sessions were included in 6 studies 1 to 3 times per week (27,28,41–44), with one study not including any continuous training (45).

Maximal Aerobic Power

Only one study (27) reported a *large*, significant increase of 4.9% in $\dot{V}O_{2max}$ in response to the training intervention (ES: 1.86, $P = 0.007$). Non-significant, *trivial* changes in $\dot{V}O_{2max}$ of less than 0.7% (ES: 0.02 - 0.06) were reported in 4 studies (42–45). Smith et al. (28) reported *nearly perfect*, non-significant increases in $\dot{V}O_{2max}$ of 5.9% (ES: 5.33) and 4.2% (ES: 7.02) in the 60% of the time to exhaustion (TTE) and 70% TTE experimental groups, respectively. Only one study (41) reported a non-significant, *trivial* decrease in $\dot{V}O_{2max}$ of -0.9% (ES: 0.14) (Table 2).

Table 2

Continuous Training

In all studies including supplementary continuous training, sessions were performed at 60-75% $s\dot{V}O_{2max}$ for 0:30:00 – 1:00:00, 1 to 3 times per week (Table 3).

Interval Training characteristics

Work Intensity

The lowest intensity for the work period was prescribed as the median speed between the sLT and $s\dot{V}O_{2max}$ ($s\Delta50$) (41–43). The $s\dot{V}O_{2max}$ was prescribed as the work intensity in 3 studies (27,28,44). The highest work intensity was prescribed as 90-100% maximum effort sprints in 1 study (45) (Table 3).

Work Duration

The longest work durations were prescribed as 50% TTE at sΔ50 (41–43). Work durations were prescribed as 60-75% TTE at s$\dot{V}O_{2max}$ in studies using s$\dot{V}O_{2max}$ as the intensity (27,28,44). The shortest work durations were prescribed as 5-15 s, 90-100% maximum effort sprints over 40-100m (45) (Table 3).

Relief Intensity

Static rest was prescribed as the relief intensity in 3 studies using s$\dot{V}O_{2max}$ as the work intensity (27,28,44). Active relief periods were prescribed as 50% s$\dot{V}O_{2max}$ in the 3 studies using sΔ50 as the work intensity (41–43), and walking or jogging back to the start of a sprint effort in one study (45) (Table 3).

Relief Duration

The shortest relief durations of 25% TTE at sΔ50 were prescribed in 3 studies using sΔ50 as the work intensity (41–43). Relief durations prescribed as the time taken to recover to 65% HR_{max} were almost equal to the work durations in one study using s$\dot{V}O_{2max}$ as the work intensity (44). The relief duration was prescribed as a 1: 2 work: rest ratio in 2 studies using s$\dot{V}O_{2max}$ as the work intensity (27,28). In the one study using sprint efforts (45), relief durations were prescribed as progressively declining work: rest ratios throughout the training intervention of 1: 5, 1: 4, and 1: 3 (Table 3).

Interval-Training Duration

Repetitions

The higher the work intensity the greater number of repetitions performed per training session and throughout the study intervention. In the only study using sprint efforts (45) the highest repetitions per training session (n = 22) and in total (n = 412) were performed over the 6-week intervention. The lowest repetitions per training session (n = 2-4) and in total (n = 37-64) were performed in the 3 studies using the lowest work intensity of sΔ50 (41–43). In the 3 studies using s$\dot{V}O_{2max}$ as the work intensity (27,28,44), repetitions performed per training session (n = 5-6) and in total (n = 40-60) were similar (Table 3).

Table 3

Duration

The average training session durations were longest (0:33:00 – 0:40:00) in the two 4-week studies using $s\dot{V}O_{2max}$ as the work intensity (27,28), along with the highest average time spent at the work intensity per session (0:13:00 – 0:15:00). Two studies using sΔ50 (41,42) and the 6-week study using $s\dot{V}O_{2max}$ as the work intensities (44) had the shortest average training session durations (0:12:00 – 0:20:00), with equal average time spent at the work intensity per session (0:11:00). The shortest average time spent at the work intensity per session (0:04:00) was in the only study using sprint efforts as the work intensity (45), despite a relatively long average training session duration of 0:33:00 (Figure 3A).

The total time at the work intensity increased as the prescribed intensity decreased over the duration of the training intervention. In the 8-week studies using the lowest work intensity of sΔ50 (41–43) the total time at the work intensity was highest (3:00:00 – 4:20:00). The total time spent at the work intensity was lowest (1:10:00) in the 1 study using the highest work intensity of sprint efforts for 6-weeks (45) (Figure 3A).

The total training volume was highest (25:30:00 – 30:30:00) in the 8-week interventions using sΔ50 as the work intensity (41–43) and lowest (3:40:00 – 4:00:00) in the 4-week studies using $s\dot{V}O_{2max}$ as the work intensity (27,28) (Figure 3A).

Training Load

Total Training Impulse per week (W_{TRIMP})

The total W_{TRIMP} increased as the work intensity prescribed decreased, with the 3 studies using the lowest work intensity of sΔ50 over the 8-week intervention (41–43) having the highest total W_{TRIMP} (237-294 $AU \cdot wk^{-1}$). In contrast, the 6-week study with the highest work intensity of sprint efforts (45) had the lowest total W_{TRIMP} of 123 $AU \cdot wk^{-1}$ (Figure 3B).

Interval Training Impulse per week (IT W_{TRIMP})

The training impulse score per week for only the interval-training performed (IT W_{TRIMP}) was lowest (67-80 AU·wk^{-1}) in two of the 8-week intervention studies using sΔ50 for the work intensity (41,43), accounting for 30% of the total W_{TRIMP}. In the two 4-week studies using s$\dot{V}O_{2max}$ for the work intensity (27,28) the IT W_{TRIMP} (118-140 AU·wk^{-1}) was highest, accounting for 80% of the total W_{TRIMP}. The only study to use sprint efforts for the work intensity (45) had an IT W_{TRIMP} of 123 AU·wk^{-1} accounting for 100% of the total W_{TRIMP} as no continuous training was prescribed as part of the training intervention (Figure 3B).

Continuous Training Impulse per week (CT W_{TRIMP})

The training impulse score per week for the continuous training only (CT W_{TRIMP}) was lowest and identical (30 AU·wk^{-1}) in the two 4-week studies using s$\dot{V}O_{2max}$ for the work intensity (27,28), with a CT TRIMP: IT TRIMP ratio of approximately 1: 4. The 8-week studies using sΔ50 for the work intensity (41–43) had the highest CT W_{TRIMP} (157-180 AU·wk^{-1}), with a CT TRIMP: IT TRIMP ratio of approximately 2: 1 (Figure 3B).

Figure 3

Dose-response relationship

Training distribution and change in $\dot{V}O_{2max}$

Improvements in $\dot{V}O_{2max}$ decreased as the percentage of total training time spent <VT_1 increased (Figure 4A). In contrast, improvements in $\dot{V}O_{2max}$ increased as the percentage of total training time spent >VT_2 increased (Figure 4B). The greatest improvements in $\dot{V}O_{2max}$ (2.5-3.6 mL·kg^{-1}·min^{-1}) were reported in 2 studies (27,28) with the highest percentage of total training time >VT_2 (46.1% - 49.9%). By contrast, a decrease in $\dot{V}O_{2max}$ of -0.6 mL·kg^{-1}·min^{-1} was reported in one study (41) with the lowest percentage of total training time >VT_2 (10.2%).

Figure 4

Training intensity and change in $\dot{V}O_{2max}$

Improvements in $\dot{V}O_{2max}$ decreased as the average total training intensity increased (Figure 5A1); however, if the sprint interval study is removed (45) (the only study to prescribe a work intensity above $s\dot{V}O_{2max}$), improvements in $\dot{V}O_{2max}$ increased as the average total training intensity increased (Figure 5A2). Similarly, improvements in $\dot{V}O_{2max}$ decreased as the work intensity prescribed increased (Figure 5B1). After removing the sprint interval study (45), improvements in $\dot{V}O_{2max}$ increased as the work intensity increased (Figure 5B2). When using aerobic intensities $\leq s\dot{V}O_{2max}$, greater improvements in $\dot{V}O_{2max}$ are shown with higher average total training intensities and higher interval-training intensities up to $s\dot{V}O_{2max}$ (Figures 5A2 & 5B2).

Figure 5

Total Training Load and change in $\dot{V}O_{2max}$

As the TOT_{TRIMP} and total W_{TRIMP} performed during the training interventions increased, improvements in $\dot{V}O_{2max}$ decreased (Figures 6A & 6C). By contrast, when displayed as the total TRIMP per training session (S_{TRIMP}), improvements in $\dot{V}O_{2max}$ increased as the total S_{TRIMP} increased (Figure 6D). The total TRIMP required to change $\dot{V}O_{2max}$ by 1 $mL\cdot kg^{-1}\cdot min^{-1}$ ($TRIMP\cdot mL\cdot kg^{-1}\cdot min^{-1}$) showed no clear relationship with the average total training intensity used throughout the training interventions (Figure 6B).

Figure 6

Interval-Training Load and change in $\dot{V}O_{2max}$

As the IT TRIMP performed during the training interventions increased, improvements in $\dot{V}O_{2max}$ decreased (Figure 7A). When displayed as the IT W_{TRIMP} and IT TRIMP per training session (IT S_{TRIMP}) however, improvements in $\dot{V}O_{2max}$ increased as the IT W_{TRIMP} and IT S_{TRIMP} increased (Figures 7C & 7D). The IT TRIMP required to change $\dot{V}O_{2max}$ by 1 $mL\cdot kg^{-1}\cdot min^{-1}$ (IT $TRIMP\cdot mL\cdot kg^{-1}\cdot min^{-1}$) increased with higher interval-training intensities (Figure 7B).

Figure 7

Discussion

This systematic review aimed to provide an updated evaluation of current evidence investigating the efficacy of interval-training interventions to improve $\dot{V}O_{2max}$ in well-trained, middle- and long-distance runners. A further aim was to examine if a dose-response relationship existed between the interval-training load and changes in $\dot{V}O_{2max}$ in a well-trained population. Empirical evidence to support the efficacy of interval-training to improve $\dot{V}O_{2max}$ in well-trained runners remains in the same inconclusive state as the review previously conducted by Midgley (25). A dose-response relationship might be evident, with a higher total load and individual session load correlating with greater increases in $\dot{V}O_{2max}$. Furthermore, intensities up to, but not exceeding s$\dot{V}O_{2max,}$ performed for long durations (>2 min) provide the greatest stimulus for improvements in $\dot{V}O_{2max}$. These findings however, should be interpreted with caution due to the limited number of included studies with small sample sizes and relatively short training interventions (4-8 weeks). This might be due to the difficulties associated with overcoming the reluctance of this population to alter their training regime for extended periods (46). The quality of the studies included within this review are considered acceptable based on the quality checklist for RCT and Observational studies modified by Kennelly (33), with all studies displaying fair to good quality assessment scores (*n* = 19-26).

Training Intensity Distribution

The data analysed here indicate that interval-training interventions have little effect on changes in $\dot{V}O_{2max}$ in well-trained runners, contrary to previous findings reporting significant improvements in $\dot{V}O_{2max}$, albeit in lesser-trained populations (10,14,20). Nevertheless, the available data suggests increasing the percentage of total training time performed above VT_2 in comparison to the percentage of training time performed below VT_1 elicits greater improvements in $\dot{V}O_{2max}$, but only in short-term training interventions (< 8 weeks). Supporting the inclusion of high proportions of training performed at high intensities within a micro-cycle, top-class marathon runners have been shown to train at relatively higher velocities for more total kilometres per week than lower-level competitors, and exhibit significantly higher $\dot{V}O_{2max}$ values (47). Recent analyses have also reported the volume of training performed above VT_2 to be a predictor of world-class endurance running performance, with well-trained endurance runners performing high volumes of long intervals slightly above VT_2 (48,49). This conflicts the training intensity distribution (TID) of well-trained endurance athletes who reportedly perform the majority of their training below VT_1 (approximately 80%), in comparison to the training performed above VT_2 (7,9,47,50–53). Previous observations of TID have been reported over longer training durations (8 weeks to a season) (7,50–53) than the study interventions presented here (4-8 weeks) (27,28,41–44) therefore, increased training time above VT_2 might be indicative of greater $\dot{V}O_{2max}$ improvements, but only in short-term training interventions (< 8 weeks). It is likely sustained durations of increased training intensity (> 8 weeks) are not conducive to performance improvements, particularly due to the high mechanical and neuromuscular demands associated with running at high velocities (50,54). Appropriately periodising training intensity is therefore necessary, with polarised TID models shown to elicit greater performance improvements without inducing signs of overtraining, even with an equal TRIMP, than other TID models (38,50,55–58).

Interval Intensity and Duration

The results of this review suggest short-term training interventions (4-6 weeks) with work intervals at $s\dot{V}O_{2max}$, sustained for long durations (>2 min) are the most effective in improving $\dot{V}O_{2max}$ in well-trained runners, so long as the intensity allows a sustained $T@\dot{V}O_{2max}$ to create a strong enough stimulus to elicit $\dot{V}O_{2max}$ improvements. Accumulating $T@\dot{V}O_{2max}$ in well-trained runners appears necessary as the studies that accumulated 13-16 min of running at $s\dot{V}O_{2max}$ per training session reported the greatest $\dot{V}O_{2max}$ improvements (27,28). In contrast, lesser $\dot{V}O_{2max}$ improvements were reported in the studies that accumulated running times per session of 10-16 min at $s\Delta 50$ (41–43), 9-12 min at $s\dot{V}O_{2max}$ (44), and 4-min as 90-100% maximum sprint efforts (45). This supports previous recommendations that interval-training protocols accumulating ≥ 15 min of $T@\dot{V}O_{2max}$ per session are optimal to maximally stress cardiorespiratory parameters for $\dot{V}O_{2max}$ improvements in well-trained runners (20,23,59). Selecting appropriate intensities and durations to maximise $T@\dot{V}O_{2max}$ is highlighted by the contrasting improvements in $\dot{V}O_{2max}$ shown in the studies using $s\dot{V}O_{2max}$ as the work intensity (27,28,44). Greater improvements in $\dot{V}O_{2max}$ were reported in the two studies that accumulated more time (13-16 min) running at $s\dot{V}O_{2max}$ per training session (27,28) than the study accumulating less time per training session (9-12 min) (44), despite using the same work intensity of sVO_{2max}.

The lack of improvements in $\dot{V}O_{2max}$ reported in the studies using sΔ50 as the work intensity (41–43) suggests the duration and intensity might have been too low to evoke a maximal $\dot{V}O_2$ response and in turn stimulate improvements in $\dot{V}O_{2max}$. The use of sΔ50 to elicit a maximal $\dot{V}O_2$ response relies on the presence of a $\dot{V}O_2$ slow component (60), with Billat et al. (61) previously showing the time to reach $\dot{V}O_{2max}$ to be approximately 5-min when running at sΔ50. Moreover, well-trained runners have been shown to maintain a plateau in $\dot{V}O_2$ below $\dot{V}O_{2max}$ during exhaustive runs at sΔ50 (60). These data indicate sΔ50 is insufficient to provide the T@$\dot{V}O_{2max}$ required to maximally stress cardiorespiratory parameters in well-trained runners and in turn improve $\dot{V}O_{2max}$ (23,25,59). Conversely, the one study using maximal sprint efforts reported a *trivial* increase in $\dot{V}O_{2max}$ (45), indicating this to be too high an intensity to allow a maximal $\dot{V}O_2$ response to be sustained to stimulate improvements in $\dot{V}O_{2max}$. Such high intensities above s$\dot{V}O_{2max}$ limit the duration of the interval and in turn the ability to attain and sustain a maximal $\dot{V}O_2$ response, due to the greater contribution from anaerobic metabolism increasing the intramuscular accumulation of lactate and hydrogen ion production associated with fatigue (15,23).

The use of long duration interval repetitions (≥ 2 min) performed at 100% s$\dot{V}O_{2max}$, accumulating ≥ 15 min T@$\dot{V}O_{2max}$ per training session is therefore suggested to be optimal to maximally stress cardiorespiratory parameters in well-trained endurance runners. It should be noted that despite the data suggesting this to be optimal, $\dot{V}O_{2max}$ improvements were non-significant in the included studies; perhaps due to the small sample sizes increasing the probability of type 2 errors when using probability based statistics (62). Nevertheless, based on current evidence the efficacy of interval-training to improve $\dot{V}O_{2max}$ in well-trained runners remains equivocal.

Dose – response relationship

Total Training Load and changes in $\dot{V}O_{2max}$

In this study, data from the original studies have been used to calculate a TRIMP to evaluate the relationship between the TOT_{TRIMP} and changes in $\dot{V}O_{2max}$. This novel approach provides a different interpretation of this relationship that has not been presented in previous reviews. The present data show diminishing increases in $\dot{V}O_{2max}$ as the TOT_{TRIMP} increases, both throughout the duration of an intervention and when expressed as the total TRIMP per week (W_{TRIMP}). However, when the TOT_{TRIMP} is expressed per training session (S_{TRIMP}), greater S_{TRIMP} elicited greater increases in $\dot{V}O_{2max}$.

The diminishing increases in $\dot{V}O_{2max}$ with increasing TOT_{TRIMP} and W_{TRIMP} follow the relationship displayed between the total training time $<VT_1$ and changes in $\dot{V}O_{2max}$. This suggests the high TOT_{TRIMP} values and decreasing $\dot{V}O_{2max}$ improvements displayed are a result of the inclusion of high proportions of CT $<VT_1$. Performing such high proportions of CT $<VT_1$ reduces the average intervention intensity due to a potentially excessive accumulation of fatigue affecting the ability to perform and recover from IT sessions for improvements in cardiorespiratory parameters mediating $\dot{V}O_{2max}$ to occur. This contrasts previous observations and reports on TID in well-trained endurance athletes showing greater volumes of training performed $<VT_1$, with very little performed $>VT_2$; however, these observations have been reported over much longer training durations (7,38,50,51,53,63).

The greater increases in $\dot{V}O_{2max}$ with increasing S_{TRIMP} displayed here is in line with the reportedly rapid effects of interval training on physiology and performance, albeit with rapid plateau effects as well (53). This perhaps indicates improvements in $\dot{V}O_{2max}$ are elicited in the initial 4-8 weeks of interval-training interventions but only with high S_{TRIMP} in well-trained runners, supporting suggestions that intensities greater than sΔ50 are required to improve $\dot{V}O_{2max}$ in well-trained populations (6,23,25,64). Extending to longer training interventions might require lower S_{TRIMP} due to the accumulated load of repeatedly performing high-intensity interval-training sessions, in addition to the potential de-training of other aspects of performance (65,66), especially in well-trained runners performing high volumes of training (47,48,63). In support of this, the inclusion of 10% of the weekly running volume constituting intense interval training at 3km and 10km race pace over an 8-week period significantly improved $\dot{V}O_{2max}$ in well-trained marathon runners (67). The inclusion of this interval-training however, was accompanied with a decrease in the total weekly running volume to 90% of that performed previously. This indicates that in well-trained runners, increases in training intensity can potentially elicit improvements in $\dot{V}O_{2max}$ using short-term interventions. The total volume of training might need to be reduced to allow high intensities to be reached and to recover from the demands of these sessions, thereby reducing the TOT_{TRIMP} but maintaining or even increasing the S_{TRIMP}, as indicated by the present findings.

Periodising short-term, higher intensity training blocks into the training regime is therefore recommended to ensure continued performance improvements without compromising recovery and performance in the long-term.

Interestingly, the TRIMP units required to change $\dot{V}O_{2max}$ (TRIMP·mL·kg^{-1}·min^{-1}) displayed little relationship with the average intervention intensity. This might be due to methodological differences of the interventions implemented in the included studies (total duration and inclusion of continuous training); with longer interventions displaying higher TOT_{TRIMP}, along with high volumes of CT increasing TOT_{TRIMP} further without improvements in $\dot{V}O_{2max}$. Despite this, it appears increases in average intervention training intensity reduce TRIMP·mL·kg^{-1}·min^{-1}, but only up to s$\dot{V}O_{2max}$. This supports previous recommendations regarding increasing T@$\dot{V}O_{2max}$ by using 100% s$\dot{V}O_{2max}$ as the interval intensity for long durations (≥ 2-min) as this also maximises the total S_{TRIMP} (20,23,59). In addition, decreasing the total volume of training performed as CT below VT_1 reduces the TOT_{TRIMP} and the TRIMP·mL·kg^{-1}·min^{-1} in the short-term, perhaps providing greater recovery from IT sessions. This might therefore allow higher intensities to be sustained for longer durations during IT sessions, increasing the total average intervention intensity, T@$\dot{V}O_{2max}$, and in turn improvements in $\dot{V}O_{2max}$.

Interval-Training Load and changes in $\dot{V}O_{2max}$

The IT TIRIMP (IT TOT_{TRIMP}) performed throughout the study interventions shows diminishing improvements in $\dot{V}O_{2max}$ as the IT TOT_{TRIMP} increased. This is likely the result of the shorter interventions being more intense with less CT, whereas the longer interventions were less intense with more CT. To overcome this, the IT TRIMP per week (IT W_{TRIMP}) and the IT TRIMP per session (IT S_{TRIMP}) were calculated, both showing greater improvements in $\dot{V}O_{2max}$ as the IT W_{TRIMP} and IT S_{TRIMP} increased. This further supports the notion that high training loads accumulated through high-intensity interval-training sessions are required to improve $\dot{V}O_{2max}$ in well-trained runners. This is due to the ability to increase T@$\dot{V}O_{2max}$ and thereby maximally stress cardiorespiratory parameters (6,15,23,59). In line with this, the present data indicates the IT W_{TRIMP} and IT S_{TRIMP} are of greater importance in eliciting $\dot{V}O_{2max}$ improvements than the total W_{TRIMP} and S_{TRIMP}. This suggests the intensity during interval sessions to be the likely key driver of $\dot{V}O_{2max}$ adaptations, more so than the overall training load in short-term training interventions. It is recognised that $\dot{V}O_{2max}$ is predominantly limited by maximal cardiac output ($\dot{Q}_{max}$) (5,68). Changes in $\dot{Q}_{max}$ are primarily due to increases in stroke volume (SV), as HR_{max} displays little change in response to training, along with previous observations even reporting small decreases in HR_{max} (69–72). Increases in SV occur due to a mechanical overload of the ventricles through the filling and ejection of blood stimulating hypertrophy of the myocardium, with maximum filling pressure, and therefore maximum mechanical overload, occurring at $\dot{V}O_{2max}$ (69,70,73). This further supports the use of intensities at, or close to, $\dot{V}O_{2max}$ to provide the mechanical overload necessary to elicit improvements in $\dot{Q}_{max}$, and in turn $\dot{V}O_{2max}$.

Greater improvements in $\dot{V}O_{2max}$ with greater IT S_{TRIMP} were observed here, in well-trained runners. Studies using 100% s$\dot{V}O_{2max}$ as the interval intensity displayed greater IT S_{TRIMP} and improvements in $\dot{V}O_{2max}$ than studies using sΔ50 as the intensity. This suggests short-term training interventions aiming to improve $\dot{V}O_{2max}$ should increase the IT TOT_{TRIMP} by increasing the time spent running at 100% s$\dot{V}O_{2max}$ during IT sessions to provide the optimal stimulus for adaptation. This should be incorporated into the training regime however, by increasing both IT S_{TRIMP} rather than increasing the weekly volume of IT, and reducing the total running volume to allow recovery and reduce the risk of overtraining. While the importance of high total running volumes in well-trained distance runners is not to be dismissed (48,63), when the focus of training is to improve $\dot{V}O_{2max}$, the intensity of training is the predominant factor regulating improvements that can be optimised through interval-training. Supporting this, in well-trained endurance athletes, maximal (and near maximal) intensities (90-100% $\dot{V}O_{2max}$) have been suggested to be optimal in eliciting maximal SV values, increasing the time spent at $\dot{Q}_{max}$ (T@$\dot{Q}_{max}$) and therefore the cardiopulmonary stress (23,59). This is in line with the optimal intensity suggested to increase T@$\dot{V}O_{2max}$ during interval-training sessions; however, Seiler et al. (22) showed that an interval protocol enabling 90% HR_{max} to be sustained for 32-min induced greater increases in cardiorespiratory parameters than an interval protocol enabling 95% HR_{max} to be sustained for 16-min. While SV and $\dot{Q}$ were not measured, this raises the question as to whether slightly lower intensities may be optimal in increasing T@$\dot{Q}_{max}$, rather than higher intensities that increase T@$\dot{V}O_{2max}$. These findings were reported in recreational cyclists, therefore the intensity and mode of exercise might differ in well-trained runners (22). By contrast, maximal SV and $\dot{Q}$ values were elicited following an exhaustive exercise bout at 100% power at $\dot{V}O_{2max}$ (p$\dot{V}O_{2max}$), whereas an exhaustive bout at the power at Δ50 (pΔ50) was unable to elicit maximal SV and $\dot{Q}$ values in well-trained triathletes ($\dot{V}O_{2max}$ = 64 $mL \cdot kg^{-1} \cdot min^{-1}$) (74). Even though this was shown during exhaustive cycling, it is speculated that higher intensities are able to elicit maximal SV and $\dot{Q}$ responses in well-trained runners; thereby increasing T@$\dot{Q}_{max}$ and in turn T@$\dot{V}O_{2max}$, optimising the overall stimulus for $\dot{V}O_{2max}$ improvements. The use of IT methods appear to be effective in enabling intensities eliciting $\dot{Q}_{max}$ to be attained and sustained; thus providing the stimulus required to further improve $\dot{V}O_{2max}$ in well-trained runners.

In the studies using work intensities at 100% s$\dot{V}O_{2max}$ performed for long durations (> 2 mins), increases in $\dot{V}O_{2max}$ per IT TRIMP unit are greater than in studies using work intensities above (sprint efforts) and below (Δ50) s$\dot{V}O_{2max}$. This suggests interval intensities of 100% s$\dot{V}O_{2max}$ performed for long durations (> 2 mins) to be an optimal protocol to increase $\dot{V}O_{2max}$ in well-trained runners, with the lowest IT TRIMP units required to improve $\dot{V}O_{2max}$ (IT $TRIMP \cdot mL \cdot kg^{-1} \cdot min^{-1}$). In contrast, the current data show work intensities below (sΔ50) and above (sprint efforts) s$\dot{V}O_{2max}$ would require more IT $TRIMP \cdot mL \cdot kg^{-1} \cdot min^{-1}$ for the same increase in $\dot{V}O_{2max}$. This indicates that higher volumes of interval-training would need to be performed either during individual training sessions or by including a greater frequency of interval-training sessions. Increasing the IT TRIMP by increasing the volume of running however, increases the risk of overtraining and injury, particularly due to high frequencies of running at high velocities limiting the recovery time available between training bouts (55,57). Furthermore, as evidence suggests sΔ50 to be an intensity unable to evoke maximal $\dot{V}O_2$ and $\dot{Q}$ responses in well-trained runners (60,74), it is speculated these sessions may be more characteristic of 'threshold' training where long durations of running are performed close to, or slightly above the maximal steady state, accumulating blood lactate concentrations of approximately 2-4 $mmol \cdot L^{-1}$ (7,52). Well-trained runners typically exhibit high fractional utilisation in addition to a high $\dot{V}O_{2max}$ allowing high but sub-maximal velocities, such as sΔ50, to be sustained (47,60,75,76); with well-trained endurance runners running at sΔ50 reportedly sustaining blood lactate concentrations comparable to that achieved during a 10-km race (9,60,75). Greater volumes of running at sΔ50 to increase the IT TRIMP would lead to well-trained runners performing higher volumes of ‘threshold’ training; however, this exerts a greater demand on the autonomic nervous system (55,77), endocrine system (63,78), and carbohydrate fuelling (50,79). This in turn restricts training time due to an increased recovery time and limited glycogen storing, increasing the risk of overtraining without offering further $\dot{V}O_{2max}$ improvements. This further supports the need to maximise the cardiorespiratory demand during training interventions to provide the optimal stimulus required to improve $\dot{V}O_{2max}$ in well-trained runners, without increasing the risk of overtraining and injury during such short-term interventions. It is therefore suggested to utilise 100% s$\dot{V}O_{2max}$ for repetition durations >2-min, accumulating >15-min of total work at this intensity to provide the greatest IT S_{TRIMP}, thereby maximising T@$\dot{V}O_{2max}$ and T@$\dot{Q}_{max}$ whilst reducing the IT TRIMP·mL·kg^{-1}·min^{-1} in well-trained runners.

Limitations

The limited number of studies included in this review highlights the lack of training studies in well-trained runners to establish the efficacy of interval-training, making it difficult to provide valid training recommendations in this population. This is likely due to the reluctance of well-trained runners to modify their training programmes for a significant period (46). Nevertheless, conclusions based on a systematic analysis of the literature can be made, but interpretations should be made within the limitations of this review. Furthermore, all recommendations and analyses presented within this review are only applicable to endurance running therefore caution is advised if these results are attempted to be applied to other endurance disciplines. For all studies included in the review, interpretations of the data are based predominantly upon probability values, however, these can be misleading due to the low sample sizes and the heterogeneity in the pool of participants studied. In addition, the recommendations and conclusions presented on how to periodise interval-training into the training regime are limited to the results and analyses of the short-term interventions (4-8 weeks) of the studies included in this review, with the absence of longer-term intervention studies not allowing comparisons to be made as to whether longer intervention durations elicit inferior or superior adaptations. A further limitation is related to the calculation of the training load within the included studies as no studies reported HR data during training sessions. Previous work supports the approach used here to calculate training load (80), however it is acknowledged that the calculation of training load and demarcation of training zones is based upon the intended prescription of the training interventions, which might differ to the actual physiological response evoked during the sessions. Arguably, the greatest limitation when interpreting the conclusions made is the lack of studies including more than one experimental group. This makes evaluating the efficacy of interval-training to improve $\dot{V}O_{2max}$ difficult due to the lack of a control group to compare training effects. It is acknowledged however, that including control groups within this population presents challenges due to well-trained runners potentially being unwilling to participate in a reduced training volume or intensity for a training block. Finally, the ecological validity of the training interventions implemented within the included studies is debateable, with evidence from a survey under review showing the interval sessions completed by runners differ to those implemented in study interventions (81). Consequently, the lack of research conducted on well-trained runners along with the questionable ecological validity, mean the conclusions drawn as it pertains to the efficacy of interval-training to improve $\dot{V}O_{2max}$ might be misleading. This is due to the interval-training methods prescribed in practice potentially resulting in different physiological responses compared to those reported in research.

Practical Applications

The novel TRIMP quantification presented in this review displays a relationship between a high IT TRIMP per session (IT S_{TRIMP}) and $\dot{V}O_{2max}$ improvements that coaches of well-trained runners can implement to optimise training adaptations during focussed interval-training blocks aiming to improve $\dot{V}O_{2max}$. The data presented herein suggests performing 2 to 3 interval-training sessions per week, at a work intensity of 100% s$\dot{V}O_{2max}$ for repetitions > 2 min, accumulating > 15 min of total work per session at this intensity to optimally accumulate a high IT S_{TRIMP}. Such protocols appear to maximise the T@$\dot{V}O_{2max}$ and T@$\dot{Q}_{max}$, thereby reducing the total interval-training TRIMP required to improve $\dot{V}O_{2max}$. The total running volume performed below VT_1 should be decreased in already well-trained runners during such periods of training intensification in the short-term (≤ 8 weeks) to appropriately balance training stress, recovery and adaptation. When the aim is to improve $\dot{V}O_{2max}$, the current data indicate short-term training blocks (≤ 8 weeks) prioritising the intensity of interval-training sessions and reducing the total volume of running are an effective means of improving $\dot{V}O_{2max}$. High-intensity training focussed on improving $\dot{V}O_{2max}$ should be periodised appropriately into the training regime over prolonged periods (> 8 weeks) due to the stress associated with high-intensity training, with a polarised TID model appearing to be effective in eliciting training adaptations without inducing signs of overtraining. Such short-term blocks of training intensification might not display the typical polarised TID observed in the long term, however, the reduction in running volume to accommodate the increase in intensity appears to be optimal for interval-training sessions to be performed at the necessary intensity, whilst also allowing for appropriate recovery and adaptation.

Conclusions and Future Research

In conclusion, the available evidence is insufficient to unequivocally support the efficacy of interval-training to improve $\dot{V}O_{2max}$ in well-trained runners. The novel method of analysis used here for the first time has quantified the IT across different studies and has shown that a dose-response relationship appears to be evident, perhaps providing a guide as to the minimal dose required to improve $\dot{V}O_{2max}$. The lack of research supporting the use of interval-training in well-trained runners warrants further research to elucidate the effectiveness of these training methods, with particular reference to the training intensity and total training load required to improve $\dot{V}O_{2max}$. Furthermore, future research should aim to include interval-training protocols performed by well-trained runners with more than one experimental group to allow confident conclusions to be drawn, and in turn provide worthwhile recommendations to researchers and practitioners alike.

This review provides an updated systematic analysis of the literature to date regarding the use of interval-training methods to improve $\dot{V}O_{2max}$ in well-trained middle- to long-distance runners. The dose-response relationship evident between the IT S_{TRIMP} and changes in $\dot{V}O_{2max}$ suggest this novel method to be a useful metric coaches can implement to optimise the interval-training protocols prescribed. Evidence from this review suggests interval-training interventions performed at 100% $s\dot{V}O_{2max}$ for repetitions >2 min, accumulating >15 min of total work per session at this intensity maximise the T@$\dot{V}O_{2max}$ and T@$\dot{Q}_{max}$, reducing the interval-training load required to improve $\dot{V}O_{2max}$ in well-trained runners.

Acknowledgements

Not applicable

Disclosure of Interest

The authors report no conflicts of interest

Funding

Not applicable

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Tables

Table 1 – Participant characteristics (Mean ± SD) and quality assessment results of each study.

Study	Participant Characteristics						Quality Assessment						
	n	**Sex**	**Age (years)**	**Stature (cm)**	**Mass (kg)**	**Training level**	**Reporting**	**External Validity**	**Internal Validity - Bias**	**Internal Validity - Confounding**	**Power**	**Total Quality Score**	**Qualitative Inference**
Demarle et al. 2001	6	Not Reported	27 ± 5.1	174.2 ± 2.9	68.5 ± 5.4	Endurance trained, middle- and long-distance runners	9	1	7	2	0	19	Fair
Slawinski et al. 2001	6	Not Reported	27 ± 4	175 ± 6	72 ± 9	Well-trained runners	9	1	7	2	0	19	Fair
Ferley et al. 2013	12	M&F	27.4 ± 3.8	173.6 ± 6.4	66 ± 7.1	Well-trained club runners	12	4	5	5	0	26	Good
Garcin et al. 2002	8	M	20.1 ± 4	176 ± 5.1	62.5 ± 5.1	High-level endurance-trained runners	11	1	7	3	0	22	Good
Bickham et al. 2004	7	M	27 ± 6.9	Not Reported	77.1 ± 9.8	Endurance trained distance runners	10	2	7	2	0	21	Good
Smith et al. 1999	5	M	22.8 ± 4.5	181 ± 4.7	74.1 ± 3.2	Well-trained middle-distance state-level runners	9	1	7	2	0	19	Fair
Smith et al. 2003	60% TTE: 9 70% TTE: 9	Not Reported	25.2 ± 0.2	178.8 ± 0.3	72.2 ± 0.3	Well-trained competitive middle-distance, triathlete, 10km runners	12	2	5	4	0	23	Good

TTE Time to exhaustion

Table 2 – The $\dot{V}O_{2max}$ response to the training intervention used along with statistical interpretation is displayed (Mean ± SD).

Study	**Training response**						
	Initial VO_{2max} ($ml{\cdot}kg^{-1}{\cdot}min^{-1}$)	**Post VO_{2max} ($ml{\cdot}kg^{-1}{\cdot}min^{-1}$)**	**% change**	**Sig**	**Effect Size (Hedges' g)**	**95% CI for Effect Size**	**Qualitative inference**
Demarle et al. 2001	61.2 ± 6.6	61.6 ± 5.4	+0.65%	NS	0.05	-1.08 to 1.18	Trivial
Slawinski et al. 2001	61.2 ± 6	61.6 ± 4.9	+0.65%	NS	0.06	-1.07 to 1.19	Trivial
Ferley et al. 2013	59.4 ± 8.9	59.6 ± 7.6	+0.34%	NS	0.02	-0.78 to 0.82	Trivial
Garcin et al. 2002	64.8 ± 3.6	64.2 ± 3.8	-0.92%	NS	-0.14	-1.12 to 0.84	Trivial
Bickham et al. 2004	60.1 ± 3.2	60.3 ± 5.3	+0.33%	NS	0.04	-1.01 to 1.09	Trivial
Smith et al. 1999	61.46 ± 1.3	64.45 ± 0.9	+4.86%	0.007	1.86	0.38 to 3.35	Large
Smith et al. 2003 60% TTE group	60.5 ± 0.6	64.1 ± 0.6	+5.95%	NS	5.33	3.36 to 7.3	Nearly Perfect
Smith et al. 2003 70% TTE group	60.1 ± 0.2	62.6 ± 0.4	+4.16%	NS	7.02	4.55 to 9.49	Nearly Perfect

Sig Significance; *NS* Not Significant (*P*>0.05); *95% CI* 95% Confidence Interval

Table 3 – Training intervention characteristics of each study (Mean ± SD).

Study	Training Intervention Characteristics								
	Total Training Characteristics		Interval Training characteristics					Continuous Training characteristics	
	Duration	**Frequency**	**Work Intensity (km·h^{-1})**	**Work Duration (s)**	**Relief Intensity (km·h^{-1})**	**Relief Duration (s)**	**Total Intervals**	**Intensity (km·h^{-1})**	**Duration (mins)**
Demarle et al. 2001	8 weeks	2 IT/wk 3 CT/wk	sΔ50: 17 ± 0.9	50% TTE sΔ50: 294 ± 49	50% sVO_{2max}: 9.1 ± 0.2	25% TTE sΔ50: 147 ± 24	37.2 ± 7.8	60-70% sVO2max: 11.8 ± 0.5	45 – 60
Slawinski et al. 2001	8 weeks	2 IT/wk 3 CT/wk	sΔ50: 17 ± 0.7	50% TTE sΔ50: 294 ± 45.5	50% sVO_{2max}: 9.1 ± 0.3	25% TTE sΔ50: 147 ± 22.7	53.2 ± 7.9	60-70% sVO2max: 11.8 ± 0.4	60
Ferley et al. 2013	6 weeks	2 IT/wk 2 CT/wk	100% sVO_{2max}: 17.3 ± 2.1	60% TTE sVO_{2max}: 136 ± 36.7	Rest	HRR to 65% HRmax: 142 ± 45.4	60	75% sVO_{2max}: 12.9 ± 1.6	45 – 60
Garcin et al. 2002	8 weeks	2 IT/wk 3 CT/wk	sΔ50: 19.5 ± 1.0	50% TTE sΔ50: 162.5 ± 52	50% sVO_{2max}: 10.3 ± 1.0	25% TTE sΔ50: 81.2 ± 26	64	65-75% sVO_{2max}: 14.4 ± 1.0	60
Bickham et al. 2004	6 weeks	3 IT/wk	90-100% max effort sprints	5-15s, 40-100m	Walk or jog	Work:Rest - 1:5, 1:4, 1:3 5 mins between sets	412	None performed	None performed
Smith et al. 1999	4 weeks	2 IT/wk 1 CT/wk	100% sVO_{2max}: 20.5 ± 0.39	60-75% TTE sVO_{2max}: 135.3 ± 9.96 to 169.1 ± 12.45	Rest	Work:Rest - 1:2 60-75% TTE: 270.6 ± 19.92 to 338.2 ± 24.9	48	60% sVO_{2max}: 12.3 ± 0.23	30
Smith et al. 2003 60% TTE group	4 weeks	2 IT/wk 1 CT/wk	100% sVO_{2max}: 19.1 ± 0.13	60% TTE sVO_{2max}: 133.4 ± 1.4	Rest	Work:Rest - 1:2 266.8 ± 2.8	48	60% sVO_{2max}: 11.46 ± 0.13	30
Smith et al. 2003 70% TTE group	4 weeks	2 IT/wk 1 CT/wk	100% sVO_{2max}: 19.9 ± 0.4	70% TTE sVO_{2max}: 154 ± 4.5	Rest	Work:Rest = 1:2 308 ± 9	40	60% sVO_{2max}: 11.94 ± 0.4	30

wk week; *IT* Interval training; *CT* Continuous training; $s\dot{V}O_{2max}$ speed at $\dot{V}O_{2max}$; *sΔ50* median speed between the sLT and $s\dot{V}O_{2max}$; *TTE* Time to exhaustion; *HRR* Heart rate recovery; HR_{max} age predicted maximum heart rate.

Figure Legends

Figure 1 – Schematic overview of search, screening approach and selection process for suitable studies

Figure 2 – Forest plot of the pre- to post-$\dot{V}O2max$ scores in response to the training intervention implemented in each study, displayed as the bias corrected hedge's effect size with 95% confidence intervals.

Figure 3 - Panel A: Total duration of training performed in the interventions implemented by each study and the distribution of training within each intensity domain. Total training duration is displayed at the end of each stacked column in h, min and s (h:min:s). The time spent in each intensity domain is displayed above each respective section of the stacked column (h:min:s). $<VT_1$: Domain 1 – Below the first ventilatory threshold; $> VT_2 < sVO_{2max}$: Domain 3 - between the second ventilatory threshold and the velocity at maximal aerobic power; $> sVO_{2max}$: Domain 4 - above the velocity at maximal aerobic power. **Panel B**: Total training impulse per week (W_{TRIMP}) of the training interventions implemented by each study with the total W_{TRIMP} split into the interval training (IT) TRIMP and continuous training (CT) TRIMP per week. Total W_{TRIMP} is displayed at the end of each stacked column. The IT W_{TRIMP} and CT W_{TRIMP} is displayed above each respective section of the stacked column.

Figure 4 – **Panel A**: The relationship between the percentage of total training time spent below VT_1 and the change in $\dot{V}O_{2max}$ (Δ $\dot{V}O_{2max}$) in the training intervention implemented in each study. Linear regression line, regression equation and R^2 value displayed for the relationship between the percentage of training time below VT_1 and the Δ $\dot{V}O_{2max}$. *denotes statistically significant change in $\dot{V}O_{2max}$. **Panel B**: The relationship between the percentage of total training time spent above VT_2 and the change in $\dot{V}O_{2max}$ (Δ $\dot{V}O_{2max}$) in the training intervention implemented in each study. Linear regression line, regression equation and R^2 value displayed for the relationship between the percentage of training time

above VT_2. *denotes statistically significant change in $\dot{V}O_{2max}$. Legend with coloured boxes relates to all panels to signify each study.

Figure 5 - Panel A1: The relationship between the average intensity of the total training intervention implemented in each study and the change in $\dot{V}O_{2max}$ ($\Delta\ \dot{V}O_{2max}$). Average intervention intensity is calculated scaled to the speed at $\dot{V}O_{2max}$ ($s\dot{V}O_{2max}$) with $s\dot{V}O_{2max}$ being 1. Linear regression line, regression equation and R^2 value displayed for the relationship between the average intervention intensity and the $\Delta\ \dot{V}O_{2max}$. *denotes statistically significant change in $\dot{V}O_{2max}$. **Panel B1**: The relationship between the prescribed intensity of the interval training work period implemented in each study and the change in $\dot{V}O_{2max}$ ($\Delta\ \dot{V}O_{2max}$). Interval intensity is calculated scaled to the speed at $\dot{V}O_{2max}$ ($s\dot{V}O_{2max}$) with $s\dot{V}O_{2max}$ being 1. Linear regression line, regression equation and R^2 value displayed for the relationship between the interval intensity and the $\Delta\ \dot{V}O_{2max}$. *denotes statistically significant change in $\dot{V}O_{2max}$. **Panel A2**: The relationship between the average intensity of the total training intervention implemented in each study and the change in $\dot{V}O_{2max}$ ($\Delta\ \dot{V}O_{2max}$) excluding data from Bickham & Le Rossignol (2004). Average intervention intensity is calculated scaled to the speed at $\dot{V}O_{2max}$ ($s\dot{V}O_{2max}$) with $s\dot{V}O_{2max}$ being 1. Linear regression line, regression equation and R^2 value displayed for the relationship between the average intervention intensity and the $\Delta\ \dot{V}O_{2max}$. *denotes statistically significant change in $\dot{V}O_{2max}$. **Panel B2**: The relationship between the prescribed intensity of the interval training work period implemented in each study and the change in $\dot{V}O_{2max}$ ($\Delta\ \dot{V}O_{2max}$) excluding data from Bickham & Le Rossignol (2004). Interval intensity is calculated scaled to the speed at $\dot{V}O_{2max}$ ($s\dot{V}O_{2max}$) with $s\dot{V}O_{2max}$ being 1. Linear regression line, regression equation and R^2 value displayed for the relationship between the interval intensity and the $\Delta\ \dot{V}O_{2max}$. *denotes statistically significant change in $\dot{V}O_{2max}$. Legend with coloured boxes relates to all panels to signify each study.

Figure 6 – **Panel A**: The relationship between the total training impulse (TRIMP) of the training intervention implemented in each study and the change in $\dot{V}O_{2max}$ ($\Delta\ \dot{V}O_{2max}$). The total TRIMP is the

accumulated TRIMP of both interval and continuous training sessions completed throughout the training intervention. Linear regression line, regression equation and R^2 value displayed for the relationship between the TRIMP and the change in $\dot{V}O_{2max}$. *denotes statistically significant change in $\dot{V}O_{2max}$. **Panel B**: The relationship between the average intensity of the total training intervention implemented in each study and the total training impulse units required to change $\dot{V}O_{2max}$ by 1 $ml^{-1}{\cdot}kg^{-1}{\cdot}min^{-1}$ ($TRIMP{\cdot}mL{\cdot}kg^{-1}{\cdot}min^{-1}$). Average intervention intensity is calculated scaled to the speed at $\dot{V}O_{2max}$ ($s\dot{V}O_{2max}$) with $s\dot{V}O_{2max}$ being 1. Linear regression line, regression equation and R^2 value displayed for the relationship between the average intervention intensity and the $TRIMP{\cdot}ml^{-1}{\cdot}kg^{-1}{\cdot}min^{-1}$. *denotes statistically significant change in $\dot{V}O_{2max}$. **Panel C**: The relationship between the total training impulse per week (Total W_{TRIMP}) and the change in $\dot{V}O_{2max}$ (Δ $\dot{V}O_{2max}$). Total W_{TRIMP} is the accumulated TRIMP of both interval and continuous training sessions completed per week. Linear regression line, regression equation and R^2 value displayed for the relationship between the W_{TRIMP} and the change in $\dot{V}O_{2max}$. *denotes statistically significant change in $\dot{V}O_{2max}$. **Panel D**: The relationship between the total training impulse per session (Total S_{TRIMP}) and the change in $\dot{V}O_{2max}$ (Δ $\dot{V}O_{2max}$). Linear regression line, regression equation and R^2 value displayed for the relationship between the S_{TRIMP} and the change in $\dot{V}O_{2max}$. *denotes statistically significant change in $\dot{V}O_{2max}$. Legend with coloured boxes relates to all panels to signify each study.

Figure 7 - Panel A: The relationship between the interval training impulse (IT TRIMP) implemented in each study and the change in $\dot{V}O_{2max}$ (Δ $\dot{V}O_{2max}$). The IT TRIMP is the TRIMP of only the interval training sessions completed throughout the training intervention. Linear regression line, regression equation and R^2 value displayed for the relationship between the IT TRIMP and the change in $\dot{V}O_{2max}$. *denotes statistically significant change in $\dot{V}O_{2max}$. **Panel B**: The relationship between the prescribed intensity of the interval training work period implemented in each study and the interval training impulse units required to change $\dot{V}O_{2max}$ by 1 $ml^{-1}{\cdot}kg^{-1}{\cdot}min^{-1}$ (IT $TRIMP{\cdot}mL{\cdot}kg^{-1}{\cdot}min^{-1}$). Interval intensity is calculated scaled to the speed at $\dot{V}O_{2max}$ ($s\dot{V}O_{2max}$) with $s\dot{V}O_{2max}$ being 1. Linear regression line, regression equation and R^2 value displayed for the relationship between the interval intensity and

the IT TRIMP·mL·kg^{-1}·min^{-1}. *denotes statistically significant change in $\dot{V}O_{2max}$. **Panel C**: The relationship between the interval training impulse per week (IT W_{TRIMP}) and the change in $\dot{V}O_{2max}$ (Δ $\dot{V}O_{2max}$). IT W_{TRIMP} is the TRIMP of only the interval training sessions completed per week. Linear regression line, regression equation and R^2 value displayed for the relationship between the IT W_{TRIMP} and the change in $\dot{V}O_{2max}$. *denotes statistically significant change in $\dot{V}O_{2max}$. **Panel D**: The relationship between the interval training impulse per session (IT S_{TRIMP}) and the change in $\dot{V}O_{2max}$ (Δ $\dot{V}O_{2max}$). Linear regression line, regression equation and R^2 value displayed for the relationship between the IT S_{TRIMP} and the change in $\dot{V}O_{2max}$. *denotes statistically significant change in $\dot{V}O_{2max}$. Legend with coloured boxes relates to all panels to signify each study