TITLE

Changes in cardiorespiratory fitness following exercise training prescribed relative to traditional intensity anchors and to physiological thresholds: a systematic review with meta-analysis of individual participant data

Running heading

Cardiorespiratory Fitness and Exercise Intensity Prescription: Individual Participant Data Meta-analysis

AUTHORS

Samuel J. R. Meyler[1], Paul A. Swinton[2], Lindsay Bottoms[1], Lance C. Dalleck[4], Ben Hunter[5], Mark A. Sarzynski[6], David Wellsted[1], Camilla J. Williams[7], Daniel Muniz-Pumares[1]

Affiliations

[1]School of Life and Medical Sciences, University of Hertfordshire, Hatfield, England, UK

[2]School of Health Sciences, Robert Gordon University, Aberdeen, Scotland, UK

[4]Recreation, Exercise and Sport Science Department, Western Colorado University, Gunnison, CO, USA

[5]School of Human Sciences, London Metropolitan University, London, UK

[6]Department of Exercise Science, University of South Carolina, Columbia, SC, USA

[7]School of Human Movement and Nutrition Sciences, The University of Queensland, Brisbane, QLD, Australia

Corresponding author

Daniel Muniz-Pumares, d.muniz@herts.ac.uk

ABSTRACT

Background

It is unknown whether there are differences in maximal oxygen uptake (VO_{2max}) response when prescribing intensity relative to traditional (TRAD) anchors or to physiological thresholds (THR).

Objectives

The present meta-analysis sought to compare: a) mean change in VO_{2max}; b) proportion of individuals increasing VO_{2max} beyond a minimum important difference (MID); and c) response variability in VO_{2max} between TRAD and THR.

Methods

Electronic databases were searched, yielding data for 1544 individuals from 42 studies. Two datasets were created, comprising studies with a control group ('controlled' studies), and without a control group ('non-controlled' studies). A Bayesian approach with multi-level distributional models was used to separately analyse VO_{2max} change scores from the two datasets and inferences were made using Bayes factors (BF). The MID was predefined as one metabolic equivalent (MET; 3.5 $mL \cdot kg^{-1} \cdot min^{-1}$).

Results

In controlled studies, mean VO_{2max} change was greater in THR compared to TRAD (4.1 vs 1.8 $mL \cdot kg^{-1} \cdot min^{-1}$, BF>100) with 64% of individuals in THR experiencing an increase in VO_{2max} >MID, compared to 16% of individuals taking part in TRAD. Evidence indicated no difference in standard deviation of change between THR and TRAD (1.5 vs 1.7 $mL \cdot kg^{-1} \cdot min^{-1}$, BF=0.55), and greater variation in exercise groups relative to non-exercising controls (1.9 vs 1.3 $mL \cdot kg^{-1} \cdot min^{-1}$, BF=12.4). In non-controlled studies, mean VO_{2max} change was greater in THR vs TRAD (4.4 vs 3.4 $mL \cdot kg^{-1} \cdot min^{-1}$, BF=35.1) with no difference in standard deviation of change (3.0 vs 3.2 $mL \cdot kg^{-1} \cdot min^{-1}$, BF=0.41).

Conclusion

Prescribing exercise intensity using THR approaches elicited superior mean changes in VO_{2max} and increased the likelihood of increasing VO_{2max} beyond the MID compared to TRAD. Future exercise training studies should thus consider the use of THR approaches to prescribe exercise intensity where possible. Analysis comparing interventions with controls suggested the existence of intervention response heterogeneity, however, evidence was not obtained for a difference in response variability between THR and TRAD. Future primary research should be conducted with adequate power to investigate the scope of inter-individual differences in VO_{2max} trainability, and if meaningful, the causative factors.

Key Points

- Prescribing exercise training relative to physiological thresholds rather than traditional intensity anchors, elicited superior changes in cardiorespiratory fitness and increased the proportion of individuals increasing cardiorespiratory fitness by at least one metabolic equivalent.
- No difference in cardiorespiratory response variability was observed between exercise groups. Comparisons with controls, however, provided evidence of inter-individual response variability that warrants further investigation.
- Considering the link between cardiorespiratory fitness and both health and performance outcomes, future studies should aim to prescribe exercise relative to physiological thresholds where possible.

DECLARATIONS

Funding

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Conflicts of interest

Authors Samuel J. R. Meyler, Paul A. Swinton, Lindsay Bottoms, Lance C. Dalleck, Ben Hunter, Mark A. Sarzynski, David Wellsted, Camilla J. Williams, Daniel Muniz-Pumares declare that they have no conflicts of interest relevant to the content of this review.

Availability of data and material

Datasets analysed in the current review are available upon reasonable request but are subject to permission from original authors.

Ethics approval

Each study received ethical approval from their respective institutions, conformed to the guidelines of the Declaration of Helsinki, and obtained written informed consent from each participant prior to commencing data collection.

Author contributions

All authors: (1) made substantial contributions to the conception or design of the work; or the acquisition, analysis, or interpretation of data; and (2) drafted the work or revised it critically for important intellectual content. All authors read and approved the final version of the manuscript.

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1 INTRODUCTION

Cardiorespiratory fitness, measured as maximum oxygen uptake ($\dot{V}O_{2max}$), represents the upper limit of cardiopulmonary-muscle oxidative function [1], quantifying the body's ability to transport and utilise oxygen [2]. As such, $\dot{V}O_{2max}$ is recognised as a key determinant of endurance performance, with elite endurance athletes demonstrating some of the highest $\dot{V}O_{2max}$ values ever recorded [3,4]. Additionally, $\dot{V}O_{2max}$ is an important marker of cardiovascular health [5–7] and low levels of $\dot{V}O_{2max}$ are a strong risk factor for all-cause and disease-specific mortality [5]. Despite being the only major risk factor not routinely assessed in clinical practice, growing epidemiological and clinical evidence suggests that $\dot{V}O_{2max}$ may be a stronger predictor of mortality than traditionally assessed risk factors such as smoking, type 2 diabetes mellitus, and obesity [7]. Increasing $\dot{V}O_{2max}$ is thus a commonly sought-after phenotypic change across different populations. Evidence indicates that increasing $\dot{V}O_{2max}$ by one metabolic equivalent (MET; 3.5 $mL{\cdot}kg^{-1}{\cdot}min^{-1}$) can reduce mortality risk by ~10-30% [5,8] and health care costs by ~5% [9,10]. In turn, a value of one MET can be used as a minimum important difference (MID) when evaluating changes in $\dot{V}O_{2max}$ following a period of exercise training [7,11].

Changes in $\dot{V}O_{2max}$ can be explained by the Fick principle, where $\dot{V}O_{2max}$ is the product of maximum cardiac output and arteriovenous oxygen difference [12,13]. Adaptations causing changes in cardiac output (i.e., the product of heart rate and stroke volume) represent 'central' adaptations whereby phenotypic modifications alter convective oxygen delivery, whereas adaptations causing changes in arteriovenous oxygen difference reflect 'peripheral' adaptations, comprised of changes in oxygen extraction and utilisation [14]. The most effective means of increasing $\dot{V}O_{2max}$ is through endurance training, typically in the form of constant load continuous training and/or interval-based training, which are shown to increase $\dot{V}O_{2max}$ by ~5.5 and ~4.9 $mL{\cdot}kg^{-1}{\cdot}min^{-1}$, respectively [15]. On the other hand, $\dot{V}O_{2max}$ is markedly reduced by periods of inactivity (e.g., bed rest) [16]. Whilst both approaches of exercise training have been demonstrated to be efficacious at the group level [15], the individual effect of exercise training on $\dot{V}O_{2max}$ appears to exhibit a heterogenous distribution [17,18], suggesting that some individuals do not attain some of the benefits of exercise.

Several biological and methodological factors underpin this apparent ‘response variability’ (for a review see [19]), as well as measurement error and day-to-day biological variability [20]. To tackle response variability, and specifically the number of individuals attaining a change in $\dot{V}O_{2max}$ surpassing a predefined threshold, interventions commonly adopt ‘additive’ approaches (for a review see [21]). For example, augmenting the exercise stimulus (i.e., increasing training volume, frequency, and/or intensity) often proves effective in increasing response rate as a result of greater group mean increases in $\dot{V}O_{2max}$ [22–25]. Aiming to elicit superior changes in $\dot{V}O_{2max}$ and reduce response variability to the initial stimulus, an example of a ‘subtractive’ approach [21], may be achieved through changing the method used to prescribe exercise intensity [19]. However, the effect of using different means of exercise prescription to do so are unclear.

Exercise intensity is commonly prescribed relative to traditional (TRAD) intensity anchors (Table 1) [15] whereby recommended percentages of such values are used to prescribe exercise in a given intensity domain. It is worth noting that whilst various nomenclature is used to describe the different intensity domains in performance and health settings [26], the three-domain classification (moderate, heavy, and severe intensity exercise) will be referred to in the present study. Notably, TRAD approaches are evidenced to elicit marked variation in acute physiological responses and exercise tolerance [27–33]. As changes in $\dot{V}O_{2max}$ manifest in response to specific exercise-induced adaptive stimuli [34], when different stimuli are experienced by individuals over time, it is plausible that this may contribute to a portion of $\dot{V}O_{2max}$ response variability [19,31,35].

Table 1. ‘Traditional’ anchors of exercise intensity

Intensity Anchor	Abbreviation	Description
Maximum oxygen uptake	$\dot{V}O_{2max}$	Maximum oxygen uptake attained during maximal exercise despite increases in external workload
Oxygen uptake reserve	$\dot{V}O_2R$	Difference between maximum and resting oxygen uptake
Maximum heart rate	HR_{max}	Maximum heart rate reached during maximal exercise despite increases in external workload

Heart rate reserve	HRR	Difference between maximum and resting heart rate
Maximum work rate	WR_{max}	Maximum work rate achieved during an incremental exercise test

Instead, using physiological thresholds that demarcate the intensity domains as intensity anchors (Table 2) has shown to elicit more homogenous acute physiological responses to an exercise bout [29,32,33,36]. It is of interest to explore whether this has a positive impact on longer term responses (i.e., training-induced changes in $\dot{V}O_{2max}$) regarding their magnitude and variability. If the magnitude of training-induced changes in $\dot{V}O_{2max}$ can be increased among a larger proportion of individuals, and the number of individuals experiencing negligible changes in their $\dot{V}O_{2max}$ is reduced, this could have profound implications for improving health outcomes and approaches to exercise prescription.

Table 2. Physiological thresholds delineating the boundary of the moderate and heavy intensity domain and the heavy and severe intensity domain

Physiological threshold	**Description**
Boundary between the moderate and heavy intensity domain	
Lactate threshold (LT)	Blood lactate concentration rises above baseline levels
Gas exchange threshold (GET)	First breakpoint at which $\dot{V}CO_2$ increases disproportionately to $\dot{V}O_2$
First ventilatory threshold (VT_1)	An increase in $\dot{V}_E/\dot{V}O_2$ with no concurrent increase in $\dot{V}_E/\dot{V}CO_2$
Boundary between the heavy and severe intensity domain	
Maximum lactate steady-state (MLSS)	Highest constant workload that leads to a balance between lactate production and elimination
Respiratory compensation point (RCP)	Second breakpoint at which $\dot{V}_E$ increases disproportionately to $\dot{V}O_2$
Second ventilatory threshold (VT_2)	A simultaneous increase in both $\dot{V}_E/\dot{V}O_2$ and $\dot{V}_E/\dot{V}CO_2$
Critical power (CP)	Asymptote of the power–duration relationship

$\dot{V}CO_2$: Carbon dioxide production, $\dot{V}_E$: minute ventilation, $\dot{V}O_2$: oxygen uptake

1.1 Objectives

Examining differences between THR and TRAD exercise programmes (and using non-exercising control groups [CON] where applicable), we sought to: a) compare the mean change scores in $\dot{V}O_{2max}$ and the proportion of individuals expected to attain increases in $\dot{V}O_{2max}$ beyond a MID of one MET (3.5 $mL \cdot kg^{-1} \cdot min^{-1}$) between THR and TRAD; and b) test the hypothesis that $\dot{V}O_{2max}$ response variability is lower in THR compared to TRAD.

2 METHODS

2.1 Protocol and registration

This review was pre-registered on PROSPERO (id: CRD42021226644) and the present protocol has been conducted in accordance with the Preferred Reporting Items for Systematic Review and Meta-analysis of Individual Participant Data guidelines [37] (Supplementary file).

2.2 Eligibility criteria

2.2.1 Type of study

Randomised controlled and non-controlled training studies, written in English, and published before October 2023.

2.2.2 Type of participants

Healthy males and females, ≥18 years of age, BMI ≤30 $kg \cdot m^2$, and were not suffering from any acute or chronic disease(s).

2.2.3 Type of interventions

Training interventions had to meet the following criteria: a) exercise training lasted ≥3 weeks; b) consisted of either continuous training, interval training, or a combination of both, c) exercise was either walking, running or cycling; d) $\dot{V}O_{2max}$ was directly measured pre- and post-intervention via indirect calorimetry during an incremental test to task failure; and e) individuals were either allocated to traditionally prescribed exercise training (TRAD), whereby exercise intensity was prescribed relative to a physiological value, as outlined in Table 1; and/or to a physiological threshold (THR) as outlined in Table 2. The latter includes studies using the delta method (Δ) whereby intensity is prescribed using a physiological threshold and physiological value (i.e., 50% Δ = gas exchange threshold + [0.5 x (critical power-gas exchange threshold)]). Exercise groups involving additional interventional manipulations, such as nutritional supplementation and/or environmental manipulation were excluded. Two datasets were created from eligible studies, one containing 'controlled' studies, where studies included volume-matched THR and TRAD exercise group and a non-exercising control group (CON); and 'non-controlled' studies, where data from any single THR and TRAD exercise group was included.

2.3 Identifying studies for systematic review - information sources and search strategy

Electronic databases PubMed and Scopus were searched initially in 2021 and updated in 2023 such that papers published before October 2023 were included. Databases were searched using the following terms: 'high-intensity interval training', 'continuous training', 'endurance training', 'maximum oxygen uptake', 'peak oxygen uptake', '$\dot{V}O_{2max}$', 'cardiorespiratory fitness', 'healthy adults'. Additional resources were sought via the scrutinisation of reference lists, review articles, and contact with research teams of relevant papers. The literature search and study selection process was carried out independently by two authors (SM and BH) using a systematic review software (Covidence, Veritas Health Innovation, Australia). A third reviewer (author DM) resolved any disagreements regarding study eligibility. The title and abstracts were extracted from the database searches and duplicates were removed automatically by the Covidence software. Papers that were not relevant based on the title were removed. Title and abstracts were screened to identify studies that appeared to meet the predefined eligibility criteria. Full texts of studies passing the title and abstract screening were then scrutinised to determine their eligibility for inclusion in the review.

2.4 Data collection processes

Corresponding authors of eligible studies were contacted via email or by other means of contact (e.g., ResearchGate, social media). Authors were provided with a brief summary of the aims of the present study and invited to share anonymised individual participant data (IPD). Anonymised IPD included age, sex, height (cm), pre- and post-intervention mass (kg), $\dot{V}O_{2max}$ (mL·kg^{-1}·min^{-1} and L·min^{-1}), and BMI for all individuals. Lead authors were contacted in the same manner if corresponding authors were unreachable. A follow-up email containing a deadline for response was sent to authors in the absence of a reply.

2.5 IPD integrity

Once IPD was received, data were checked for consistency with the published report, at the individual level for inconsistencies and missing data. Only individuals with a complete data set were included in the review and individual data not meeting the participant eligibility criteria were excluded. Any discrepancies between IPD and published reports were discussed with the study authors.

2.6 Risk of bias

Risk of bias was assessed in each individual study by two reviewers (SM and DMP). For randomised trials, the Cochrane risk-of-bias tool for randomised trials (RoB2) was used [38]. The ROBINS-I tool was used for assessing risk of bias in non-randomised and uncontrolled intervention studies [39]. An inter-reviewer reliability analysis using the Kappa statistic (k) was performed to determine consistency between reviewers (supplementary file).

2.7 Specification of outcomes and effect measures

All analyses were conducted using $\dot{V}O_{2max}$ (mL·kg^{-1}·min^{-1}) change scores, calculated for each individual as the post-intervention value minus the baseline value. Measures of effect were based on group differences according to this absolute scale and percentage expected to exceed the MID.

2.8 Synthesis methods

Across all analyses, one-stage IPD meta-analysis models were developed. All models were conducted within a Bayesian framework with random intercepts to account for systematic variation across individual studies. Change scores relative to baseline were calculated for each participant on an absolute scale (mL·kg^{-1}·min^{-1}) and distributional models were used to estimate both the mean difference and standard deviation of the difference. A group term (TRAD vs. THR, or Exercise vs. Control) was added as a predictor for the mean and standard deviation, with a log link used for the latter. Posterior distributions were summarised by reporting the median and 95% credible intervals (CrI) for the mean and 75% CrIs for the standard deviation. Separate Bayes factors were estimated comparing models with and without the group predictor for the mean and standard deviation. A Bayes factor greater than 1.0 provided evidence supporting a group difference, whereas values less than 1.0 provided evidence supporting no group difference. The overall strength of evidence in favour of the different models was evaluated according to a previously defined scale [40], with non-neutral descriptions ranging from anecdotal to extreme evidential strength (Table 3).

Table 3. Category of evidence for Bayes Factor interpretation

Bayes Factor (BF)	Strength of Evidence
≥100	Extreme
30-100	Very strong
10-30	Strong
3-10	Moderate
1-3	Anecdotal
1	No evidence

To investigate the proportion of individuals exceeding the MID, we used the posterior samples from the distributional model to generate posterior predictions (n=10,000) and calculated the proportion that exceeded the threshold in each group. Default weakly informative priors were used including Student-t and half-t priors with 3 degrees of freedom. All analyses were performed using the R wrapper package brms interfaced with Stan to perform sampling [41] and the R package bridgesampling to calculate Bayes factors. Convergence of parameter estimates was obtained for all models with Gelman-Rubin R-hat values below 1.1 [42].

3 RESULTS

3.1 Study selection and IPD obtained

See Figure 1 for the flow diagram pertaining to study identification and screening, and the amount of IPD obtained.

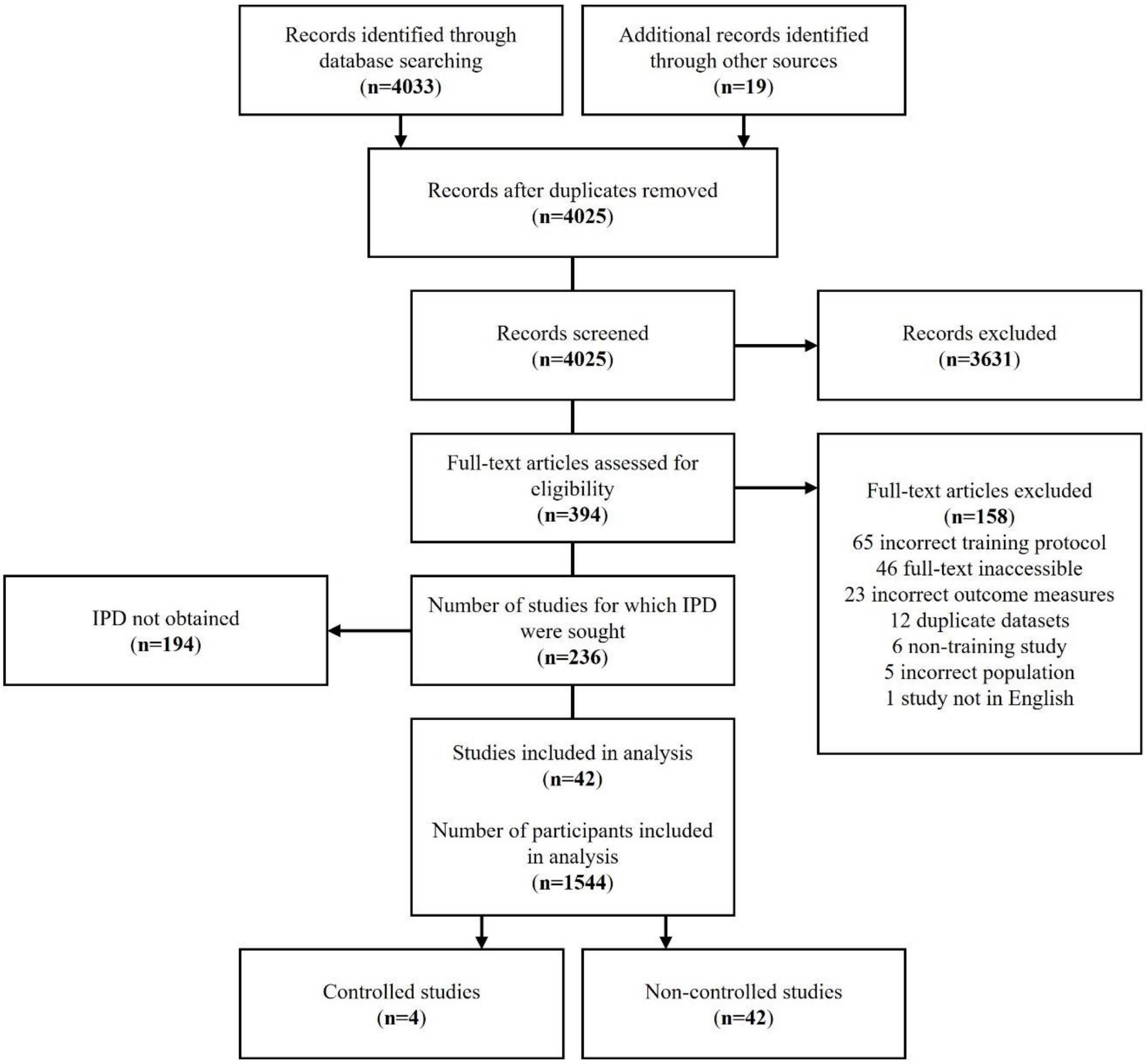

Figure 1. Flow diagram of the study identification and screening process.

3.2 IPD integrity and risk of bias within studies

There were no issues that needed to be raised following the checking of IPD. Risk of bias assessments for individual studies are included in the supplementary file. There was no need for any weighting adjustments prior to the subsequent analyses. Domain 1: low risk 87%, some concerns 3%, high risk 10%; Domain 2: low risk 100%; Domain 3: low risk 100%; Domain 4: low risk 100%; Domain 5: low risk 10%, high risk 90%; Overall: low risk 10%, some concerns 80%, high risk 10% (Supplementary file). Of note, IPD from the HERITAGE study [17] was included in the current analyses. Due to the large amount of HERITAGE IPD analysed (n=562) compared to that of the other eligible studies combined (n=953), the analyses were run with and without its inclusion. There was, however, no difference between the primary results in either case and thus the results are reported including the HERITAGE IPD.

3.3 Study characteristics

Individual study characteristics are presented in Table 4 and summary characteristics of THR and TRAD studies are presented in Table 5.

Table 4. Participant characteristics, sample size, training characteristics and $\dot{V}O_{2max}$ change scores for studies included in the present individual participant data meta-analysis

Study	Year	Participants (age)	Sex	n	Method	Type	Mode (sessions)	Protocol	$\dot{V}O_{2max}$ (mL·kg^{-1}·min^{-1}) Pre Mean ± SD	Post Mean ± SD	Change % Mean ± SD	Change mL·kg^{-1}·min^{-1} Mean ± SD
Arboleda et al. [43]	2019	Sedentary (29±8)	M	18	TRAD	INT	Running (24)	15 x 30 s @ 90-95% HRmax	40.1 ± 6.2	43.7 ± 6.2	9.7 ± 9.8	3.6 ± 3.5
				20	TRAD	CT	Running (24)	40 min @ 65-75% HRmax	43.5 ± 8.6	44.9 ± 8.7	4.3 ± 15.4	1.4 ± 6.7
Astorino et al. [44]	2018	Active (27±8)	M/F	14	THR	INT	Cycling (9)	8-10 x 1 min @ 130% VT	38.8 ± 4.3	41 ± 4.6	5.7 ± 3.9	2.2 ± 1.6
Astorino et al. [45]	2013	Sedentary (24±7)	F	4	TRAD	INT	Cycling (33)	6-10 x 1 min @ 80-90% Wmax	31.7 ± 4.4	36.4 ± 4.2	15.4 ± 9.1	4.7 ± 2.5
				8	TRAD	INT	Cycling (33)	6-10 x 1 min @ 60-80% Wmax	30.6 ± 4.2	37.1 ± 3.4	22.1 ± 8.1	6.5 ± 1.6
Berger et al. [46]	2006	Active (23±4)	M	8	TRAD	CT	Cycling (18-24)	30 min @ 60% VO2max	33.7 ± 3.8	39.8 ± 6	18 ± 7.7	6.1 ± 3
				8	TRAD	INT	Cycling (18-24)	20 x 1 min @ 90% VO2max	34.6 ± 6.8	43 ± 8.3	24.3 ± 5.1	8.4 ± 2.1

Bonafiglia et al. [47]	2016	Active (20±1)	M/F	21	TRAD	CT	Cycling (12)	30 min @ 65% VO2max	42.2 ± 6.5	43.9 ± 6.5	4.4 ± 7.9	1.7 ± 3.2
Bouchard et al. [17]	1999	Sedentary (35±14)	M/F	562	TRAD	CT	Cycling (60)	30-50 min @ 55-75% VO2max	33.1 ± 8.6	38.7 ± 9.1	18 ± 9.9	5.6 ± 2.9
Branch et al. [48,49]	1997, 1999	Sedentary (32±5)	F	8	TRAD	CT	Running (40)	150-375 kcal/session @ 80% HRmax	36.2 ± 4.9	38.8 ± 7.5	6.8 ± 8.8	2.6 ± 3.8
				10	TRAD	CT	Cycling (40)	150-375 kcal/session @ 80% HRmax	29.2 ± 7.9	35.5 ± 7	24.6 ± 13.7	6.3 ± 2.6
				8	TRAD	CT	Cycling (40)	150-375 kcal/session @ 40% HRmax	29.8 ± 4.6	34.1 ± 6.6	16.5 ± 25.3	4.3 ± 7.9
Byrd et al. [50]	2019	Sedentary (32±9)	M/F	11	THR	INT + CT	Cycling + Running (30)	CT: 30-50 min @ <VT1 to >VT2; INT: 8-12 x 60 s @ 100% V̇O2max	33.6 ± 4	38.4 ± 4.4	14.3 ± 3.6	4.8 ± 1.1
				11	TRAD	INT + CT	Cycling + Running (30)	CT: 30-50 min @ 40-65% HRR	30.4 ± 6.2	33 ± 7.2	8.1 ± 3.3	2.5 ± 1.2
Casaburi et al. [51]	1987	Sedentary (23±1)	M/F	9	THR	CT	Cycling (40)	45 min @ 50-75% Δ	34.5 ± 4.1	40.3 ± 4.1	17.3 ± 8	5.8 ± 2.5
Dalleck et al. [52]	2008	Sedentary (37±6)	F	13	TRAD	CT	Walking (30-40)	(~180 min) 250-1000 kcal/wk @ 50% V̇O2R	35.5 ± 5.9	37.9 ± 4.5	7.8 ± 8	2.5 ± 2.3

Dalleck et al. [53]	2016	Sedentary (68±8)	M/F	10	THR	CT	Aerobic exercise (21)	25-50 min @ <VT1 to >VT2	25.9 ± 3.8	29.7 ± 4.9	14.7 ± 7.8	3.8 ± 2.2
				9	TRAD	CT	Aerobic exercise (21)	25-50 min @ 40-65% HRR	24.1 ± 12.3	26.3 ± 11.9	11.4 ± 9.5	2.2 ± 1.5
Daussin et al. [54]	2008	Sedentary (46±8)	M/F	13	THR	CT	Cycling (24)	20-35 min rep 5 min (4 min @ LT, 1 min @ 90% Pmax)	29.1 ± 5.9	31.9 ± 6.4	9.8 ± 8.7	2.8 ± 2.5
				13	THR	INT	Cycling (24)	Work matched with INT	27.5 ± 5.3	32.3 ± 6.5	18.5 ± 16.7	4.8 ± 4.9
Fiorenza et al. [55]	2019	Sedentary (57±8)	M	12	TRAD	INT	Cycling (18)	10-15 min of '10-20-30 training', 3 min rec between 5 min bouts @30%, 50%, 100% max intensity	36.6 ± 8.4	39.4 ± 4.8	7.8 ± 7.8	2.8 ± 2.7
Ghiarone et al. [56]	2019	Active (26±5)	M	8	THR	INT + CT	Cycling (18)	Train twice daily (3d/wk) CT: 5 min @ LT1 plus 100 min @ 50% Δ (LT1 and LT2), INT: 10 x 2 min @ 20% Δ (LT2 and PPO)	36 ± 4.3	39.3 ± 5.4	9 ± 7	3.3 ± 2.5

				7	THR	INT + CT	Cycling (18)	Train once daily (6d/wk) CT: CT: 5 min @ LT1 plus 100 min @ 50% Δ (LT1 and LT2), INT: 10 x 2 min @ 20% Δ (LT2 and PPO)	37.9 ± 7.9	40.2 ± 6.6	8.6 ± 21.9	2.3 ± 5.8
Gormley et al. [57]	2008	Active (22±3)	M/F	14	TRAD	CT	Cycling (22)	30-40 min @ 50-75% HRR	34.5 ± 8.6	39.1 ± 9	13.9 ± 10.3	4.6 ± 3.3
				12	TRAD	INT	Cycling (18)	Wk 1 and 2: 30-40 min @ 50-75% HRR, Wk 3-6: 5 x 5 min @ 95% HRR	36.5 ± 5.8	43 ± 7.6	17.7 ± 10.2	6.5 ± 3.8
				14	TRAD	CT	Cycling (23)	30-60 min @ 50% HRR	35.5 ± 7.9	38.8 ± 9.1	10 ± 10.9	3.4 ± 4
Granata et al. [58]	2016	Active (21±2)	M	10	THR	INT	Cycling (52)	4-7 x 4 min @ 35-75% Δ (LT and WRpeak); 5-12 x 4 min @ 30-80% Δ; 8-20 x 2 min @ 50-80% Δ	45.1 ± 7.6	52.2 ± 7.8	16.2 ± 6.6	7.1 ± 2.8
Hov et al. [59]	2022	Healthy (23±2)	M	10	TRAD	INT	Running (24)	4 x 4 min @ 90-95% HRmax	62.1 ± 4.8	66 ± 5	6.3 ± 2.4	3.9 ± 1.5

Jacques et al. [60]	2021	Moderately trained (35±10)	M	15	THR	INT	Cycling (36)	6-14 x 2 min @ 40-70% Δ	52.3 ± 9.8	56.5 ± 10	8.8 ± 12.6	4.2 ± 6.2
Landen et al. [61]	2021	Moderately trained (35±7)	F	18	THR	INT	Cycling (12)	6-14 x 2 min @ 40-70% Δ	44.5 ± 9	45.9 ± 8.1	3.9 ± 5.2	1.5 ± 2.1
Litleskare et al. [62]	2020	Active (25±4)	M/F	12	TRAD	CT	Running (24)	30-60 min @ 70-80% HRpeak	47.9 ± 5.9	49.7 ± 6.2	3.9 ± 5.6	1.8 ± 2.6
Maturana et al. [63]	2021	Sedentary (27±6)	M/F	21	THR	CT	Cycling (18)	60 min @ LTP1	30.4 ± 4.3	32.7 ± 4.2	7.9 ± 8.6	2.3 ± 2.6
				21	TRAD	INT	Cycling (18)	4 x 4 min @ 90% HRmax	31.9 ± 4.1	37.2 ± 4.1	17 ± 7.9	5.3 ± 2.1
Maunder et al. [64]	2021	Active (32±7)	M	8	THR	INT + CT	Cycling (15)	4-6 x 8 min @ VT2; 90 min @ 95% VT1; 3 x 25 min @ 50% Δ (VT1 and VT2); 6-10 x 3 min	52.5 ± 6.4	53.4 ± 6.9	1.7 ± 3.5	0.9 ± 1.8
McNicol et al. [65]	2009	Active (21±5)	M/F	14	THR	CT	Running (18)	20 min @ 0.8 km/h less than LTv + 0.1 km/h per session	44 ± 5.5	47.6 ± 6.5	8.7 ± 12.2	3.6 ± 5.1
				13	THR	CT	Running (18)	20 min @ 0.8 km/h less than LTv	44 ± 6.9	45.3 ± 7	3 ± 2.4	1.3 ± 1

Mendes et al. [66]	2013	Untrained (23±2)	M	13	THR	CT	Cycling (18)	24-39 min @ MLSS	44.9 ± 4.8	49.8 ± 4.5	11.2 ± 7.2	4.9 ± 3.1
Myrkos et al. [67]	2023	Young adults (21±3)	M/F	13	TRAD	INT	Running (14)	Running bouts @ 90% PTV	57.7 ± 8	61.4 ± 9.23	6.5 ± 5.7	3.8 ± 3.4
				11	THR	CT	Running (14)	-2.5% of CV	58.2 ± 7.5	61.1 ± 6.4	5.6 ± 6.7	3 ± 3.7
Nicolini et al. [68]	2019	Sedentary (23±4)	M	15	TRAD	INT	Cycling (18)	5 x 1 min @ 105-135% WRpeak	35.5 ± 4.8	40 ± 5.1	12.9 ± 7	4.5 ± 2.2
Nio et al. [69]	2020	Untrained (52±4)	F	25	TRAD	INT	Cycling (36)	4 x 4 min @ 90-95% HRmax	29.4 ± 5.3	35.4 ± 5.4	21.6 ± 11.4	6.1 ± 2.9
O'Leary et al. [70]	2017	Untrained (26±5)	M/F	10	THR	CT	Cycling (18)	90% LT matched to work (KJ) done in INT	43.5 ± 5.9	47.4 ± 8	8.6 ± 8.4	3.9 ± 3.8
				8	THR	INT	Cycling (18)	6-8 x 5 min @ 50% Δ	44.8 ± 4.2	48.8 ± 5.4	8.8 ± 7.3	4 ± 3.1
Pothier et al. [71]	2021	Untrained (69±5)	M/F	21	TRAD	INT + CT	Cycling (36)	INT: 20 x 15s @ 100-110% MAP, CT: 20 min @ 65-75% MAP	22.2 ± 6.2	24.3 ± 7	10.4 ± 16.6	2.1 ± 3.4
Preobrazenski et al. [72]	2019	Active (21±2)	M	14	TRAD	CT	Cycling (15)	30 min @ 65% WRpeak	46 ± 6.7	49.7 ± 5.2	8.7 ± 7.3	3.7 ± 3.1

				14	THR	CT	Cycling (15)	30 min @ 'NEG' talk-test stage	45.8 ± 5.9	51.2 ± 6.1	12.2 ± 7.1	5.4 ± 3
Reuter et al. [73]	2023	Untrained (46±8)	M/F	16	TRAD	CT	Running/ walking (78)	50 min @ 55% HRR	34.5 ± 3.8	35.3 ± 4	2.6 ± 9.1	0.8 ± 3.1
				15	TRAD	CT + INT	Running/ walking (78)	CT: 50 min @ 55% HRR, INT: 4 x 4 min @ 95% HRmax	33.9 ± 5.3	37.3 ± 4.9	10.7 ± 8	3.4 ± 2.7
Schaun et al. [74]	2018	Healthy (23±4)	M	14	TRAD	INT	Running (48)	8 x 20 s @ 130% vV̇O2max	46.8 ± 7.1	57.7 ± 6.7	24.9 ± 15.6	11 ± 6.2
				14	THR	CT	Running (48)	30 min @ 90-95% HR at VT2	47.9 ± 7.5	56.6 ± 7.9	19.6 ± 15.6	8.8 ± 6
Schubert et al. [75]	2017	Active (30±9)	M/F	11	TRAD	INT	Cycling (12)	6-8 x 90% PPO	31.4 ± 9.7	33.1 ± 9.8	6.1 ± 5.2	1.8 ± 1.7
Scharhag-Rosenberger et al. [76]	2012	Untrained (41±6)	M/F	20	TRAD	CT	Running/ walking (156)	45 min @ 60% HRR	37.8 ± 5.3	43.1 ± 7.1	14.2 ± 11.7	5.3 ± 4.2
Stensvold et al. [77]	2015	(72±2)	M/F	77	TRAD	CT	Aerobic exercise (156)	50 min @ 70% HRpeak	31.1 ± 5.9	32.6 ± 6.1	5.5 ± 10.7	1.5 ± 3.4

			M/F	49	TRAD	INT	Aerobic exercise (156)	repetitions of 4 min intervals with 3 min recovery periods 85-95% HRpeak	31.8 ± 6.9	35.7 ± 6.7	13.7 ± 14.6	3.9 ± 4.3
Tarumi et al. [78]	2022	Older adults (70±6)	M/F	28	TRAD	CT + INT	Running/ walking (156)	CT: 25-40 min @ 75-85% and 85-90% HRmax	22.5 ± 4	25.1 ± 4.1	15 ± 28.4	2.6 ± 5.5
Tjønna et al. [79]	2013	Inactive (42±3)	M	10	TRAD	INT	Running/ walking (30)	1 x 4 min @ 90% HRmax	39.2 ± 5.3	44.1 ± 5.6	12.9 ± 7.7	4.9 ± 2.7
				12	TRAD	INT	Running/ walking (30)	4 x 4 min @ 90% HRmax	44.8 ± 5.3	51 ± 4.6	14.4 ± 8.9	6.2 ± 3.6
Vanhatalo et al. [80]	2008	Habitually active (29±6)	M/F	9	THR	INT	Cycling (12)	2 x p/wk 6 x 5 min at 105% EP + 1 x p/wk 10 x 2 min @ 50% WEP expenditure during the first 2 min period	50.7 ± 5.4	56 ± 6	10.5 ± 5.3	5.3 ± 2.7
Vollaard et al. [81]	2009	Healthy (24±2)	M	23	TRAD	CT	Cycling (24)	45 min @70% V̇O2max	49.2 ± 5.2	55.6 ± 7.1	13.1 ± 10.8	6.4 ± 4.9

Weatherwax et al. [82]	2019	Sedentary (46±11)	M/F	16	THR	CT	Aerobic exercise (33)	Energy Expenditure of 5.6-15.4 kcal/kg/wk @ HR <VT1 to >VT2	30.5 ± 6.6	34 ± 7.7	11.4 ± 3.9	3.5 ± 1.5
				13	TRAD	CT	Aerobic exercise (33)	Energy Expenditure of 5.6-15.4 kcal/kg/wk @ 40-65% HRR	25.2 ± 4.7	26.5 ± 4.2	6.1 ± 7.7	1.4 ± 1.9
Wolpern et al. [83]	2015	Sedentary (33±10)	M/F	9	THR	CT	Running (31)	20-30 min @ HR <VT1 to >VT2	35.4 ± 8.8	39.5 ± 8.8	12.2 ± 5.2	4.1 ± 0.9
				11	TRAD	CT	Running (31)	20-30 min @ 40-65% HRR	35.1 ± 5.5	36.4 ± 5.7	4 ± 5.4	1.4 ± 1.8
Yan et al. [84]	2017	Moderately trained (32±8)	M	66	THR	INT	Cycling (12)	6-14 x 2 min @ 40-70% Δ	49.2 ± 8	50.5 ± 7.7	3.2 ± 9.4	1.3 ± 4.3

THR: exercise prescribed relative to physiological thresholds, TRAD: exercise prescribed relative to a traditional intensity anchor, CT: continuous exercise, INT: interval exercise, HR_{max}: maximum heart rate, HR_{peak}: peak heart rate, HRR: heart rate reserve, $\dot{V}O_{2max}$: maximum oxygen uptake, $\dot{V}O_2R$: oxygen uptake reserve, VT: ventilatory threshold, WEP: work above end power during a 3 min all out test, PPO: peak power output, $v\dot{V}O_{2max}$: velocity at $\dot{V}O_{2max}$, WR_{peak}: peak work rate, MAP: maximum aerobic power, LT: lactate threshold, Δ: delta method, MLSS: maximum lactate steady state, LTv: velocity at LT, CV: critical velocity, PTV: peak treadmill velocity, LTP: lactate turn point, Pmax: maximum power, M: males, F: females.

Table 5. Summary characteristics of controlled and non-controlled THR and TRAD studies included in the present individual participant data meta-analysis

	Study group		
Controlled Studies	**THR**	**TRAD**	**CON**
Studies (n)	4	4	4
Individuals (n)	46	44	49
Sex (M, F)	18, 28	16, 28	20, 29
Age (y)	43±17	46±17	44±14
Body mass (kg)	72±11	73±11	75±10
Baseline $\dot{V}O_{2max}$ ($mL \cdot kg^{-1} \cdot min^{-1}$)	31±7	29±5	29±6
Training duration (wks.)	13±1	13±1	
Training sessions (n)	29±5	29±5	
Continuous exercise	3	3	
Interval exercise	0	0	
Combination	1	1	
Non-controlled Studies	**THR**	**TRAD**	
Studies (n)	18	25	
Individuals (n)	354	1190	
Sex (M, F)	239, 115	565, 622	
Age (y)	31±12	38±18	
Body mass (kg)	75±13	71±13	
Baseline $\dot{V}O_{2max}$ ($mL \cdot kg^{-1} \cdot min^{-1}$)	42±10	34±9	
Training duration (wks.)	7±4	14±14	
Training sessions (n)	23±11	43±39	
Continuous exercise	13	19	
Interval exercise	8	16	
Combination	4	4	

$\dot{V}O_{2max}$: maximum oxygen uptake. Data are presented as means or mean ± standard deviation.

3.4 Result of syntheses

3.4.1 Changes in maximum oxygen uptake

Controlled studies

'Extreme' evidence (BF>100) was identified in support of a greater improvement in $\dot{V}O_{2max}$ for THR (4.1 [95%CrI: 3.1 to 5.0 mL·kg^{-1}·min^{-1}]) compared to TRAD (1.8 [95%CrI: 0.9 to 2.8 mL·kg^{-1}·min^{-1}]; Figure 2). Individuals were estimated to be approximately four times more likely to experience an increase in $\dot{V}O_{2max}$ greater than the MID in THR (64%) compared to TRAD (16%). There was 'anecdotal' evidence (BF=0.55) in support of no difference in variation of $\dot{V}O_{2max}$ change scores between THR (1.5 [75%CrI: 1.2 to 1.8 mL·kg^{-1}·min^{-1}]) and TRAD (1.7 [75%CrI: 1.4 to 2.1 mL·kg^{-1}·min^{-1}]; Figure 2). When THR and TRAD were combined, 'strong' evidence (BF=12.4) was identified in support of a greater variation in $\dot{V}O_{2max}$ change scores in the training groups (1.9 [75%CrI: 1.7 to 2.2] mL·kg^{-1}·min^{-1}]) compared to CON (1.3 [75%CrI: 1.1 to 1.6] mL·kg^{-1}·min^{-1}]; Figure 3).

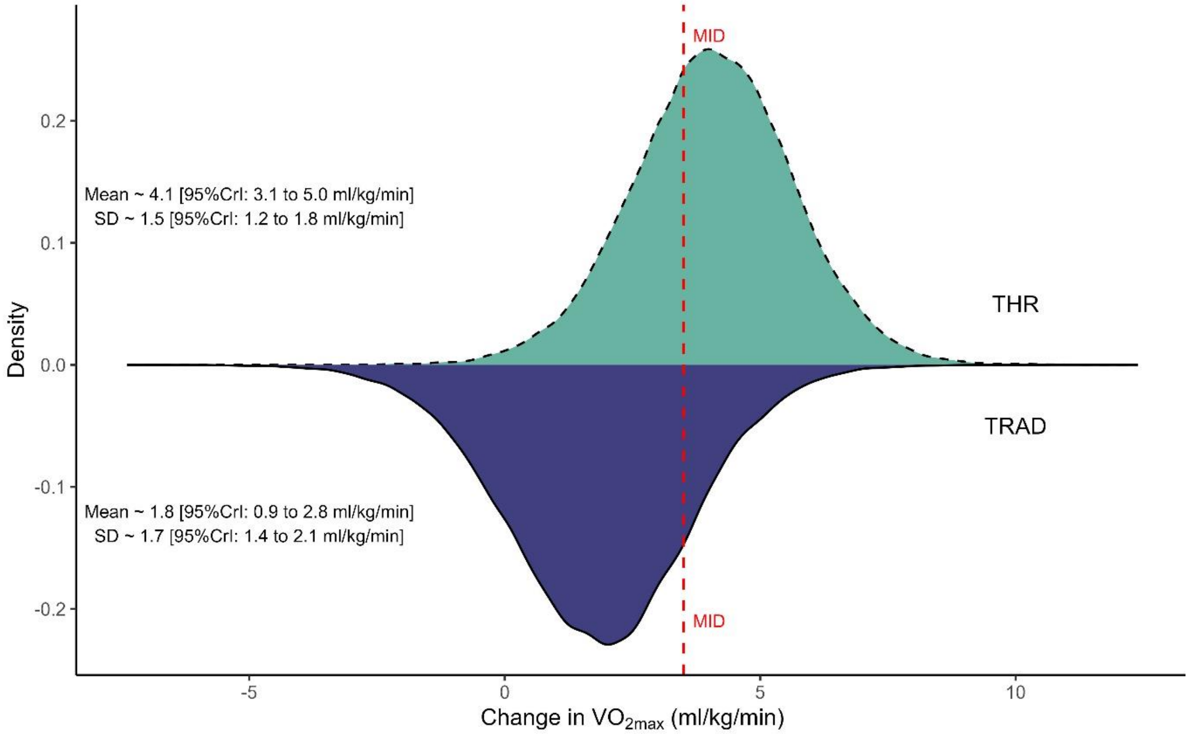

Figure 2. Modelled changes in $\dot{V}O_{2max}$ (mL·kg^{-1}·min^{-1}) from controlled studies comparing exercise prescription using traditional intensity anchors or physiological thresholds. MID: minimum important difference, THR: exercise training prescribed relative to physiological thresholds (n=46),

TRAD: exercise training prescribed relative to traditional intensity anchors (n=44), SD: standard deviation; CrI: credible interval.

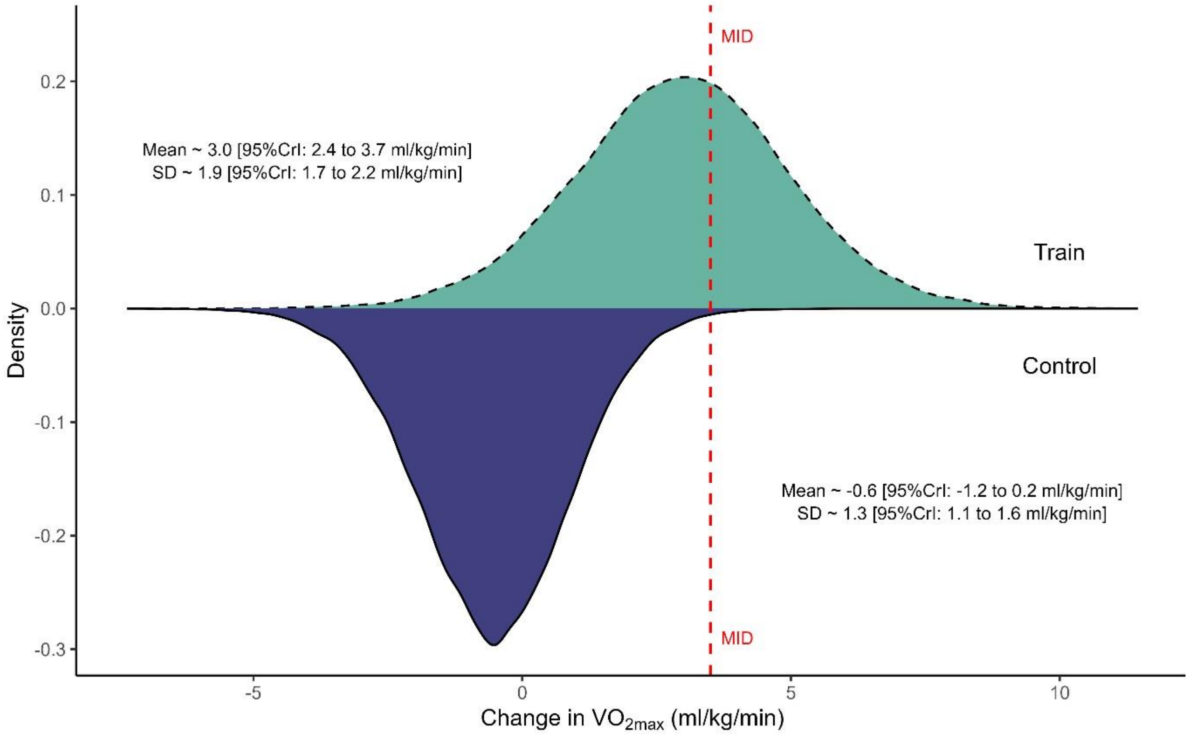

Figure 3. Modelled changes in $\dot{V}O_{2max}$ (mL·kg^{-1}·min^{-1}) from controlled studies comparing pooled data from all training groups and control. MID: minimum important difference Train: comprises data from groups where exercise training is prescribed using either traditional intensity anchors or relative to physiological thresholds (n=90), Control: comprises data from non-exercising control groups (n=49), SD: standard deviation; CrI: credible interval.

Non-controlled studies

In general, similar findings to those obtained for controlled studies were observed in non-controlled studies. ‘Very strong’ evidence (BF=35.1) was identified in support of a greater improvement in $\dot{V}O_{2max}$ for THR (4.4 [95%CrI: 3.7 to 5.2 mL·kg^{-1}·min^{-1}] compared to TRAD (3.4 [95%CrI: 2.8 to 4.1 mL·kg^{-1}·min^{-1}]; Figure 4). Predictions using the fitted model estimated 60% of individuals in THR should be expected to increase $\dot{V}O_{2max}$ beyond the MID, with 47% expected in TRAD. ‘Anecdotal’ evidence (BF=0.41) was identified in support of no difference in variation of $\dot{V}O_{2max}$ change scores between THR (3.0 [75%CrI: 2.7 to 3.3 mL·kg^{-1}·min^{-1}]) and TRAD (3.2 [75%CrI: 2.9 to 3.5 mL·kg^{-1}·min^{-1}]; Figure 4).

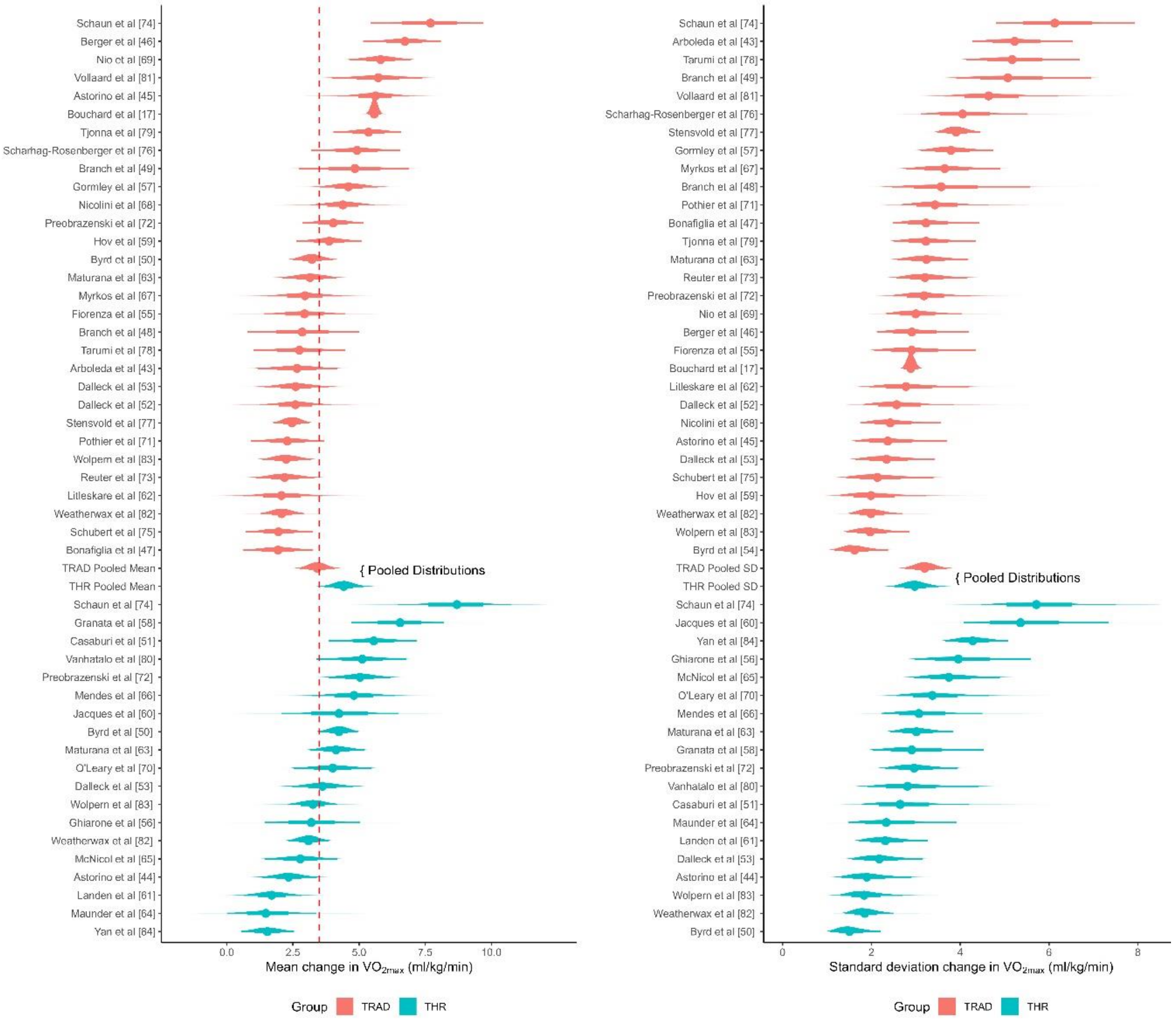

Figure 4. Forest plot of modelled mean (left) and standard deviation (right) change in $\dot{V}O_{2max}$ (mL·kg^{-1}·min^{-1}) across non-controlled studies comprising exercise prescription using either traditional intensity anchors or physiological thresholds. Distributions represent "shrunken estimates" based on all relevant effect sizes, the random effects model fitted, and borrowing of information across studies to reduce uncertainty. Circles and connected intervals represent the median value and 95% credible intervals for the shrunken estimates. Pooled estimates across conditions are presented in the centre of the plot. Red line illustrates the minimum important difference threshold. THR: exercise training prescribed relative to physiological thresholds, TRAD: exercise training prescribed relative to traditional intensity anchors.

4 DISCUSSION

This is the first IPD meta-analysis to explore the magnitude and variation in $\dot{V}O_{2max}$ change scores elicited by training programmes using THR and TRAD approaches. The main findings were: 1) prescribing exercise intensity using THR approaches elicited superior mean changes in $\dot{V}O_{2max}$ and increased the likelihood of an individual increasing $\dot{V}O_{2max}$ beyond the MID; and 2) there appeared to be no difference in response variability between THR and TRAD.

4.1 Mean changes in $\dot{V}O_{2max}$

Superior increases in $\dot{V}O_{2max}$ were observed in THR compared to TRAD in both the controlled and non-controlled analyses. In the controlled studies, it was estimated that individuals were approximately four times as likely to experience an increase in $\dot{V}O_{2max}$ beyond the MID. This estimate was based on the statistical model indicating 64% of participants undergoing THR would experience an increase of ≥3.5 $mL \cdot kg^{-1} \cdot min^{-1}$ compared with 16% of participants undergoing TRAD. In the non-controlled studies, greater variability was observed across the larger data set, however, it was estimated that on average, 60% and 47% of individuals would experience changes beyond the MID in THR and TRAD, respectively.

Regarding the notion of increasing ‘response rates’, herein defined as the proportion of individuals improving a given parameter beyond a predefined threshold, the present findings agree with previous literature whereby increased $\dot{V}O_{2max}$ response rates are typically explained by greater mean change scores as opposed to reductions in inter-individual variability [25]. In turn, using THR approaches represents a viable approach in increasing response rates, and thus, increasing the likelihood of individuals attaining the health- and performance-related benefits of exercise training. Importantly, instead of requiring increases in training dose following TRAD (i.e., by increasing training intensity, frequency, and/or duration), using THR approaches appears to be an effective method to increase the proportion of individuals attaining increases in $\dot{V}O_{2max}$ beyond a predefined threshold in response to the initial exercise stimulus.

4.2 Variability in $\dot{V}O_{2max}$ change scores

An interesting finding of the current analysis was that greater variability in $\dot{V}O_{2max}$ change scores were observed in exercising groups compared with the non-exercising control group (Figure 3). Whilst the magnitude of this evidence was small, this provides evidence of inter-individual differences in $\dot{V}O_{2max}$ trainability [18,19,85–87]. This warrants further investigation as currently, differences in inter-individual variability are often found to be attributable to measurement error and biological variability as opposed to differences in trainability [20,88,89].

However, contrary to our hypothesis, weak evidence was obtained in support of no difference in the variability of $\dot{V}O_{2max}$ change scores between THR and TRAD in both analyses. It has been shown that using THR approaches better normalises exercise intensity among individuals compared to when using TRAD anchors, reducing the variability in exercise tolerance and eliciting more homogenous acute physiological responses [29,32,33,36]. Based on the acute data presented in these studies, it was hypothesised that repeated performance of THR would manifest in a more consistent chronic stimulus across participants, resulting in reduced variation in change scores. Previous studies have reported increased $\dot{V}O_{2max}$ response rates following exercise training prescribed using THR compared to TRAD [50,53,82,90], however, in such studies it was unclear whether the increased response rates were the product of a reduction in response variability or simply increased group mean changes in $\dot{V}O_{2max}$, or both. Based on the present findings and a lack of evidence supporting a difference in the variability in $\dot{V}O_{2max}$ change scores following THR, it appears that increased response rates are primarily explained by greater mean $\dot{V}O_{2max}$ change scores.

Typically, THR studies implemented continuous training [53,66,67,70,72,82,90–94]. It is plausible that the prescribed intensities were low enough such that acute metabolic responses to THR and TRAD exercise were not markedly different, despite what may have been large differences in external work rate among individuals [33]. Notably, when intensities approach or exceed the boundary between the heavy- and severe-intensity domain, marked differences in exercise durations and responses can be observed despite only minimal differences in external work rate [33,95–97]. Using physiological thresholds to prescribe and control exercise around this transition may be where such approaches hold their value. Furthermore, the activation of signalling pathways associated with key physiological changes promoting increases in $\dot{V}O_{2max}$ (e.g., mitochondrial biogenesis) are shown to increase at intensities within the severe intensity domain compared to the moderate and heavy intensity domains [98]. Thus, having the ability to prescribe exercise accurately both above and below the boundary between the heavy and severe intensity domain, as is shown when using THR approached, might have beneficial implications on the manifestation of subsequent adaptation.

Various approaches are used to determine and apply physiological thresholds for training purposes [99,100]. Whilst they all aim to approximate the transition between the moderate and heavy intensity domain or the heavy and severe intensity domain, they are not identical [101]. Critical power is often considered the most accurate representation of the latter boundary [96] and as aforementioned is shown to better control exercise intensity than when using TRAD approaches. This is likely explained by the fact that using TRAD approaches do not account for the relative positioning of an individual's critical power relative to a maximum physiological value, such as $\dot{V}O_{2max}$ or HR_{max} [33]. Using critical power as a tool for exercise prescription, however, appears to be limited in exercise-related research with only one study in the present dataset [80] using the concept for training purposes. An advantage of using critical power is that a given work rate can be used to define the exercise session(s), negating the need to adjust exercise intensity to match a given heart rate or $\dot{V}O_2$ response. In the HERITAGE study, the fluctuation in the training work rate was the third most impactful factor (6%) on $\dot{V}O_{2max}$ response variability, despite overall adherence being greater than 95% [102]. It would thus be interesting to investigate whether a reduction in response variability is observed to a higher degree were critical power used as an intensity anchor, particularly when comparing studies prescribing heavy- and/or severe-intensity exercise using a traditional intensity anchor, as this is where we may expect to see a more profound difference in response variability.

It is worth noting that the relative intensity of exercise is consistently shown to influence the magnitude of training-induced adaptations [15,54,57,65,103–105] and that similar adaptations can be observed following a small volume of exercise performed at very high intensities and a large volume of exercise performed at lower intensities [106–110]. In a recent study by Inglis et al. [105], eighty-four healthy participants performed moderate, heavy, severe, or extreme intensity exercise training where exercise intensity was prescribed using a 'domain-based' approach (i.e., THR) using the LT and the maximum metabolic steady state (based on blood lactate and $\dot{V}O_2$ responses) to determine the boundaries between the moderate-heavy and heavy-severe intensity domains, respectively. Interestingly, all exercise groups bar the moderate intensity exercise group increased $\dot{V}O_{2max}$, the power output at the LT, and the power output at the maximum metabolic steady state. Such results further support the notion that that exercise intensity is a key determinant of training-induced changes in training-induced adaptations. All in all, exercise intensity demonstrates a clear influence on the magnitude of subsequent changes in markers such as $\dot{V}O_{2max}$.

Such findings incite the argument that the method used to prescribe exercise intensity is in fact irrelevant, and that irrespective of whether a THR or TRAD approach is used, whichever approach elicits the highest relative exercise intensity will likely induce the largest increases in $\dot{V}O_{2max}$ thereafter. On this, it is important to consider the findings of Collins et al. [104] who conducted a training intervention comprised of CT prescribed at 44% of the maximum power output achieved in a GXT (P_{GXT}) and INT prescribed at 80% P_{GXT}. Of note, there were instances where exercise intensity, when expressed relative to critical power, was higher in the CT group compared to the INT group, and as a result, these individuals experienced superior changes in critical power post-training. At first glance, this contradicts the argument that high intensity INT is superior to lower intensity CT [15,54,57,65,103–105]; however, it instead supports the notion that when prescribing exercise intensity, whether that be for CT or INT, anchoring intensity relative to a maximum physiological value such as $\dot{V}O_{2max}$ is not appropriate [31,33,35,111]. Overall, the authors concluded that the higher the training intensity is when expressed relative to critical power, instead of relative to $\dot{V}O_{2max}$, the greater the training-induced changes thereafter [104]. Therefore, whilst the argument may be presented that the method used to prescribe exercise intensity is inconsequential so long as high intensity exercise is prescribed, a THR based approach should be used to ensure that exercise intensity is in fact 'high' for a given individual based on their unique intensity domains and not just *intended* to be 'high' based on a generalised approach to exercise intensity prescription. Additionally, in the instance that an individual has not achieved a change in $\dot{V}O_{2max}$, for example, above a given 'response' threshold, the possibility exists that the intensity elicited when using a TRAD based approach was simply too low when expressed relative to critical power [19,33,104,112]. Using critical power, or an alternative threshold, would negate this issue of heterogeneity in the prescribed exercise intensity; however, further studies are warranted to confirm this notion [104].

4.4 Limitations

A limitation of the present study was the limited amount of IPD obtained from those meeting the inclusion criteria. Whilst 236 studies met the predefined criteria (Figure 1), the response rate of IPD obtained was 18% (N=42). Additionally, THR IPD (n=354) was limited compared to that of TRAD IPD (n=1190). Exercise training programmes are still routinely prescribed at intensities anchored relative to traditional parameters (i.e., $\dot{V}O_{2max}$ and HR_{max}) [15,18,85,113,114]. Understandably, using HR-based parameters can negate the need for laboratory or field testing, making this an attractive approach, albeit not the most accurate. However, the continued use of $\dot{V}O_{2max}$ as an intensity anchor is surprising given its known inaccuracy in controlling exercise intensity among individuals [29,31,33,36,115,116]. Moreover, if measuring $\dot{V}O_{2max}$, data used to determine given physiological thresholds (e.g., gas exchange threshold) is readily available. Alternatively, self-assessed threshold tools such as rating of perceived exertion (RPE) can be used as surrogates for physiological thresholds and provide an easily accessible means of prescribing and controlling exercise intensity based off a threshold-based approach [117–119]. For example, using the 6-20 Borg scale, moderate, heavy, and severe intensity exercise can be prescribed at approximately ≤13, 14-16, and ≥17, respectively [118]. Lehtonen et al. [118] also note that pairing RPE with external work (e.g., running pace or power output) and internal physiological response (e.g., heart rate) would add a further element of sophistication to the prescription and monitoring of exercise training. There is also evidence demonstrating that critical power and the running equivalent critical speed, can be derived from habitual training data and/or a series of time trials [120–122]. This allows for a more accessible means of critical speed and/or critical power determination, negating the need for laboratory-based testing [122]. The results presented herein will hopefully encourage greater consideration of using THR approaches, where possible, when designing future exercise research studies.

Another limitation of the present study is that compared to the controlled dataset, the non-controlled dataset contained IPD from studies with marked differences in study characteristics. For example, studies adopted various training doses, populations, modes of exercise and training types (Table 3). Effects of these differences were easily observed when comparing the range in mean $\dot{V}O_{2max}$ improvements estimated across the different studies (Figure 4). Despite differences in study characteristics, overall findings from both analyses were consistent. As such, the two datasets and analyses complement each other and help account for their individual limitations; for example, the controlled studies comprise similar study characteristics but are small in sample size, whereas the non-controlled studies express a much larger sample size but marked differences in study characteristics. If enough data were available, stricter eligibility criteria could have been used such that a more homogenous non-controlled dataset could have been analysed. This would have allowed a more robust comparison between THR and TRAD studies regarding the magnitude and variability in $\dot{V}O_{2max}$ change scores, as was done in the controlled study analysis. However, more THR studies are needed for this to occur. Additionally, information regarding adherence to training at the individual level in each independent study was not sought. Thus, conclusions concerning the impact of training adherence on subsequent $\dot{V}O_{2max}$ change scores cannot be elucidated.

5 CONCLUSION

The current IPD meta-analysis found no difference in $\dot{V}O_{2max}$ response variability between training programmes utilising THR and TRAD approaches. However, using THR approaches appears to be a more effective means of increasing the likelihood of an individual attaining meaningful increases in $\dot{V}O_{2max}$, and thus, increased response rates may be more commonly observed using such approaches. The current analysis also provides some evidence supporting the existence of inter-individual differences in $\dot{V}O_{2max}$ trainability based on greater variation in change scores between exercise and control groups. Future primary research should be conducted with adequate power to investigate the scope of inter-individual differences in $\dot{V}O_{2max}$ trainability, and if meaningful, the causative factors.

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