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Original research

The delta concept does not effectively normalise exercise responses to exhaustive interval training

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ABSTRACT

Objectives: This study was designed to quantify inter- and intra-individual variability in performance, physiological, and perceptual responses to high-intensity interval training prescribed using the percentage of delta (%Δ) method, in which the gas exchange threshold and maximal oxygen uptake (VO_{2max}) are taken into account to normalise relative exercise intensity.
Design: Repeated-measures, within-subjects design with mixed-effects modelling.
Methods: Eighteen male and four female cyclists (age: 36 ± 12 years, height: 178 ± 10 cm, body mass: 75.2 ± 13.7 kg, VO_{2max}: 51.6 ± 5.3 $ml \cdot kg^{-1} \cdot min^{-1}$) undertook an incremental test to exhaustion to determine the gas exchange threshold and VO_{2max} as prescription benchmarks. On separate occasions, participants then completed four high-intensity interval training sessions of identical intensity (70 %Δ) and format (4-min on, 2-min off); all performed to exhaustion. Acute high-intensity interval training responses were modelled with participant as a random effect to provide estimates of inter- and intra-individual variability.
Results: Greater variability was generally observed at the between- compared with the within-individual level, ranging from 50 % to 89 % and from 11 % to 50 % of the total variability, respectively. For the group mean time to exhaustion of 20.3 min, inter- and intra-individual standard deviations reached 9.3 min (coefficient of variation = 46 %) and 4.5 min (coefficient of variation = 22 %), respectively.
Conclusions: Due to the high variability observed, the %Δ method does not effectively normalise the relative intensity of exhaustive high-intensity interval training across individuals. The generally larger inter- versus intra-individual variability suggests that day-to-day biological fluctuations and/or measurement errors cannot explain the identified shortcoming of the method.

Practical implications

- The delta concept, a method advocated for setting relative exercise intensities, should not be used for high-intensity interval training prescription due to its inability to adequately normalise exercise responses across individuals.
- Performance, physiological, and perceptual responses to high-intensity interval training are highly variable, making it unlikely that methods devised for continuous exercise, such as the delta concept, would be universally applicable.
- Differences in how individuals respond to high-intensity interval training are more often due to the method used to set exercise intensities than day-to-day fluctuations in physical condition or measurement errors.

1. Introduction

It has been suggested that improvements in physical performance are driven by repeated exposure to the metabolic stress associated with single exercise sessions.[1] Therefore, training should be meticulously programmed to provide an optimal stimulus for adaptation. As the magnitude of several exercise responses is intensity dependent,[2]

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work rate choice can play a critical role in the regulation of adaptive processes.[3,4] Specifically, if a uniform work rate is prescribed (e.g. 200 W), factors such as training status, body dimensions, and sex can differentiate how each person in a group responds. The effective expression of intensity thus depends on an individual's physiological capacity (i.e. relative intensity). Whilst this issue has been long recognised,[5] debate persists as to the best method to normalise exercise intensity prescription,[2,6,7] with implications for the interpretative validity of training studies.[7–9]

Traditionally, exercise intensity is normalised as a percentage of maximal oxygen uptake (%$\dot{V}O_{2max}$). This approach has nevertheless been criticised for eliciting inconsistent physiological responses across individuals when used for exercise prescription.[2,6,10–12] Essentially, %$\dot{V}O_{2max}$ disregards the intensity domains regulating gas exchange, blood acid–base, and intramuscular responses to exercise.[2,6,9] Consequently, the percentage of delta (%Δ) method has been proposed for continuous exercise, due to its ability to reduce inter-individual variability in time to exhaustion (TTE) and physiological/perceptual responses compared with %$\dot{V}O_{2max}$[11,13]:

$$\dot{W}_{target} = \dot{W}_{GET} + \left[\left(\dot{W}_{VO2\ max} - \dot{W}_{GET}\right) \cdot \%\Delta\right] \quad (1)$$

where $\dot{W}_{target}$ is the target work rate, $\dot{W}_{GET}$ is the work rate associated with the gas exchange threshold, $\dot{W}_{VO2max}$ is the work rate associated with the maximal oxygen uptake, and %Δ is the relative intensity chosen. Despite its advantages, %Δ is far from being universally adopted in sport and exercise sciences, indicating that further research may be necessary to confirm its effectiveness.

Whilst %Δ has been scrutinised in the context of continuous exercise, its applicability to high-intensity interval training (HIIT) performed within the severe intensity domain remains elusive (notwithstanding any endorsements of the method[14]). Assuming equivalent energy expenditure, HIIT has been shown to elicit larger improvements in cardiorespiratory fitness compared with continuous training[15–17]; yet, inter-individual variability in adaptive responses seems to be equally pronounced.[16–18] This observation might indicate that simply increasing exercise intensity to strengthen the training stimulus is insufficient to minimise adaptive variability. Whilst cognizant of the role played by genetics,[7,8,19,20] it is possible that adaptive variability stems mostly from a methodological problem. Specifically, inconsistent levels of homeostatic disturbance across individuals, secondary to an inadequate intensity normalisation, may lead to inter-individual variability in training adaptations.[7–9] Assessing the utility of %Δ for HIIT prescription is therefore crucial in understanding whether a large and homogeneous training stimulus can be delivered to a group of individuals undertaking training.

If a method of intensity normalisation is to be useful, exercise responses need to be minimally reproducible from session to session. So far, little attention has been paid to this source of variability in the context of training prescription.[12,20–22] In a secondary analysis of the HERITAGE study, Sarzynski et al.[20] investigated whether recorded heart rates and work rates matched prescribed targets for each training session. Remarkably, session-to-session fluctuations accounted for at least 6 % of the inter-individual variability in $\dot{V}O_{2max}$ adaptations,[20] highlighting the importance of ensuring a reproducible training stimulus. Yet, it remains to be determined whether normal oscillations in HIIT responses influence the effectiveness of an intensity normalisation method.

The aim of this study was to quantify inter- and intra-individual variability in performance, physiological, and perceptual responses to repeated HIIT sessions prescribed as %Δ. It was assumed that these variability estimates would represent the consistency with which a certain training stimulus can be achieved. Based on previous findings,[11,13] low levels of inter- and intra-individual variability in most dependent variables were hypothesised.

2. Methods

2.1. Participants

Eighteen male and four female recreationally trained cyclists volunteered for this study. A minimum sample size of twenty individuals was targeted as recommended by Atkinson & Nevill[23] for reliability analyses. This study was performed according to the ethical standards established by the Declaration of Helsinki. The study was approved by the Research Ethics Committee at the University of Kent (Prop 74_2017_18). All participants provided written informed consent.

2.2. Study design

Participants attended the laboratory on five occasions, at the same time of the day, separated by at least 48 h, but ensuring that no more than two testing sessions were conducted per week. In the first visit, they completed an incremental test to exhaustion. In each of the next four visits, HIIT sessions of identical format and intensity were performed to exhaustion. Performance, physiological, and perceptual responses were modelled to provide estimates of inter- and intra-individual variability. Participants were instructed to refrain from all types of intense exercise 48 h before laboratory visits and to prepare as they would for competition. They were requested to standardise meals and avoid caffeine 24 h before each visit. Tests were performed free from distractions, under similar environmental conditions (16–17 °C), and in the presence of a fan. Participants were always strongly encouraged.

2.3. Incremental test

The incremental test was started immediately after a 10-min warm-up (100 W for men, and 50 W for women), with work rate increasing continuously at 25 $W \cdot min^{-1}$ until voluntary exhaustion, or participants' inability to maintain cadence above 70 $rev \cdot min^{-1}$. This protocol was chosen to target a test duration of approximately 10 min. Breath-by-breath gas exchange was monitored throughout the test. $\dot{V}O_{2max}$ was identified as the highest 30-s mean oxygen uptake ($\dot{V}O_2$), and maximal work rate ($\dot{W}_{max}$) as the mean power output of the last minute. The gas exchange threshold (GET) was obtained by following the procedures described by Lansley et al.,[11] as the first disproportionate increase in carbon dioxide output versus $\dot{V}O_2$; an increase in ventilatory equivalent for oxygen with no increase in ventilatory equivalent for carbon dioxide; and an increase in end-tidal oxygen tension with no fall in end-tidal carbon dioxide tension. Two-thirds of the ramp rate was deducted from the work rate at GET to account for the $\dot{V}O_2$ response time. Immediately after the incremental test, a capillary blood sample was taken from a fingertip to establish blood lactate concentration [La^-], and peak rating of perceived exercise (RPE; 6–20) was noted. Peak heart rate (HR) was identified as the highest value recorded. Attainment of $\dot{V}O_{2max}$ was accepted if at least two of the following criteria were met: respiratory exchange ratio ≥ 1.1, [La^-] ≥ 8 $mmol \cdot L^{-1}$, peak RPE ≥ 18, and peak HR ≥ 95 % of age predicted value (i.e. 220 − age).

2.4. HIIT sessions

The HIIT warm-up consisted of three 7-min bouts consecutively at 60 %, 70 %, and 80 % $\dot{W}_{GET}$. After a 2-min break, HIIT comprising 4-min work intervals and 2-min active recoveries was performed until exhaustion (same criteria as the incremental test) or up to ten work intervals. Participants were not aware of this arbitrary endpoint. The work rate of the work intervals (i.e. $\dot{W}_{target}$) was calculated via Eq. (1), based on the relative intensity of 70 %Δ. The recovery intervals were performed at 20 %$\dot{W}_{target}$. Informed by pilot testing, these relative intensities were chosen to strike a balance between avoiding

immediate exhaustion and ensuring that exhaustion was attained by most participants. The 4-min on, 2-min off format was decided based on the first author's anecdotal observations as a coach, noting that cyclists often report inaccuracies in their assigned training zones for this type of HIIT session. In the last 10 s before HIIT started, participants increased cadence to >100 rev·min^{-1}, but cadence was self-selected afterwards. Breath-by-breath gas exchange and HR were continuously monitored throughout HIIT. RPE was indicated immediately after each work interval and at exhaustion. Capillary blood samples for the assessment of [La$^-$] were collected 20 s into the recovery interval, and 20 s after exhaustion. Ten minutes after HIIT, session RPE (sRPE; 0–10) was recorded. Power output, HR, elapsed time, and cadence were visible to participants.

2.5. Equipment

Cyclists used their own bikes mounted on a cycle ergometer (Cyclus 2, RBM Elektronik-Automation, Leipzig, Germany) set at power mode (i.e. cadence independent). HR was monitored through an ANT+ belt transmitter (Cyclus 2, RBM Elektronik-Automation, Leipzig, Germany). Gas exchange was monitored through a metabolic cart (MetaLyzer 3B, Cortex Biophysik, Leipzig, Germany) calibrated before every test according to the manufacturer's instructions. Blood samples were assessed for [La$^-$] in an automatic analyser (Biosen C-Line, EKF Diagnostics, Penarth, UK).

2.6. Data processing

Raw breath-by-breath gas data were smoothed to 5-s averages. Time at >90 %$\dot{V}O_{2max}$ and time at >95 %$\dot{V}O_{2max}$ were calculated for each HIIT session by summing all $\dot{V}O_2$ samples above the established cut-off. Time at >90 %$\dot{V}O_{2max}$ and time at >95 %$\dot{V}O_{2max}$ were also calculated as %TTE. Cadence was analysed as the average of each work interval. Relative $\dot{V}O_2$, HR, ventilation ($\dot{V}E$), and respiratory frequency (f_R) were analysed as the average of the last minute of each work interval, or the completed duration if shorter than 1 min.

2.7. Questionnaires

Upon arrival at the laboratory, participants answered a series of questions to determine their intrinsic and success motivations[24] as well as sport emotions (i.e. anxiety, dejection, excitement, anger, and happiness).[25] They also indicated their sleep duration, and rated from 1 to 10 their sleep quality, motivation to train, appetite, overall recovery status, muscle soreness, how heavy they were feeling, and how heavy their legs were feeling. These latter scales were adapted from a previous version of the Norwegian Olympic Committee's training diary (http://olt-dagbok.nif.no) and are hereafter referred to as training diary scales. At the end of each exercise session, participants rated subjective workload using the National Aeronautics and Space Administration Task Load Index (NASA-TLX) composed of six subscales: mental demand, physical demand, temporal demand, performance, effort, and frustration.[26] Questionnaires and scales were administered in the first visit for familiarisation purposes only.

2.8. Data analysis

Data were assessed for normality using the Shapiro–Wilk test and normal quantile plots. One-way repeated measures analyses of variance and Bonferroni pairwise comparisons were performed to examine systematic changes between HIIT sessions (Prism 8, GraphPad, San Diego, USA). To assess inter- and intra-individual variability across HIIT sessions, linear mixed models were fitted to the dependent variables with participant as a random effect (R 4.0.4, R Foundation for Statistical Computing, Vienna, Austria). When exercise responses were associated with each work interval, work interval was included as a fixed factor, as well as its quadratic and cubic terms. No specific function was assumed, and the best model was selected based on the Akaike information criterion. Inter-individual variability and intra-individual variability are reported as standard deviations (absolute) and percentages (relative). Ninety-five per cent confidence limits were calculated by bootstrap sampling with 200 repetitions. To determine whether inter-individual variability in exercise responses manifests holistically or independently, correlation coefficients adjusted for repeated observations within participants were computed for each pair of the dependent variables TTE, time at >90 %$\dot{V}O_{2max}$, time at >95 %$\dot{V}O_{2max}$, and sRPE. The significance level was set at $p \leq 0.05$. Results are presented as mean ± SD, unless otherwise stated. When appropriate, partial eta squared is presented as an effect size measure (η_p^2). Rendered R Markdown files are available online as Supplementary material.

3. Results

Participants' characteristics and incremental test results are presented in Table 1. The work and recovery intervals of the HIIT sessions were performed at 4.00 ± 0.43 W·kg^{-1} (85 ± 3 %$\dot{W}_{max}$) and 0.80 ± 0.09 W·kg^{-1} (17 ± 1 %$\dot{W}_{max}$), respectively.

No systematic changes over repeated HIIT sessions were evident for TTE ($F = 2.10$, $p = 0.13$, $\eta_p^2 = 0.09$), time at >90 %$\dot{V}O_{2max}$ ($F = 2.08$, $p = 0.12$, $\eta_p^2 = 0.09$), sRPE ($F = 0.16$, $p = 0.84$, $\eta_p^2 = 0.01$), intrinsic motivation ($F = 2.57$, $p = 0.08$, $\eta_p^2 = 0.11$), success motivation ($F = 0.79$, $p = 0.46$, $\eta_p^2 = 0.04$), dejection ($F = 0.88$, $p = 0.43$, $\eta_p^2 = 0.04$), anger ($F = 0.74$, $p = 0.48$, $\eta_p^2 = 0.03$), sleep duration ($F = 2.15$, $p = 0.12$, $\eta_p^2 = 0.09$), or any of the training diary scales (all $F \leq 2.04$, $p \geq 0.13$, $\eta_p^2 \leq 0.09$) and NASA-TLX subscales (all $F \leq 2.34$, $p \geq 0.10$, $\eta_p^2 \leq 0.10$).

However, there was a between-HIIT session effect for time at >95 % $\dot{V}O_{2max}$ ($F = 3.55$, $p = 0.027$, $\eta_p^2 = 0.14$), anxiety ($F = 4.29$, $p = 0.010$, $\eta_p^2 = 0.17$), excitement ($F = 4.72$, $p = 0.006$, $\eta_p^2 = 0.18$), and happiness ($F = 3.26$, $p = 0.039$, $\eta_p^2 = 0.13$). Bonferroni pairwise comparisons revealed that time at >95 %$\dot{V}O_{2max}$ was higher in session 4 compared with 1 ($p = 0.022$), anxiety was lower in session 4 compared with 2 ($p = 0.040$), and both excitement and happiness were lower in session 3 compared with 1 (both $p \leq 0.012$).

Inter- and intra-individual variability components of performance, physiological, and perceptual responses to HIIT are presented in Table 2. Models are illustrated in Fig. 1. Positive correlations were found between TTE and time at >95 %$\dot{V}O_{2max}$ ($r = 0.34$, $p = 0.004$), TTE and time at >90 %$\dot{V}O_{2max}$ ($r = 0.59$, $p < 0.001$), and time at >95 %$\dot{V}O_{2max}$ and time at >90 %$\dot{V}O_{2max}$ ($r = 0.85$, $p < 0.001$). In contrast, no correlations were observed between TTE and sRPE ($r = 0.11$, $p = 0.36$), time at >95 %$\dot{V}O_{2max}$ and sRPE ($r = 0.07$, $p = 0.57$), and time at >90 %$\dot{V}O_{2max}$ and sRPE ($r = 0.04$, $p = 0.74$).

Table 1
Participants' characteristics and preliminary testing results (mean ± SD).

Age (years)	36 ± 12
Height (cm)	178 ± 10
Body mass (kg)	75.2 ± 13.7
$\dot{V}O_{2max}$ (ml·kg^{-1}·min^{-1})	51.6 ± 5.3
$\dot{V}O_{2max}$ (L·min^{-1})	3.85 ± 0.64
$\dot{W}_{max}$ (W·kg^{-1})	4.72 ± 0.48
$\dot{W}_{max}$ (W)	352 ± 55
HR_{max} (b·min^{-1})	179 ± 14
$[La]_{peak}$ (mmol·L^{-1})	11.9 ± 2.3
$\dot{V}E_{peak}$ (L·min^{-1})	158 ± 26
f_{Rpeak} (cycles·min^{-1})	59 ± 9
RER_{peak}	1.16 ± 0.10
RPE_{peak}	19.0 ± 0.9
GET (ml·kg^{-1}·min^{-1})	35.7 ± 4.1
GET (L·min^{-1})	2.68 ± 0.57

$\dot{V}O_{2max}$: maximal oxygen uptake, $\dot{W}_{max}$: maximal work rate during the incremental test, HR_{max}: maximal heart rate, $[La]_{peak}$: peak blood lactate concentration, $\dot{V}E_{peak}$: peak minute ventilation, f_{Rpeak}: peak breathing frequency, RER_{peak}: peak respiratory exchange ratio, RPE_{peak}: peak rating of perceived exertion, GET: gas exchange threshold.

Table 2
Linear mixed model estimates [95 % confidence limits].

Dependent variable	Best model	Intercept	Inter-individual SD	Intra-individual SD	Inter-individual variability (%)	Intra-individual variability (%)
TTE (min)	Individual random effect	20.3 [15.9–24.2]	9.3 [6.4–12.2]	4.5 [3.7–5.2]	81.2 [65.2–89.3]	18.8 [10.6–32.8]
Cadence ($rev \cdot min^{-1}$)	Work interval (linear), individual random effect	97 [94–100]	7 [4–9]	4 [4–4]	71.7 [53.1–81.5]	28.3 [17.6–46.8]
Oxygen Uptake ($ml \cdot kg^{-1} \cdot min^{-1}$)	Work interval (linear), individual random effect	49.9 [48.0–51.7]	4.6 [3.1–6.3]	2.4 [2.2–2.7]	77.9 [62.2–86.4]	22.1 [13.5–35.5]
RPE	Work interval (quadratic), individual random effect	14.5 [13.8–15.2]	1.6 [1.2–2.1]	1.0 [0.9–1.0]	72.9 [56.4–82.8]	27.1 [17.1–41.1]
$[La^-]$ ($mmol \cdot L^{-1}$)	Work interval (cubic), individual random effect	4.2 [3.1–5.5]	2.0 [1.4–2.5]	1.6 [1.4–1.7]	61.1 [44.4–72.8]	38.9 [27.1–55.3]
Heart rate ($beats \cdot min^{-1}$)	Work interval (cubic), individual random effect	162 [156–167]	12 [8–16]	4 [4–5]	88.6 [76.4–93.1]	11.4 [6.5–22.3]
Ventilation ($L \cdot min^{-1}$)	Work interval (quadratic), individual random effect	128 [116–139]	25 [18–33]	11 [11–12]	83.1 [71.3–89.2]	16.9 [10.7–28.2]
Respiratory frequency ($cycles \cdot min^{-1}$)	Work interval (quadratic), individual random effect	41 [38–45]	8 [5–10]	4 [4–4]	79.0 [62.8–86.1]	21.0 [13.3–36.3]
Time at > 90 $\%\dot{V}O_{2max}$ (s)	Individual random effect	502 [346–652]	337 [238–447]	144 [118–169]	84.5 [70.8–90.9]	15.5 [8.7–28.0]
Time at > 95 $\%\dot{V}O_{2max}$ (s)	Individual random effect	320 [218–422]	279 [170–358]	139 [116–162]	80.0 [55.3–88.3]	20.0 [11.5–42.0]
Time at > 90 $\%\dot{V}O_{2max}$ (%TTE)	Individual random effect	40.8 [35.2–46.2]	11.3 [7.2–15.6]	11.3 [9.2–13.3]	50.0 [25.2–70.3]	50.0 [29.3–73.8]
Time at > 95 $\%\dot{V}O_{2max}$ (%TTE)	Individual random effect	25.3 [20.0–31.5]	12.5 [7.4–16.4]	11.5 [9.3–13.3]	54.2 [29.1–72.9]	45.8 [27.0–70.4]
sRPE	Individual random effect	7.8 [7.3–8.3]	1.3 [0.8–1.7]	0.7 [0.6–0.8]	77.0 [51.5–86.4]	23.0 [13.3–45.0]

SD: standard deviation, RPE: ratings of perceived exertion, $[La^-]$: blood lactate concentration, $\dot{V}O_{2max}$: maximal oxygen uptake, TTE: time to exhaustion, sRPE: session ratings of perceived exertion.

4. Discussion

This is the first investigation on the effectiveness of %Δ as a method to normalise HIIT intensity across individuals where repeated testing was implemented to statistically partition inter- and intra-individual variability.[12,21] Even though %Δ has been advocated in the context of intensity prescription for continuous exercise,[11,13] our findings raise questions regarding its broad-spectrum utility. The absolute magnitude of inter- and intra-individual variability was considerable for several dependent variables, refuting the study hypothesis. Importantly, the generally larger inter-individual variability (ranging from 50 % to 89 % of the total variability), relative to intra-individual variability (11 % to 50 %), suggests that %Δ's poor normalisation of exercise intensity cannot be attributed to day-to-day biological fluctuations and/or measurement errors.

4.1. Inter-individual variability

There is growing consensus that $\%\dot{V}O_{2max}$ should not be used for exercise intensity normalisation.[2,6,9–12] As an alternative, McLellan & Skinner[13] and Lansley et al.[11] have proposed that both $\dot{V}O_{2max}$ and GET are taken into account (i.e. %Δ) for more homogenous exercise responses across individuals. In the first study, McLellan & Skinner[13] sought to identify the best intensity expression to predict TTE as their participants exercised continuously at work rates eliciting approximately 75 %, 85 %, and 95 $\%\dot{V}O_{2max}$. By modelling the relationship between the logarithm of TTE and intensity, authors reported a larger explained variance ($R^2 = 0.88$ versus 0.85) and a lower standard error of estimate (SEE = 0.102 [~3 min] versus 0.118 [~3.4 min]) for %Δ compared with $\%\dot{V}O_{2max}$.[13] Whilst %Δ was not compared with any other method in the present study, our results conflict with those of McLellan & Skinner,[13] as the TTE associated with HIIT appears to be more unpredictable, given the inter- and intra-individual SDs of 9.3 and 4.5 min, respectively. In the second study, Lansley et al.[11] investigated the relationship between exercise intensity expression (i.e. %Δ versus $\%\dot{V}O_{2max}$) and inter-individual variability in several exercise responses. Relative to the mean TTE (20.3 min), the inter-individual SD for HIIT performed at 70 %Δ in the present study (9.3 min or 45.8 %) was higher than the SDs reported by Lansley et al.[11] for continuous exercise at either 80 %Δ (8.6 ± 1.8 min or 20.9 %) or 90 $\%\dot{V}O_{2max}$ (5.4 ± 2.3 min or 42.6 %). Whilst the aforementioned TTE results are not entirely comparable due to differences in the study design, exercise pattern (continuous versus intermittent), and tested exercise intensity bands, the inter-individual variability observed for RPE, $[La^-]$, HR, and $\dot{V}E$ in the present study was similar or exceeded that reported by Lansley et al.[11] for the worst performing condition (i.e. 90 $\%\dot{V}O_{2max}$). Considering all three studies together, it may be concluded that a) individual responses to HIIT are naturally more unpredictable compared with continuous exercise, and/or b) the use of %Δ should not be recommended for HIIT prescription.

4.2. Intra-individual variability

The limited understanding of the reproducibility of performance, physiological, and perceptual responses to each type of training session within a programme complicates the prescription of exercise intensity.[21,22] As acute exercise responses reflect the metabolic stress of a training session, ultimately signalling the start of adaptive processes,[1,3,4] large intra-individual SDs could mean that individual adaptive rates are unpredictable on the basis of a given training stimulus. Large intra-individual SDs would also make it difficult to assess the effectiveness of a relative intensity prescription based on the observed inter-individual variability. Fundamentally, the results of the present study minimise these concerns. Greater variability was generally observed at the between- compared with the within-individual level, ranging from 50 % to 89 % and from 11 % to 50 % of the total variability, respectively. Therefore, a potential mismatch between intended and observed responses to HIIT would mostly reflect a methodological issue in the intensity normalisation, rather than day-to-day biological fluctuations and/or measurement errors.

In absolute terms, the intra-individual SDs may be considered high for some variables, with implications that should not be overlooked. For example, the SD for TTE (4.5 min) was greater than the duration of the work intervals (i.e. 4 min). This might suggest that the intensity of fixed-duration HIIT sessions of similar format (i.e. 4-min on, 2-min off) should be conservatively set to allow individuals to complete one or two work intervals more than predicted if all training sessions of a programme are to be finished. Crucially, the high level of intra-individual variability is not exclusive to this study. Relative to the mean TTE, the intra-individual SD (22.2 %) was similar to that reported by Faude et al.[21] for continuous exercise at the maximal lactate steady state (24.6 %), although it was higher than that reported by Midgley et al.[27] for running-based HIIT at $\dot{V}O_{2max}$ (11.5 %). Whilst the intra-individual SDs for

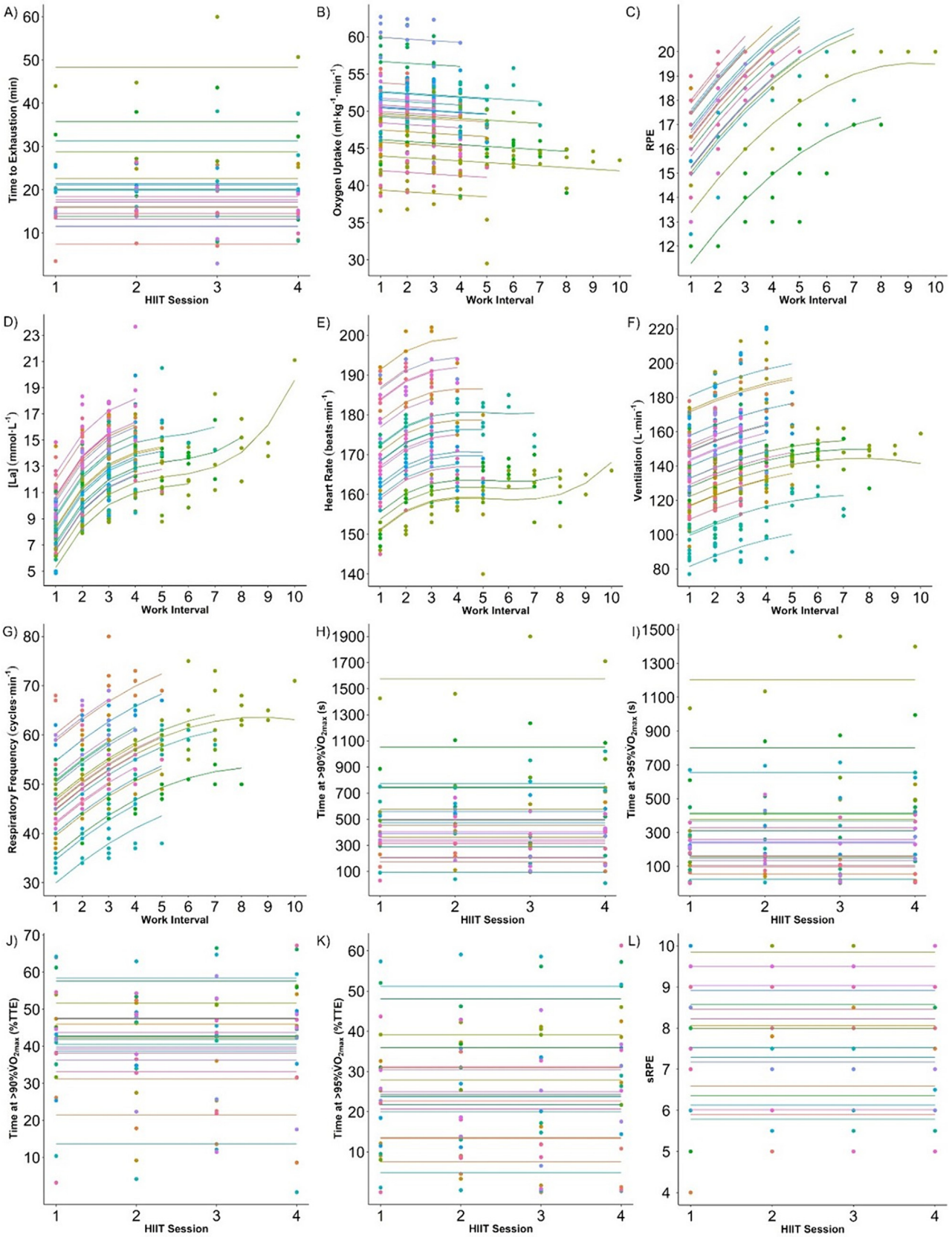

Fig. 1. Model illustration for time to exhaustion (panel A), oxygen uptake (panel B), ratings of perceived exertion (RPE, panel C), blood lactate concentration ([La^-], panel D), heart rate (panel E), ventilation (panel F), respiratory frequency (panel G), time above 90 % or 95 % of maximal oxygen uptake (time at >90 %$\dot{V}O_{2max}$/>95 %$\dot{V}O_{2max}$, panels H, I, J, and K), and session ratings of perceived exertion (sRPE, panel L). Dots represent individual measures and lines represent modelled participants' responses.

VO_2 (2.4 versus 1.6 ml·kg^{-1}·min^{-1}), RPE (1.0 versus 0.4), [La$^-$] (1.6 versus 0.8 mmol·L^{-1}), VE (11 versus 8 L·min^{-1}), and f_R (4 versus 2 cycles·min^{-1}) were higher than those reported by Faude et al.,[21] these figures might be judged comparable if the higher exercise intensity and associated heightened responses of the present study are considered. Time at >90 %VO_{2max} (SD = 144 s, CV = 28.6 %) and time at >95 %VO_{2max} (SD = 139 s, CV = 43.4 %), which are commonly used to quantify the adaptive potential of a HIIT session,[28] were poorly reproducible, corroborating the data from Midgley et al.[27] on running-based HIIT (time at >90 %VO_{2max} SD = 119 s, CV = 24.5 %; and time at >95 %VO_{2max} SD = 82 s, CV = 34.5 %). Our estimates therefore reflect moderate-to-large levels of uncertainty that must be dealt with whatever the method used for HIIT intensity normalisation. From a training perspective, it is currently unclear whether the intra-individual variability reported here and elsewhere[21,27] represents "biological noise" or indeed an inconsistent training stimulus following identical exercise sessions.

4.3. Interpreting variability estimates

In the context of relative intensity prescription, disagreement is expected regarding the delineation of acceptable levels of inter- and intra-individual variability in exercise responses. This uncertainty may be exacerbated by occupation-specific perspectives, whereby practitioners and scientists could hold divergent opinions depending on their unique task requirements (e.g. single athlete HIIT prescription versus research study involving HIIT). To bring clarity to our discourse, we propose specific benchmarks of practical significance, along with their underlying rationale, to guide the interpretation of inter- and intra-individual variability in absolute terms (Table 3). The extent to which variability estimates exceeded these benchmarks can be viewed as a measure of the practical challenges inherent to the use of %Δ for the prescription of exhaustive HIIT. That being said, readers are reminded to avoid dichotomous thinking, such as treating these benchmarks as strict cut-off points, and to acknowledge the nuances of statistical analysis and interpretation.

Although the proposed benchmarks aid in understanding the magnitude of individual variability, it remains unclear which variables most accurately reflect the training stimulus consistency. Specifically, which responses to exercise should researchers and practitioners focus when prescribing HIIT? Considering the nature of HIIT response variability, providing a definitive answer may prove challenging. Our correlational analyses revealed that TTE, time at >90 %VO_{2max}, and time at >95 %VO_{2max} are somewhat interrelated, whereas variability in sRPE manifests independently. It is thus unlikely that identical performance responses across individuals will consistently translate into similar physiological and perceptual outcomes, or vice versa, underscoring the need for a multidimensional approach to quantify the magnitude of the training stimulus.[12]

4.4. Adaptive variability revisited

Whilst the largest estimates of inter-individual variability reported here are specific for prescriptions based on %Δ, there is no reason to believe that traditional (and simpler) methods such as %VO_{2max} would elicit more homogeneous HIIT responses, given the consensual literature on the topic.[2,6,9–12] Therefore, the present findings reinforce the hypothesis that inter-individual variability in training adaptation, as demonstrated following either HIIT or continuous training programmes,[16–18] is not primarily attributed to genetics.[33,34] For instance, in the HERITAGE family study, from which heritability estimates of around 50 % have been derived for VO_{2max} gains with training,[19,20] exercise intensity as %VO_{2max} was prescribed based on individual VO_2–HR relationships, which can be biased by several factors.[35] This leaves open the possibility that the role of genetics has consequently been overestimated due to a methodological issue.

Table 3
Proposed benchmarks to contextualise inter- and intra-individual variability.

Dependent variable	Benchmark	Rationale
TTE (min)	4	Duration of work intervals in this study. Anecdotally, from a coaching perspective, completing one work interval more or less than predicted is considered normal and it is usually manageable. However, a larger degree of variability might affect athletes' confidence and/or potentially influence their adaptive responses to the training programme.
Cadence (rev·min^{-1})	N/A	Freely chosen cadence is largely individual and its determinants are not well established.[29]
Oxygen uptake (ml·kg^{-1}·min^{-1})	3.5	One metabolic equivalent (MET), which is a rough approximation of the energy expended by humans whilst at rest. Multiples of the nominal MET value have been used to express exercise intensity.[30]
RPE	1	Typical inter-individual variability (SD) when continuous exercise is performed at the maximal lactate steady state, an indicator of common physiological stress profile between individuals, often used for relative intensity prescription.[21]
[La$^-$] (mmol·L^{-1})	1.2	Typical inter-individual variability (SD) when continuous exercise is performed at the maximal lactate steady state, an indicator of common physiological stress profile between individuals, often used for relative intensity prescription.[21]
Heart rate (beats·min^{-1})	9	Typical inter-individual variability (SD) when continuous exercise is performed at the maximal lactate steady state, an indicator of common physiological stress profile between individuals, often used for relative intensity prescription.[21]
Ventilation (L·min^{-1})	15	Typical inter-individual variability (SD) when continuous exercise is performed at the maximal lactate steady state, an indicator of common physiological stress profile between individuals, often used for relative intensity prescription.[21]
Respiratory frequency (cycles·min^{-1})	5	Typical inter-individual variability (SD) when continuous exercise is performed at the maximal lactate steady state, an indicator of common physiological stress profile between individuals, often used for relative intensity prescription.[21]
Time at >90 % VO_{2max} (s)	99	Typical (mean) difference in time at a high percentage of VO_{2max} between HIIT sessions of similar total work but leading to contrasting VO_{2max} improvements.[31]
Time at >95 % VO_{2max} (s)	99	Typical (mean) difference in time at a high percentage of VO_{2max} between HIIT sessions of similar total work but leading to contrasting VO_{2max} improvements.[31]
Time at >90 % VO_{2max} (%TTE)	N/A	No benchmark of practical significance is currently available.
Time at >95 % VO_{2max} (%TTE)	N/A	No benchmark of practical significance is currently available.
sRPE	1	The 6–20 and 0–10 RPE scales are largely correlated.[32] Hence, the benchmark for RPE is reproduced here.

SD: standard deviation, RPE: ratings of perceived exertion, [La$^-$]: blood lactate concentration, VO_{2max}: maximal oxygen uptake, TTE: time to exhaustion, sRPE: session ratings of perceived exertion, HIIT: high-intensity interval training, N/A: not applicable.

4.5. Methodological considerations

A key decision in the planning of this study was not to differentiate between male and female cyclists for recruitment purposes. This approach was predicated on the absence of evidence or guidelines indicating that the %Δ application should be sex specific. Furthermore, employing various intensity normalisation methods across sexes is common practice.[9] Thus, assuming method adequacy, any sex

differences should be inherently accounted for within the physiological benchmarks used for intensity prescription. Regarding sample size, whilst more participants would likely enhance the accuracy of variability estimates, 22 cyclists completed four HIIT sessions for data modelling purposes, representing a level of methodological rigour rarely found in the intensity normalisation literature. We also incorporated easily administered questionnaires to collect secondary data, aiming to understand potential shifts in HIIT responses, if systematically manifested across exercise variables. Consistent with most analysis of variance results, we nevertheless opted not to include HIIT session as a fixed factor in the linear mixed models, and the relevance of the questionnaire data reduced.

In terms of generalisability, we contend that it is very unlikely that %Δ would elicit uniform HIIT responses among untrained individuals, who may exhibit greater variability in their ability to meet the mental and physical demands of exhaustive training compared with cyclists. Conversely, should the %Δ method prove more effective among elite athletes, this would represent an exception to the norm. Our cumulative experience further suggests that the challenge of normalising HIIT intensity might extend beyond the 4-min on, 2-min off format employed in the present study. This insight, derived from pilot testing, hints at a broader issue within the realm of exercise intensity prescription for HIIT.

4.6. Limitations

The accuracy of the metabolic cart employed in this study may be seen as a limitation. It did not rank among the top performers in a recent comparison involving fourteen other devices.[36] Even though the repetition of HIIT sessions was employed to mitigate biological fluctuations and measurement errors, conceivably, our variability estimates might have been slightly lower had we used the highest-rated metabolic carts. In addition, it was not possible to confirm whether all participants indeed standardised their meals 24 h before each laboratory visit, which, if not, may have also contributed to extra variability in exercise responses.

Given that time at >95 $\%\dot{V}O_{2max}$ was higher in session 4 compared with 1, a small training effect arising from the repeated HIIT sessions cannot be ruled out. There might have been also a psychological effect arising from differences in exercise emotions prior to HIIT sessions. Specifically, anxiety was lower in session 4 compared with 2, and both excitement and happiness were lower in session 3 compared with 1. The extent to which these changes affected the variability estimates is unknown, and a much larger sample would be required to model these effects.

5. Conclusions

The results of this study demonstrate that %Δ does not effectively normalise the relative intensity of exhaustive HIIT across individuals. The levels of inter- and intra-individual variability observed were substantial for several acute exercise responses. Importantly, inter-individual variability was generally larger relative to intra-individual variability, suggesting that the poor normalisation of exercise intensity produced by %Δ cannot be attributed to day-to-day biological fluctuations and/or measurement errors. Future studies should investigate the validity of alternative methods of intensity prescription for HIIT and the impact of both inter-individual variability and intra-individual variability in acute exercise responses on training adaptations.

CRediT authorship contribution statement

A.H.B. and J.H. conceived the research and designed the experiment; A.H.B. and W.T. recruited participants and performed the experiment; A.H.B., W.T., and D.C. performed the statistical analysis; A.H.B., W.T., D.C., L.P., and J.H. interpreted the results of the experiment; A.H.B. prepared tables, figures, and supplementary material; A.H.B. drafted the manuscript; A.H.B., W.T., D.C., L.P., and J.H. revised and edited the manuscript; A.H.B., W.T., D.C., L.P., and J.H. approved the final version of the manuscript.

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Confirmation of ethical compliance

All procedures in this study were in accordance with the ethical standards of the institutional research committee and the 1964 Helsinki declaration and its later amendments. Informed consent was obtained from all individual participants included in the study. The present authors all consent to the publication of this work.

Declaration of interest statement

The authors declare that they have no conflict of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jsams.2024.07.019.

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