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Workout intensity and structure affect breathing pattern dynamics during cycling

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Abstract

Purpose The two main components of breathing pattern, respiratory frequency (f_R) and tidal volume (V_T), respond to variable exercise intensity in distinct ways; little is known about how they respond to abrupt changes in workload such as during intermittent workouts (e.g., high-intensity interval training [HIIT]). This study aimed to assess how breathing pattern changes between and within continuous and intermittent workouts in a large cohort varying in biological sex and fitness.

Methods Participants (n = 92, 39 F) completed a ramp test and six individualized cycling workouts (four intermittent). Continuous breath-by-breath data were collected as well as ratings of perceived exertion (RPE) at fixed time points. Variables were normalized to % reserve and analyzed with linear-mixed models. For the intermittent workouts, the inflection point and response magnitude of each variable was estimated across the recovery to work transition.

Results f_R was particularly sensitive to between-workout differences, tracking time-on-task and RPE more closely than the other variables. During HIIT, f_R typically responded first to the recovery to work transition, and it was the only variable whose response magnitude increased monotonically with the work-rate step. V_T increased at work bout onset in 5x4 and SEP but fell in the shorter-recovery 15x1 and 30x30. Large sex and fitness differences mostly disappeared when adjusting to reserve values.

Conclusion Since f_R tracks RPE, time-on-task, abrupt work-rate changes, and generalizes across sex and fitness, it is a particularly valuable monitoring target when applied in the field alongside other variables.

Keywords breathing monitoring; high-intensity interval training; respiratory frequency; tidal volume; ventilation; perceived exertion

Abbreviations

5x4, 15x1, 30x30	HIIT protocols with 5 × 4-min, 15 × 1-min and 30 × 30-s work intervals
EE	Energy expenditure
ET	Ramp (incremental) exercise test
f_R	Respiratory frequency
HIIT	High-intensity interval training
HR	Heart rate
HR_{max}	Maximal heart rate
IQR	Interquartile range
LIT	Low-intensity training
LME	Linear mixed-effects model
P_{LIT}	Low-intensity power
P_{peak}	Peak power output
P_{THR}	Threshold power
RMR	Resting metabolic rate
RPE	Rating of perceived exertion
SEP	Speed endurance production
THR	Threshold training
$\dot{V}CO_2$	Carbon dioxide output
$\dot{V}_E$	Minute ventilation
$\dot{V}O_2$	Oxygen uptake

$\dot{V}O_{2peak}$	Peak oxygen uptake
V_T	Tidal volume

Introduction

Breathing is a complex behavior that continuously adjusts to various physiological, biomechanical, and psychological stimuli. While minute ventilation ($\dot{V}_E$) closely tracks changes in carbon dioxide production ($\dot{V}CO_2$) during exercise, it is ultimately the product of respiratory frequency (f_R) and tidal volume (V_T), which respond to a variety of stimuli. Scientific literature has previously reported f_R and V_T dynamics inconsistently, leading some authors to label it "overlooked" since breathing patterns may provide more insights than $\dot{V}_E$ reporting alone (Nicolò et al. 2017b). For example, recent experiments report a stronger association between breathing frequency (f_R) and ratings of perceived exertion compared to $\dot{V}O_2$ or heart rate (HR) during incremental exercise and time-trials of various durations (Nicolò et al. 2016; Nicolò et al. 2017a). f_R also tracks effort better than other indices (i.e., $\dot{V}O_2$ and HR) during experimental manipulations of exercise tolerance (Fullerton et al. 2021; D'Alleva et al. 2025), muscle damage (Davies et al. 2011), and glycogen depletion (Busse et al. 1991). Stevenson et al. (2024) demonstrated that during 185 minutes of cycling at constant power below the first ventilatory threshold, f_R increased by 16% while V_T decreased by 16%, despite stable $\dot{V}_E$ and $\dot{V}O_2$. This was accompanied by a downward shift in the subsequent first ventilatory threshold power (-10%) as measured in repeated pre and post-exercise ramp tests. f_R may be uniquely sensitive to physiological adjustments during longer-duration exertion.

Breathing depth also increases together with exercise intensity, but with different responses compared to f_R. During low to moderate-intensity exercise, healthy individuals typically increase V_T before f_R (Aliverti 2016). As exercise intensity increases into the heavy domain, both f_R and V_T increase, until the "respiratory compensation point", after which f_R is the primary contributor to further $\dot{V}_E$ increases. Historically, V_T was thought to be rigidly determined by mechanical optimization; specifically, the minimization of respiratory muscle work and oxygen cost of breathing (Mead 1960). However, breathing pattern shifts systematically during exercise in ways that cannot be explained by mechanical optimization alone. As noted above, during prolonged constant-load exercise f_R progressively increases while V_T decreases or plateaus, despite stable metabolic demand (Gronwald et al. 2025; Rogers et al. 2025; Nuuttila et al. 2025). These findings are supported by a newer ventilatory control theory, the "differential control model", which proposes that f_R and V_T are regulated through partially independent mechanisms (Nicolò and Sacchetti 2023). According to this model, f_R is modulated by non-metabolic inputs including central motor command and muscle afferent feedback, while V_T responds primarily to metabolic inputs. At higher relative exercise intensities f_R is even more sensitive to central command and effort; this "tachypneic shift" dominates the $\dot{V}_E$ response, and V_T stabilizes or slowly decreases. High-intensity exercise may be particularly suitable for breathing monitoring applications since it stimulates a unique f_R -driven pattern, but high-quality evidence is scarce outside of incremental and constant-load exercise contexts. More scientific research is necessary to understand how to evaluate and interpret breathing pattern responses in sport-specific workout structures such as self-paced exercise or interval training.

High-intensity interval training (HIIT) is a popular, well-described approach with demonstrated improvements in health and sport performance outcomes (Coates et al. 2023). Since HIIT includes repeated workload transitions and often supramaximal intensity bouts, the resulting intermittent metabolic responses and neural drive may provoke physiological responses fundamentally different from those observed during incremental or steady-state exercise. Hence, HIIT presents challenges for load and intensity monitoring: choosing the appropriate interval:recovery ratio, recovery duration, and load quantification are still debated (Stöggl et al. 2024). Currently HIIT is typically monitored using HR, subjective scales, and/or $\dot{V}O_2$ to manage intensity and recovery (Taylor et al. 2019). HR is a popular

monitoring target in part due to the availability of commercial wearables; however, HR exhibits slow kinetics in response to abrupt workload changes, dissociates from metabolic demand during prolonged exercise (Billat et al. 2022), and has limited sensitivity to supramaximal intensities (Bok et al. 2026). These limitations are particularly problematic when attempting to characterize responses to HIIT. In contrast, HIIT may be particularly suited to breathing monitoring since f_R and $\dot{V}_E$ are especially sensitive to abrupt changes in workload at higher intensities (Girardi et al. 2026; Girardi et al. 2021; Bok et al. 2026)

Only a small number of studies have characterized breathing responses to the work–recovery transitions of HIIT in detail, reporting that f_R rises promptly at work onset and falls during recovery while V_T shows a smaller and opposite response, such that f_R predominantly drives the $\dot{V}_E$ fluctuation across the work-recovery cycle (Girardi et al. 2026; Nicolò et al. 2017a; Bok et al. 2026). These patterns appear robust to environmental perturbation such as hypoxia and hyperthermia, and f_R tracks exercise tolerance and perceived exertion more closely than aural temperature (Girardi et al. 2026). However, studies have thus far examined relatively homogenous HIIT structures and participant demographics, so it is still unclear if different workout structures and groups express such breathing responses. Hence, the aim of this study was to systematically investigate how breathing patterns change within and between different workouts in a large cohort of individuals differing in biological sex and fitness level. It was hypothesized that f_R would be more sensitive than $\dot{V}_E$ or HR to time-on-task and work-recovery transitions, and that f_R tracks RPE closer than other ventilatory variables.

Materials and methods

This study is a follow-up analysis of Stöggl et al. (2023); an expanded description of its purpose and methods can be viewed there.

Participants

This study was approved by the University of Salzburg ethics committee (EK-GZ: 25/2018) and was conducted in accordance with the Declaration of Helsinki. One hundred four healthy individuals volunteered for this study, completed pre-participation questionnaires regarding training history and medical contraindications, and gave written informed consent. The sample included 21 recreationally trained and 18 trained women, and 25 recreationally trained and 28 trained men (age 29 ± 8 y, $\dot{V}O_{2peak}$ 52.0 ± 9.0 ml/min/kg, P_{peak} 296 ± 77 W). Fitness level was classified as “trained” or “recreationally trained” using multivariate t-distributions of $\dot{V}O_{2peak}$ and P_{peak} in line with best-practice recommendations (De Pauw et al. 2013; Decroix et al. 2016).

Study design

During the first visit, participants completed a resting metabolic rate measurement in accordance with best practice; see Stöggl et al. (2023) for details on this step and the following. Then they completed a ramp test to exhaustion to determine (1) peak oxygen uptake ($\dot{V}O_{2peak}$), (2) low-intensity power (P_{LIT}), (3) threshold power (P_{THR}), (4) peak power output (P_{peak}), and (5) maximal heart rate (HR_{max}). These parameters were used to determine the intensities of subsequent workouts. On the second visit, participants performed one of three randomly selected HIIT protocols listed below. HIIT workouts were time-matched at 30 min to compare metabolic parameters, while other workouts were matched to the total energy expenditure (EE) of the first HIIT workout. Participants performed six different workouts:

Continuous:

1. LIT: low-intensity training. Continuous cycling at P_{LIT} until the total EE matched that of the initial HIIT protocol.

2. THR: threshold. Continuous cycling at P_{THR} until the total EE matched that of the initial HIIT protocol.

Intermittent:

3. HIIT 5x4: five 4 min intervals at a power output corresponding to 90% of HR_{max}, separated by 2.5 min recovery periods at P_{LIT}
4. HIIT 15x1: fifteen 1 min intervals at P_{peak}, each separated by 1 min recovery periods at P_{LIT}
5. HIIT 30x30: thirty 30 s intervals at P_{peak}, interspersed with 30 s recovery periods at P_{LIT}
6. SEP: speed endurance production HIIT. Repeated 40 s intervals at 125% of P_{peak}, each followed by 4 min 20 s recovery at P_{LIT}, continued until the total EE matched that of the initial HIIT protocol. Henceforth distinguished from HIIT as simply "SEP".

Workouts were performed in the exercise physiology laboratory at the same time of day with a standardized warmup of five minutes at P_{LIT}. Workouts were separated by 48 h, with a maximum study duration of three weeks per participant. The previous investigation showed no statistical differences in EE between groups (biological sex or fitness level) across different HIIT protocols (Stöggl et al. 2023).

Instruments

Workouts were completed on the same cycle ergometer (Ergoselect 100, Ergoline GmbH, Bitz, Germany) calibrated to manufacturer specifications. Respiratory data were collected breath-by-breath using a Cosmed Quark CPET metabolic system (Cosmed, Si., Rome, Italy), calibrated according to manufacturer recommendations using a 3000 mL syringe for volume calibration and a reference gas mixture (16% O_2, 9% CO_2) for gas calibration. HR data was collected using Polar H10 (Polar Electro Oy, Kempele, Finland).

Ratings of perceived exertion (RPE) were rated on the Borg 6–20 scale (Borg 1982). Participants were familiarized with the scale during the initial visit (with ramp test) and encouraged to point to indicate their rating on a visual scale (rather than speaking).

RPE timing followed the test protocols:

- all workouts: final minute of the 5-min warm-up;
- THR: 10, 20, 30, 40 and 50 min in the workout; LIT: 10, 25, 40 and 55 min (ratings exist only up to the point where the isocaloric target ended the session);
- 5x4: end of each 4-min bout (5 ratings);
- 15x1: end of bouts 5, 10 and 15; 30x30: end of bouts 10, 20 and 30 (3 ratings each);
- SEP: directly after each 40-s bout and 1 min before the next bout (each bout therefore has a rating on both sides of it)

Data processing

All analyses were performed using MATLAB R2026a software (The MathWorks Inc., Natick, USA). Key variables extracted from breath-by-breath data included: f_R, V_T, $\dot{V}_E$, $\dot{V}O_2$, $\dot{V}CO_2$, HR, and cycling cadence.

Since some workouts were adapted during testing to ensure completion, any workouts with unintended interruptions or changes in cycling power were excluded. Breath-by-breath data were resampled using spline interpolation to 1 Hz for plotting only. The ramp test data were added to compare the time-course of key variables for visualization. Ramp data are shown using the isotime method (Nicolò et al. 2019b):

each participant's test was expressed as 0–100% of its duration, averaged across participants, and plotted against the group-mean test duration.

Data from the 10 min resting metabolic rate (RMR) assessment and the ramp test were used to normalize key variables to reserve values. The minimum (RMR) and maximum (ramp test) were extracted using 1 min rolling averages, from which variables were scaled 0-100%.

To compare variables across all workouts (continuous and intermittent), data were binned into 10 s averages. To analyze temporal changes in breathing pattern within the intermittent workouts, first breath-by-breath data were smoothed using a rolling, forward-facing 5-breath median. Then two distinct parameters were calculated to estimate the breathing response: inflection point and response magnitude.

1. Inflection point: this represents the first time point (expressed in seconds after work interval start) when a variable expresses a substantial, sustained change versus the previous recovery. For each recovery period the last 20 s of each variable before the transition was extracted. Then a threshold value was calculated equal to the median plus one interquartile range. For each variable during the work bout, the inflection point was detected when the first median window of five consecutive breaths exceeded the threshold (see Fig. 1). The inflection point was labelled missing if no five-breath window exceeded that threshold during the work bout.
2. Response magnitude: this captures the absolute and relative (% reserve) change of a variable (median of data 10-25 s after start of the work interval) compared to the median of the 20-0 s window before transition (see Fig. 1).
   The 10-25 s window was selected because a preliminary analysis of the power output profiles during HIIT workouts showed that power output typically stabilized ~9 s after the onset of each work interval. This brief ramp-up occurred due to the electronic braking control of the ergometer, which required several seconds to reach and stabilize at the prescribed target power following each workload transition. Hence, the 10-25 s window was selected as a comparable window with stable power between all HIIT workouts.

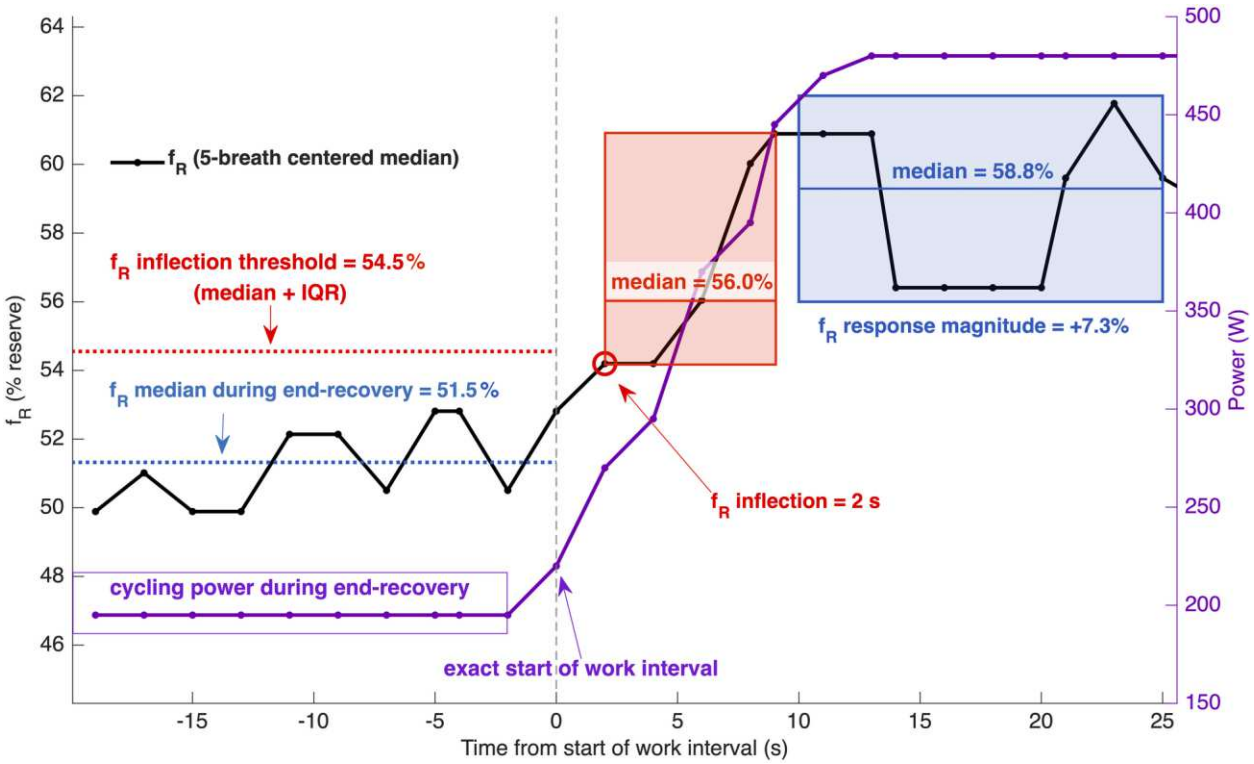


Fig. 1 Example of inflection point (red circle and box) and response magnitude (blue box) for one participant in one workout (speed endurance production) interval. The black line shows respiratory frequency (f_R); purple line shows cycling power. Note that while the inflection point occurs below the inflection threshold, the indicator (red circle) is the beginning of a 5-breath window that exceeds that threshold

To match RPE data to physiological variables (f_R, V_T, $\dot{V}_E$, $\dot{V}O_2$, $\dot{V}CO_2$, HR), the mean of the 30s before the rating was extracted. In the SEP, post-bout RPE ratings were matched with the mean of all data during that bout (specifically power stabilization [~10s after work onset] to recovery onset).

Statistical analysis

All statistical analyses were performed in MATLAB using linear mixed models (fitlme; restricted maximum likelihood, residual degrees of freedom) with a random intercept for each participant. Reserve-normalized values were used for all inferential comparisons. The corresponding models in absolute units are reported in Online Resource 1 (Tables S1–S3). Biological sex (reference: male) and fitness level (reference: trained) were included as fixed effects in every model. The ramp test was used only for reserve normalization and visualization and was not modeled.

Whole-workout comparison

The 10-s averages of each variable from all six workouts were modeled as

Variable ~ workout × time + biological sex + fitness level + (1 | participant)

with LIT as the reference workout. Time in workout (min) was centered on its mean within each workout. Per-workout mean levels and drift slopes (% reserve/min) were obtained as linear combinations of the model coefficients. Accumulated drift was calculated as the slope multiplied by the mean workout duration.

Intermittent workouts

For the four intermittent workouts, the inflection point and response magnitude of each work interval were modeled as

Outcome ~ workout × time + biological sex × time + fitness level × time + (1 | participant)

with 5x4 as the reference protocol and time (min) again centered within each protocol. Because participants completed the protocols to different durations, these models were restricted to intervals within each participant's isotime window, i.e., the duration of the shortest protocol that participant completed (Nicolò et al. 2019a). Inflection prevalence was reported as the percentage of analyzed intervals in which a variable crossed the detection threshold before the next transition. For example, V_T did not increase after some recovery-to-work transitions in the 30x30, so those intervals had no inflection point. To compare variables directly, pairs of variables were stacked, and the within-interval difference in latency and in response magnitude was modeled in the same framework. The simultaneity of inflection points was expressed as the percentage of paired inflections occurring within ±2 s of each other.

Perceived exertion

Session-peak RPE was compared between workouts (*RPE ~ workout + (1 | participant)*). RPE drift was modeled as *RPE ~ workout × time + (1 | participant)*, with time centered within workout, using in-session ratings only (for SEP, the post-bout ratings). To compare RPE and f_R drift on a common scale, RPE was expressed as a percentage of the Borg range (6–20) and stacked with f_R (% reserve) at the same ratings. The per-workout measure × time contrast was then tested, with an additional random intercept for each participant × measure. In SEP, the rise in RPE across each bout was modeled as ΔRPE ~ Δf_R (within) + Δf_R (between) + time, restricted to bouts within the isotime window, and repeated for each of the other variables. Distinct from the response magnitude calculated above, the Δf_R was extracted from the whole SEP work bout after power stabilization (about 10-40 s instead of 10-25 s).

Significance was set at $\alpha = 0.05$. p-values were adjusted with the Benjamini–Hochberg procedure: within each whole-workout model, across all coefficients of the intermittent-workout models, and across the headline RPE tests and within each family of pairwise comparisons.

Generative AI (Claude, Anthropic) was used to assist with refactoring, checking the analysis code, and packaging for publication; all code and text were reviewed and verified by the authors, who take full responsibility for the content.

Results

Of the 104 participants who completed the protocol, 12 were excluded because at least one workout deviated from the prescribed structure. The final sample for the breath-by-breath analyses was 76–87 participants per workout (HR: 58–70). In the RPE data nine questionnaire sessions were missing; of the remaining 3008 ratings, 2707 from 89 participants coincided with breath-by-breath data, contributing 67–81 participants per workout to the RPE analyses.

Between-workout differences

All workouts elicited higher f_R, V_T, $\dot{V}_E$, $\dot{V}O_2$, $\dot{V}CO_2$ and HR than LIT (all $p < 0.001$; Table 1). Complete LME results are listed in Online Resource 1, Table S1. The four higher-intensity workouts (THR, 5x4, 15x1, 30x30) fell within ~3 % reserve of each other on every variable, while SEP and LIT exhibited the lowest average reserve values. HR and V_T operated closer to their reserve maxima (79-81 %) than f_R and $\dot{V}_E$ (58-62 %) during the higher-intensity workouts. Peak RPE was similar to f_R reserve: LIT median RPE = 11 [IQR = 9, 12], THR = 16 [15, 18], 5x4 = 18 [16.5, 19], 15x1 = 18 [17, 19], 30x30 = 17 [16, 18], SEP

= 16 [15, 17] (workout effect F(5, 479) = 234.4, p < 0.001, Online Resource 1, Fig. S4d). Complete RPE analysis results are listed in Online Resource 1, Table S2.

Time on task

f_R was the most time-sensitive variable in every workout, increasing 0.31 to 1.01 % reserve/min (all p < 0.001) (Fig. 2). For example, in the 15x1 workout drift was ranked in descending magnitude: f_R 1.01 > $\dot{V}_E$ 0.68 > HR 0.59 > $\dot{V}O_2$ 0.21 > $\dot{V}CO_2$ -0.03 > V_T -0.20 (%). f_R drifted faster than $\dot{V}_E$ (~1.5×), HR (~1.7×), and $\dot{V}O_2$ (~4.8×), while $\dot{V}CO_2$ drifted negligibly (−0.06 to +0.04 %). V_T was the only variable to decline with time in every workout (-0.14 to -0.3), so the rising $\dot{V}_E$ was achieved entirely through increasing f_R.

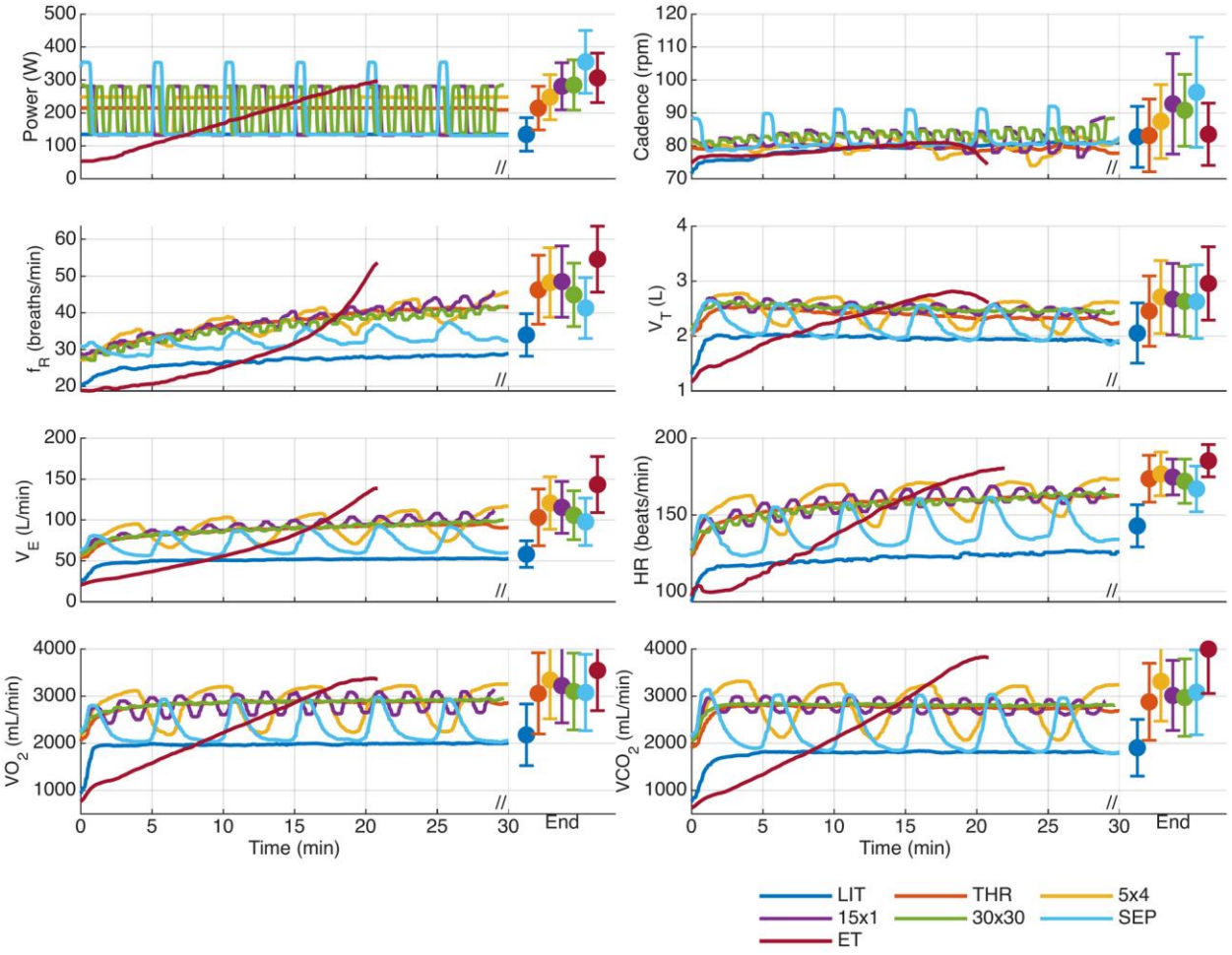


Fig. 2 Group average time-course of key variables for all participants and workouts. The ramp test (ET) is shown in relative isotime (Nicolò et al. 2019b): each participant's test was expressed as 0–100% of its duration, averaged across participants, and plotted against the group-mean test duration (20.8 ± 6.5 min). Error bars at end-exercise represent mean ± SD of the peak values from per-participant traces (30-breath rolling average). Ventilatory traces n = 76-87, HR n = 58-70. f_R, respiratory frequency; V_T, tidal volume; $\dot{V}_E$, minute ventilation; HR, heart rate; $\dot{V}O_2$, oxygen consumption; $\dot{V}CO_2$, carbon dioxide consumption; SEP, speed endurance production; LIT, low-intensity training; THR, threshold

$\dot{V}CO_2$ was essentially flat in every workout except SEP (accumulated -1.7 to +1.2 % in LIT, THR and the three HIIT protocols; -7.7 % in SEP), while $\dot{V}O_2$ rose only marginally in LIT (+1.0 %) and modestly in HIIT (+5.4 to +6.8 %). $\dot{V}_E$ captured only about half to two-thirds of the f_R drift ($\dot{V}_E$: f_R ratio 0.54-0.68) in THR and HIIT. HR drifted consistently (+0.16-0.60 %, all $p < 0.001$) at roughly half to three quarters the rate of f_R in every workout. SEP reflected different trends than HIIT: f_R drift was less than half that of the other exercise workouts (+0.31), $\dot{V}_E$ did not drift at all ($p = 0.13$), and both $\dot{V}O_2$ (-0.07 %) and $\dot{V}CO_2$ (-0.22 %) declined (both $p < 0.001$).

RPE rose within every workout except LIT: LIT 0.01 [−0.00, 0.02], $p = 0.17$, SEP 0.06 [0.05, 0.08], THR 0.09 [0.06, 0.12], 5x4 0.10 [0.08, 0.12], 30x30 0.11 [0.08, 0.13], and 15x1 0.14 [0.11, 0.16] points per minute in workout (Online Resource 1, Fig. S4a). The accumulated RPE was approximately 0.5 (LIT), 2.8 (THR), 3.0 (5x4), 3.9 (15x1), 3.1 (30x30), and 2.2 (SEP). Thus, the pre to post-workout RPE change, as well as the drift slope, ranks the same as the f_R drift slopes in Table 1 (see Online Resource 1, Table S2 for full analysis). When adjusted to % BORG range, RPE and f_R drifted at statistically indistinguishable rates in every workout (Online Resource 1, Fig. S4).

Effects of biological sex and fitness level

In absolute units, biological sex differences were large: males had higher V_T (0.79 L), $\dot{V}_E$ (27.1 L/min), $\dot{V}O_2$ (1030 mL/min), and $\dot{V}CO_2$ (1015 mL/min) (all $p < 0.001$; Online Resource 1, Table S1). After reserve normalization these effects disappeared ($p = 0.06$ to 0.43); only $\dot{V}CO_2$ differed slightly (2.7 % greater in males, $p = 0.039$). Fitness level showed had similar effect: absolute V_T (0.25 L), $\dot{V}_E$ (14.4 L/min), VO_2 (565 mL/min) and VCO_2 (537 mL/min) were greater in trained versus recreationally trained individuals ($p < 0.001$); after scaling to reserve values only $\dot{V}_E$ (3.3 % greater in trained, $p = 0.02$) and VO_2 (4.5 % greater in trained, $p < 0.001$) differences remained. f_R showed no biological sex or fitness level effect on either scale (all $p \geq 0.09$). HR effects were significant on both scales: trained individuals had on average 5.74 bpm (4.2 % reserve) higher HR than untrained ($p = .012$ and $p < 0.001$, respectively), while females showed a greater reserve response (+4.1 %, $p < 0.001$) but not absolute bpm ($p = .069$)

Responses to intermittent exercise transitions

Across all HIIT and SEP there was variable inflection point detectability. $\dot{V}_E$ (53-99 % of intervals) and f_R (58-92 %) were the most reliably detected, while V_T (22-93 %) and HR (12-80 %) were the least (Table 2). Complete LME results for the intermittent workouts analysis are listed in Online Resource 1, Table S3. Detectability fell as the recovery duration shortened: in the 30x30, only 22 % of intervals showed a V_T inflection and 12% an HR inflection, against 93 % and 80% in the 5x4. In the 30x30, 15x1, and SEP f_R was the first ventilatory variable to respond after cadence, at 4.7, 12.7, and 6.0 s respectively (see example SEP response in Fig. 3; identical figures for the other intermittent workouts in Online Resource 1, Figs. S1–S3). Relative to f_R, every other variable was simultaneous or later in those three protocols, and V_T was the latest in all of them (+5.8 to +13.7 s). The 5x4 was exceptional with a reversed order; f_R was the slowest variable of all (44.7 s).

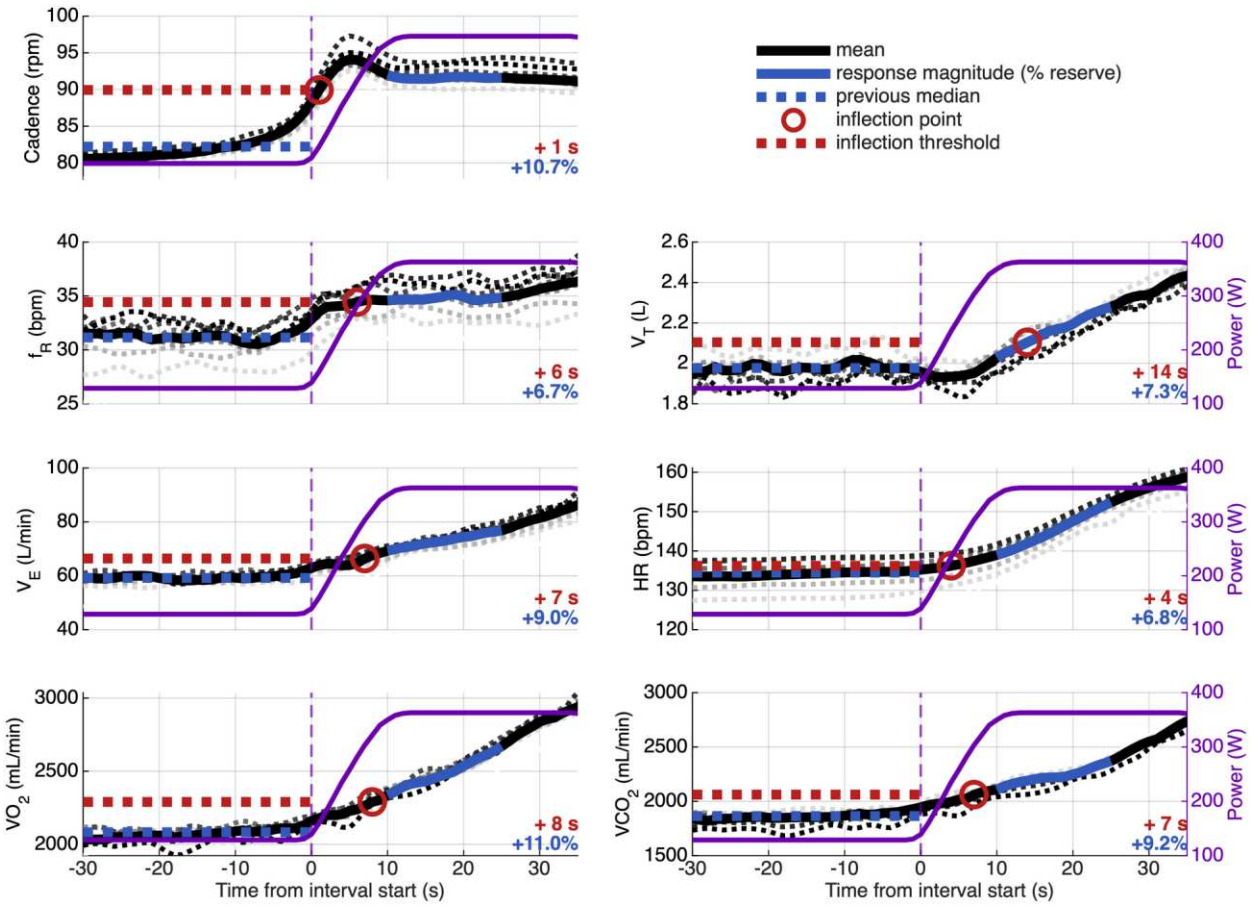


Fig. 3 Average responses to the recovery to work transition for all variables, participants, and intervals in the speed endurance production (SEP) workout. Each dotted line represents data of all individuals for one specific interval of that workout (i.e., separate lines for intervals 1-8) where darker lines reflect later intervals. Only intervals 1-8 were included as 79/92 individuals completed exactly 8 intervals in the SEP. The solid line shows the average of all intervals. Red round circles indicate the mean inflection point location across all participants/intervals. Blue percentage labels display the mean response magnitude (% reserve) of that variable in the 10-25 s window as described above. Note the progressive increase in power over the first 10 s before plateau due to cycle ergometer specifications. f_R, respiratory frequency; V_T, tidal volume; $\dot{V}_E$, minute ventilation; HR, heart rate; $\dot{V}O_2$, oxygen consumption; $\dot{V}CO_2$, carbon dioxide consumption

f_R was the only variable whose response magnitude scaled monotonically with the size of the work-rate step: +2.9 % reserve at +146 W (5x4), +4.4 at +183 W (15x1), +5.1 at +184 W (30x30) and +6.7 at +254 W (SEP; Fig. 3). In the two short-recovery protocols (30x30 and 15x1), f_R showed the largest relative response magnitude (+4.4 to 5.1 %, Fig. 4); every other physiological variable changed less than f_R (-2.5 to 3.0 %). V_T rose in the two protocols with longer recovery times (5x4, +3.3 % reserve; SEP, +7.3) and fell in the two short-recovery protocols (15x1, -2.5; 30x30, -1.9). Notably, V_T inflection detectability split the same way (93 and 80 versus 44 and 22 %). f_R and V_T inflections were almost never simultaneous (3.5 % of intervals within ± 2 s), unlike f_R and cadence (44.5 %) or f_R and $\dot{V}_E$ (41.2 %).

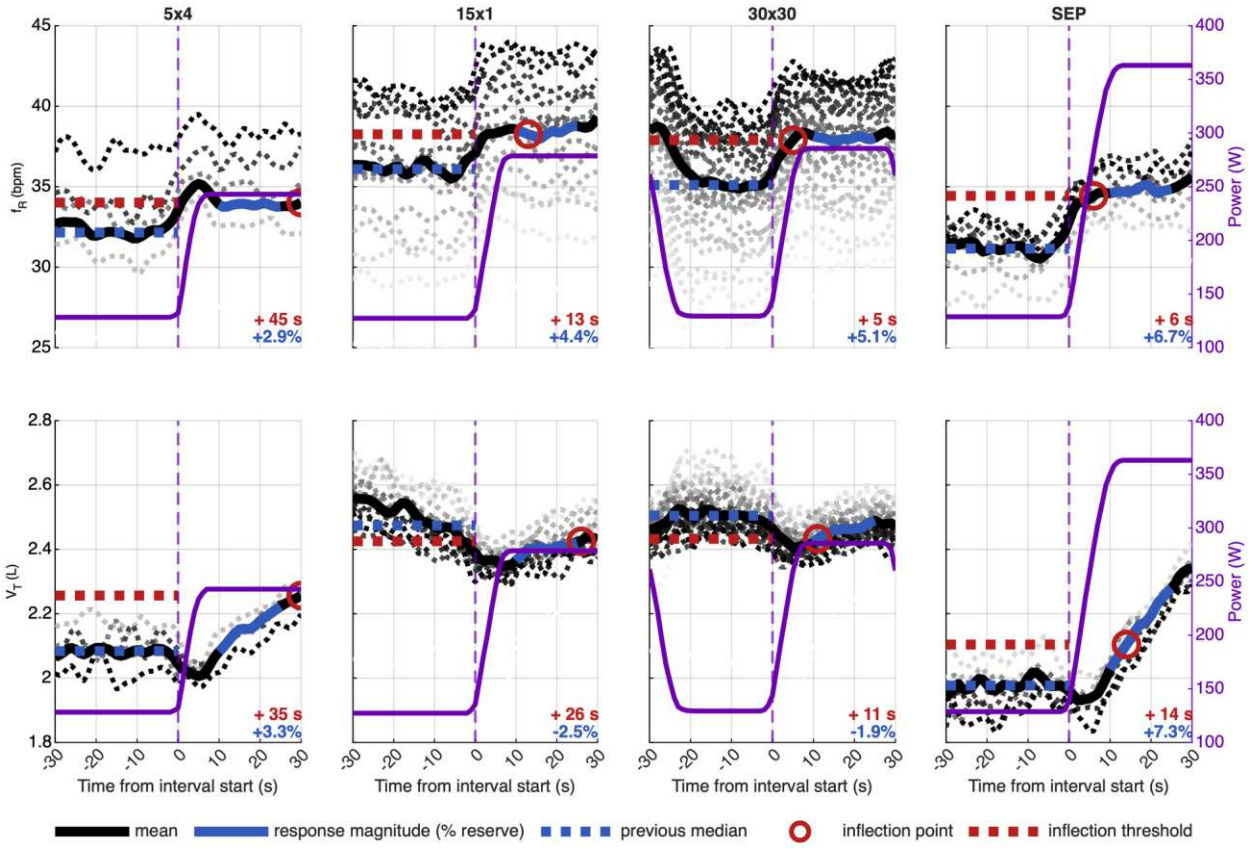


Fig. 4 Average f_R and V_T response to the recovery to work transition for all participants and intervals across the four intermittent workouts. n = 85 (5x4), 76 (15x1), 80 (30x30) and 79 (SEP). Each shaded line represents data of all individuals for one specific interval of that workout (e.g., separate lines for intervals 1-5 of the 5x4 workout) where darker lines reflect later intervals and the solid line is the overall average. Red round circles indicate the mean inflection point location across all participants/intervals. Note that V_T inflection in 5x4 occurs after 30 s; despite the visually-apparent initial rise, the values rarely exceeded the inflection threshold. Labelled percentage values display the mean relative increase (% reserve) of that variable in the 10-25 s window as described above. f_R, respiratory frequency; V_T, tidal volume; $\dot{V}_E$, minute ventilation; HR, heart rate; $\dot{V}O_2$, oxygen consumption; $\dot{V}CO_2$, carbon dioxide consumption

Upon examination of the work to recovery transition, f_R fell (-2.0 and -3.3% reserve) while V_T rose (+2.2 and +2.2) in 15x1 and 30x30. However, in the 5x4 both fell (f_R -1.1, V_T -4.6 %). SEP showed the opposite: both f_R and V_T increased beyond the work bout (+2.9 and +9.7 %, respectively), as did $\dot{V}_E$ (+8.2 %), $\dot{V}O_2$ (+5.9 %) and $\dot{V}CO_2$ (+15.0 %).

Within the SEP, the average RPE change from pre to post-work bout was 3.6 points, while mean Δf_R was 7.8% reserve (Online Resource 1, Fig. S5). Thus ΔRPE was not in proportion to f_R (0.04 points [−0.20, 0.27] per 10% reserve f_R, p = 0.76), $\dot{V}_E$, $\dot{V}CO_2$, $\dot{V}O_2$, or HR (all p adjusted > 0.85).

Discussion

This study systematically examined breathing pattern responses and trends across and within various continuous and intermittent workouts. f_R was generally the most sensitive to time on task in every workout (+0.31 to +1.01 % reserve/min), drifting ~1.5× more than $\dot{V}_E$, ~1.7× more than HR and ~4.8× more than $\dot{V}$O2, while V_T declined in every workout. Moreover, within intermittent workouts f_R generally

responded first or simultaneous to other variables across the recovery to work transition, and it was the only variable whose response magnitude increased in parallel with the work-rate step. The f_R-V_T relationship varied according to recovery duration: V_T rose with f_R when recovery was long (5x4, SEP) and fell as f_R rose when recovery was short (15x1, 30x30). RPE comparisons suggest that f_R is especially sensitive to dynamic changes in effort within a workout. While biological sex and fitness level had clear effects on absolute ventilatory responses, scaling ventilatory variables to reserve values virtually eliminated any statistical differences and supported the generalizability of the observed trends. These findings are consistent with modern theories on ventilatory control and have potential utility for breathing monitoring use cases.

f_R was the most time-sensitive variable among all examined. First, the comparison across variables was only possible after normalizing to reserve values since their measurement units inherently differ. f_R increased about 11% across LIT and 24-29 % in THR and HIIT, while $\dot{V}O_2$ increased only 1 % and 5-7 % and $\dot{V}CO_2$ decreased (-1.7 to 1.2 %). Furthermore, RPE was negatively related to $\dot{V}CO_2$ and positively associated with f_R; the RPE- f_R association was strongest in the more intense workouts (THR and HIIT, Online Resource 1, Table S2). This suggests that central command contributed to changes in f_R, as central command is considered the main sensory signal underlying perceived exertion (Marcora 2009). Conversely, these findings suggest that $\dot{V}CO_2$-related inputs did not play a substantial role in modulating f_R (Nicolò and Sacchetti 2023). $\dot{V}_E$ captured only about half to two-thirds of the f_R drift and V_T moved in the opposite direction, reinforcing that f_R carries a time-on-task signal that $\dot{V}_E$ only partially reflects and V_T alone would misrepresent. These findings align with the modern "differential control" theory (Nicolò and Sacchetti 2023), suggesting that the f_R drift during prolonged exercise is not substantially mediated by metabolic inputs across diverse workout intensities and structures (Martin et al. 1981; Hanson et al. 1982).

Within the intermittent workouts 15x1, 30x30, and SEP, f_R was the first variable to respond after cadence, while V_T was the latest (Table 2). The 5x4 workout had the opposite trend, with f_R responding both later and to a lesser magnitude than the other variables examined (see Table 2). While the other intermittent workouts differed in work-rate step and work:recovery structure, 5x4 was similar to SEP with long recoveries. Thus, the delayed f_R response in 5x4 is more likely due to the smaller work-rate step (the only intervals in this study below peak power), which may not stimulate central command as much in the first 30s after the recovery to work transition compared to the other intermittent workouts. f_R inflections were somewhat simultaneous with cadence and $\dot{V}_E$ but less with V_T or $\dot{V}CO_2$; hence, f_R inflections were likely driven by fast inputs (e.g., central command and muscle afferent feedback) more than metabolic inputs. However, while the f_R-effort link was robust on longer timescales, it was not proportional within single work bouts in SEP. Upon examination of each SEP interval, the change in RPE and f_R was consistent from the beginning to end of the workout, but the magnitude of change was different (ΔRPE = 3.6 points, Δf_R = 7.8% reserve). Hence, scaling RPE to the minimum and maximum values indicates a change of about 25%, which exceeds the change in f_R and the other variables examined. Since f_R showed continuous upward drift into the recovery period, perhaps averaging f_R within the work bout only does not fully capture its response and association to RPE. While inflection detection was quite reliable for f_R and $\dot{V}_E$, it was less so for V_T and HR. Shorter bouts compromised detectability: in the 30x30 only 22 % of intervals showed a V_T inflection and 12 % an HR inflection, against 93 % and 80 % in the 5x4. Hence, V_T and HR would have limited monitoring potential in these HIIT contexts, while f_R appears more reliable for this purpose.

Within the intermittent workouts f_R was the only variable whose response magnitude scaled monotonically with the work-rate step: 5x4 < 15x1 and 30x30 < SEP. No other variable showed the same

trend (Table 2). In the two short-recovery protocols (15x1 and 30x30), f_R showed the largest relative response of any variable measured. Conversely, the V_T response appeared to scale with recovery duration rather than by work intensity or bout length: V_T rose 10-25 s after the recovery to work transition in 5x4 and SEP, while it decreased when recoveries were short in 30x30 and 15x1. V_T inflection detectability split the same way. Since V_T operated at an average ~80 % of reserve in 15x1 and 30x30 (Table 1), the short recoveries may have limited substantial change between bouts. This extends the findings of Girardi et al. (2026), who found f_R and V_T responses in HIIT 30x30 very similar to those reported here. The examination of four intermittent workout structures suggests that the V_T response to HIIT is largely influenced by the recovery time available between bouts, while f_R shows substantial fluctuations even when work and recovery durations are relatively short.

While there were large absolute biological sex differences, they virtually disappeared after reserve normalization. Fitness level had similar effects, with only $\dot{V}_E$ and $\dot{V}O_2$ differences remaining. Both absolute and relative f_R response was consistent between and within workouts independent of fitness level and biological sex, reinforcing its role as the most generalizable variable for interpretation. Females showed a higher HR response after normalization while recreationally trained participants had a lower one. Hence, HR-based inflection points might be sex and fitness level-dependent within HIIT contexts while breathing pattern thresholds do not. Existing literature reports that female athletes typically demonstrate higher f_R, lower V_T, and attenuated breathing pattern drift (i.e., time on task effects) compared to males at equivalent relative exercise intensities (Dominelli and Molgat-Seon 2022; LoMauro and Aliverti 2021; Archiza et al. 2021). The current data reflect no such differences between sexes when normalizing to reserve values. Highly trained endurance athletes also differ from recreationally active individuals; they achieve similar $\dot{V}_E$ with lower f_R and higher V_T at submaximal intensities as well as lower f_R upward drift during prolonged exercise, likely due to differences in exercise tolerance (Unhjem 2024). In the current study, all groups showed similar drift trends when normalized to reserve values. Thus, the true effect of relative exercise intensity upon breathing pattern responses could be interpreted more clearly after reserve normalization.

The above findings are consistent with the differential control model proposed by Nicolò and Sacchetti (2023): f_R substantially responds to fast inputs and V_T to the magnitude of metabolic inputs, with V_T fine-tuned on f_R rather than the reverse. Moreover, the breathing pattern is not rigidly defined but rather changes with time-on-task and different workout structures. For example, the same relative intensity can produce different V_T behaviors depending on how long the preceding recovery was. Figure 5 visualizes this behavior: different workouts stimulate breathing responses that diverge from ramp test patterns even at equivalent levels of $\dot{V}CO_2$ or $\dot{V}_E$. While the $\dot{V}CO_2$-V_T relationship appears similar between workouts, the $\dot{V}_E$-V_T and $\dot{V}CO_2$-f_R relationships exhibit substantial heterogeneity. This is particularly evident in the present study, as the increase in $\dot{V}_E$ during prolonged exercise depends more on f_R than V_T compared with the responses observed during incremental exercise. While similar findings have previously been reported during high-intensity continuous exercise (Nicolò et al. 2023; Syabbalo et al. 1994), the current data suggest that the $\dot{V}_E$-V_T relationship is altered even during moderate-intensity exercise compared with incremental exercise. These findings challenge the assumption that the $\dot{V}_E$-V_T relationship is stable when V_T values are relatively low (Hey et al. 1966). Collectively, our findings suggest that the breathing pattern changes according to the stimuli imposed by different workout structures, rather than being primarily determined by mechanical constraints at a given level of $\dot{V}_E$ (Sheel and Romer 2012). This has important practical implications, as it suggests that the breathing pattern may provide valuable insights about the specific stimuli imposed by exercise on the human body.

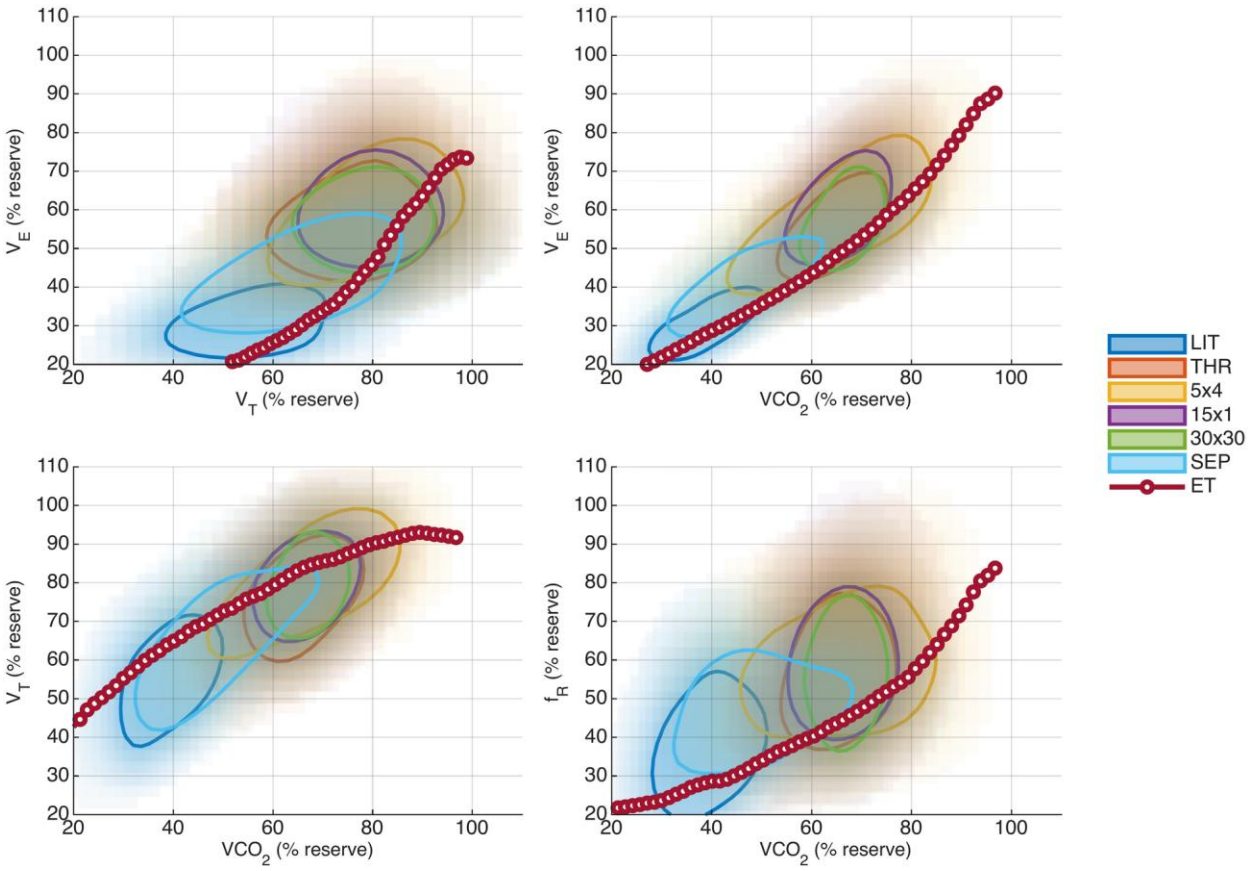


Fig. 5 Density clouds of Hey plots (Hey et al. 1966) and other key variables for each workout type. n = 76–87 participants per workout and 92 for the ramp test. Solid borders indicate that 50% of the binned 10 s data fall within that range. Variables are scaled to reserve values. f_R, respiratory frequency; V_T, tidal volume; $\dot{V}_E$, minute ventilation; HR, heart rate; $\dot{V}O_2$, oxygen consumption; $\dot{V}CO_2$, carbon dioxide consumption

Practical Applications

Breathing pattern monitoring, particularly f_R and V_T dynamics, offers several advantages over traditional cardiovascular monitoring for training monitoring and prescription especially in HIIT. f_R drift parallels changes in RPE better than any other variable across all workouts. In HIIT and SEP f_R response was consistent (reliable inflection prevalence), scales with intensity (response magnitude parallels work-rate step), and nearly identical over repeated intervals independent of biological sex or fitness level. HR response expressed none of these benefits. f_R may be preferred over HR during short, high-intensity intervals, for detecting large abrupt changes in effort, discriminating responses between similar HIIT workouts, or estimating within-session fatigue. For example, a threshold of 5 % f_R increase could be used to identify sudden increases in physical effort and be transformed into a score to complement current models of load monitoring. Conversely, a structured intermittent protocol with f_R monitoring may expose inter-individual differences in response magnitude and potentially inform physiological resilience. Since f_R is especially sensitive to intermittent changes in effort at supramaximal intensities, f_R anchors could be used to guide HIIT workout prescription: for example, the work-rate step could be adjusted to target + 5 % f_R reserve, or recovery duration could be set to a fixed % decrease. Future studies should evaluate a f_R-

structured protocol since it may be superior to HR for controlling HIIT prescription and maximizing subsequent adaptations.

Since f_R can be accurately measured with myriad laboratory setups and simple field devices (e.g., wearable sensors) (Massaroni et al. 2019), it is particularly well-suited for training and testing including outdoors and for large groups. To utilize breathing sensors for these purposes, it is preferable to extract breath-by-breath f_R data in real time. Wearable sensors can measure other breathing pattern parameters such as thoraco-abdominal motion and locomotor-respiratory coupling (Harbour et al. 2023); while these have reported associations with exercise intensity and fatigue (Harbour et al. 2025; Fulton et al. 2018), it is not yet clear how they respond to intermittent exercise.

Limitations

The current interpretation of these findings identifies f_R as responding to "fast inputs" and V_T slowly adjusting secondary to f_R, as suggested by the differential control theory (Nicolò and Sacchetti 2023). However, the role of other inputs to ventilatory control cannot be ruled out: this study examined no direct measures of chemoreflex sensitivity, respiratory mechanics or acid-base status. Hence, these interpretations are plausible hypotheses rather than causal. Time-on-task results were reported using data from the whole test; however, the initial steep rise in most variables inflates many drift slope results. As such, a knot analysis was performed: the most common breakpoint occurred around 10 min, f_R drift remains significantly positive and the strongest drifting variable among those tested (see Online Resource 1, Table S4). For the intermittent workouts, the novel inflection point analysis inherently skews latencies since any intervals without a detectable inflection point are labelled missing and not quantified in the group average. While f_R inflection detectability declined across every protocol, it remained more detectable than V_T or HR. The adaptive threshold (interquartile range-scaled) was chosen rather than a fixed % reserve criterion because it is more robust to noise. A sensitivity analysis was performed (see Online Resource 1, Table S4) and the patterns reported here (e.g., f_R slower in 5x4 than the other protocols) were retained. Within a variable the pre-transition interquartile range is stable across protocols (f_R 8.1-10.2, V_T 8.2-10.0 % reserve), so the adaptive threshold varies far less between protocols than might be assumed. Finally, this report did not include other covariates such as body size or lung capacity, which might improve the interpretation and generalizability of its conclusions.

Conclusions

This study examined breathing pattern responses in detail across a large dataset of continuous and intermittent workouts and different demographics. The findings advance the utility of f_R as an important biomarker in monitoring physical effort, and details specific analytical approaches for exploiting its use in the field. Future studies should integrate continuous f_R monitoring together with subjective scales since they may improve the understanding of load and stress in scientific research and in-field applications.

Supplementary Information

The online version contains supplementary material. **Online Resource 1** (ESM_1.pdf): Supplemental Tables S1–S4 (complete linear mixed-model results for the whole-workout comparison, perceived exertion, interval transitions and sensitivity analyses) and Supplemental Figs. S1–S5 (responses to the recovery-to-work transition in the 5x4, 15x1 and 30x30 workouts; perceived exertion and f_R during the six workouts and within SEP).

Statements and Declarations

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Competing interests The authors have no relevant financial or non-financial interests to disclose.

Ethics approval This study was performed in line with the principles of the Declaration of Helsinki. Approval was granted by the Ethics Committee of the University of Salzburg (EK-GZ: 25/2018).

Consent to participate Written informed consent was obtained from all individual participants included in the study.

Data availability The pseudonymized source data supporting this study are openly available at https://doi.org/10.5281/zenodo.23574470.

Code availability All analysis code, which reproduces every number and figure in this article, is openly available at https://doi.org/10.5281/zenodo.23574470.

Author contributions ThS conceived and designed research; ThS and TiS performed experiments; EH analyzed data; EH and AN interpreted results of experiments; EH prepared figures; EH drafted manuscript; EH, AN, TiS, and ThS edited and revised manuscript. All authors read and approved the final manuscript.

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Tables

Table 1. Linear mixed-model estimates for all six workouts, expressed as % of each participant's individual values relative to the ramp test-derived range.

Workout	f_R	V_T	$\dot{V}_E$	$\dot{V}O_2$	$\dot{V}CO_2$	HR
Mean level over the workout (% reserve)						
LIT (57 min)[a]	39.0 [35.7, 42.3]	58.5 [55.9, 61.2]	32.8 [30.5, 35.0]	51.2 [49.4, 53.1]	41.7 [39.6, 43.8]	54.5 [52.5, 56.5]
THR (31 min)	59.1** [55.8, 62.4]	78.1** [75.4, 80.7]	59.1** [56.8, 61.4]	76.9** [75.1, 78.8]	67.8** [65.8, 69.9]	80.7** [78.7, 82.7]
5x4 (30 min)	58.3** [55.0, 61.6]	80.5** [77.9, 83.2]	60.5** [58.2, 62.8]	74.9** [73.1, 76.8]	67.5** [65.5, 69.6]	78.7** [76.7, 80.7]
15x1 (30 min)	59.9** [56.6, 63.2]	81.1** [78.5, 83.8]	62.0** [59.7, 64.3]	75.3** [73.4, 77.1]	68.0** [65.9, 70.1]	80.9** [78.9, 82.9]
30x30 (30 min)	57.8** [54.5, 61.1]	80.3** [77.6, 82.9]	59.4** [57.1, 61.7]	76.1** [74.3, 78.0]	68.1** [66.0, 70.2]	80.1** [78.1, 82.0]
SEP (35 min)	49.0** [45.7, 52.4]	69.0** [66.3, 71.7]	45.7** [43.5, 48.0]	61.0** [59.1, 62.8]	53.9** [51.8, 56.0]	65.0 ** [63.0, 67.0]
Drift with time on task (% reserve/min)						
LIT[a]	+0.20 [0.19, 0.20]	-0.14 [-0.14, -0.13]	+0.05 [0.04, 0.05]	+0.02 [0.01, 0.02]	-0.01 [-0.01, 0.00]	+0.12 [0.11, 0.12]
THR	+0.77** [0.75, 0.78]	-0.30** [-0.32, -0.28]	+0.41** [0.40, 0.43]	+0.17** [0.15, 0.18]	0.00 [-0.02, 0.01]	+0.56** [0.54, 0.57]
5x4	+0.85** [0.83, 0.87]	-0.25** [-0.26, -0.23]	+0.54** [0.52, 0.55]	+0.18** [0.17, 0.20]	-0.06** [-0.07, -0.04]	+0.43** [0.41, 0.44]
15x1	+1.01** [0.99, 1.03]	-0.20 ** [-0.22, -0.18]	+0.68** [0.66, 0.70]	+0.21** [0.19, 0.23]	-0.03* [-0.05, -0.01]	+0.59** [0.57, 0.62]
30x30	+0.89** [0.87, 0.91]	-0.18** [-0.20, -0.16]	+0.60** [0.58, 0.61]	+0.23** [0.22, 0.25]	+0.04** [0.02, 0.06]	+0.53** [0.51, 0.55]
SEP	+0.31** [0.29, 0.32]	-0.31** [-0.33, -0.30]	+0.04 [0.03, 0.05]	-0.07** [-0.08, -0.06]	-0.22** [-0.24, -0.21]	+0.16 ** [0.14, 0.17]
Accumulated drift over the whole workout (% reserve)						
LIT	+11.3	-7.7	+2.7	+1.0	-0.4	+6.6
THR	+23.8	-9.3	+12.8	+5.2	0.0	+17.3
5x4	+25.4	-7.3	+16.1	+5.4	-1.7	+12.7
15x1	+29.0	-5.9	+19.6	+6.1	-0.9	+17.2
30x30	+26.2	-5.4	+17.5	+6.8	+1.2	+15.7
SEP	+10.6	-10.8	+1.3	-2.3	-7.7	+5.5

Notes. Values are estimates with 95% confidence intervals [lower, upper]. Durations next to each workout label are mean workout duration. Accumulated drift is the modeled slope multiplied by that mean duration and is therefore a derived quantity without a confidence interval. ** $p < 0.001$; * $0.001 \leq p < 0.05$; unmarked $p > 0.05$;[a] Reference category (LIT). f_R, respiratory frequency; V_T, tidal volume; $\dot{V}_E$, minute ventilation; $\dot{V}O_2$, oxygen uptake; $\dot{V}CO_2$, carbon dioxide output; HR, heart rate; LIT, low-intensity training; THR, threshold; SEP, speed endurance production.

Table 2. Response of each variable to the recovery to work transition in the four intermittent protocols.

Variable	5x4[a] 240:150 s +146 W	15x1 60:60 s +183 W	30x30 30:30 s +184 W	SEP 40:260 s +254 W
Prevalence of a detectable inflection (% of intervals)				
Cadence	76 (n = 260)	76 (n = 861)	64 (n = 1468)	85 (n = 406)
f_R	92 (n = 315)	73 (n = 821)	58 (n = 1347)	73 (n = 349)
$\dot{V}_E$	99 (n = 341)	81 (n = 911)	53 (n = 1224)	95 (n = 453)
V_T	93 (n = 320)	44 (n = 498)	22 (n = 518)	80 (n = 382)
$\dot{V}O_2$	99 (n = 340)	94 (n = 1054)	34 (n = 788)	96 (n = 458)
$\dot{V}CO_2$	100 (n = 342)	66 (n = 743)	36 (n = 839)	98 (n = 467)
HR	80 (n = 276)	71 (n = 797)	12 (n = 277)	78 (n = 372)
Latency of the inflection (s after transition)				
Cadence	9.5 [8.2, 10.8]	1.9** [1.1, 2.7]	1.6** [0.9, 2.3]	1.3** [0.3, 2.4]
f_R	44.7 [42.2, 47.1]	12.7** [10.9, 14.4]	4.7** [3.2, 6.1]	6.0** [3.7, 8.3]
$\dot{V}_E$	21.6 [19.6, 23.6]	20.3 [18.6, 22.0]	6.7** [5.1, 8.4]	6.6** [4.7, 8.5]
V_T	34.7 [32.7, 36.7]	26.4** [24.6, 28.1]	10.5** [8.8, 12.3]	14.2** [12.3, 16.1]
$\dot{V}O_2$	17.6 [16.2, 19.1]	21.4** [20.5, 22.4]	7.3** [6.2, 8.4]	7.7** [6.5, 9.0]
$\dot{V}CO_2$	20.8 [19.3, 22.4]	30.6** [29.3, 31.8]	4.6** [3.5, 5.7]	7.3** [5.9, 8.7]
HR	10.6 [8.5, 12.6]	25.6** [23.8, 27.4]	11.1 [8.8, 13.4]	4.3** [2.4, 6.3]
Magnitude of change, 10-25 s (% reserve)				
Cadence	+3.7 [+0.3, +7.1]	+4.5 [+1.2, +7.8]	+3.0 [-0.3, +6.2]	+10.7** [+7.3, +14.0]
f_R	+2.9 [+1.3, +4.5]	+4.4* [+3.0, +5.9]	+5.1** [+3.7, +6.6]	+6.7** [+5.1, +8.2]
$\dot{V}_E$	+4.5 [+3.6, +5.5]	+2.0** [+1.2, +2.9]	+3.0** [+2.1, +3.8]	+9.0** [+8.1, +9.9]
V_T	+3.3 [+1.9, +4.8]	-2.5** [-3.8, -1.2]	-1.9** [-3.2, -0.7]	+7.3** [+5.9, +8.7]
$\dot{V}O_2$	+6.8 [+6.0, +7.6]	+2.1** [+1.5, +2.8]	0.0** [-0.6, +0.6]	+11.0** [+10.3, +11.8]
$\dot{V}CO_2$	+4.5 [+3.8, +5.2]	-1.3** [-1.9, -0.7]	+0.4** [-0.2, +1.0]	+9.2** [+8.5, +9.9]
HR	+2.9 [+2.3, +3.4]	-0.2** [-0.6, +0.2]	-1.2** [-1.5, -0.8]	+5.0** [+4.6, +5.5]

Notes. Values are estimates with 95% confidence intervals [lower, upper]. Column sub-headings give the prescribed work:recovery durations and the mean measured increase in power output at the transition. Prevalence is the percentage of analyzed intervals in which the variable crossed the inflection threshold before the next transition; n is the number of intervals contributing to the latency and magnitude estimates in that column. ** $p < 0.001$; * $0.001 \leq p < 0.05$; unmarked $p > 0.05$;[a] Reference category (5x4). f_R, respiratory frequency; V_T, tidal volume; $\dot{V}_E$, minute ventilation; $\dot{V}O_2$, oxygen uptake; $\dot{V}CO_2$, carbon dioxide output; HR, heart rate; SEP, speed endurance production.

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