European Journal of Applied Physiology (2019) 119:1701–1709
https://doi.org/10.1007/s00421-019-04160-3

ORIGINAL ARTICLE

Cardiorespiratory coordination reveals training-specific physiological adaptations

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Received: 5 December 2018 / Accepted: 7 May 2019 / Published online: 11 June 2019

Abstract

Purpose To compare the effects of high-intensity interval training (HIIT) and moderate-intensity training (CONT), matched for total work, on cardiorespiratory coordination and aerobic fitness.

Methods This is a two-arm parallel group single-blind randomised study. Twenty adults were assigned to 6 weeks of HIIT or volume-matched CONT. Participants completed a progressive maximal cycling test before and after the training period. Principal component (PC) analysis was performed on the series of cardiorespiratory variables to evaluate dimensionality of cardiorespiratory coordination, before and after lactate turnpoint. PC_1 eigenvalues were compared.

Results Both HIIT and CONT improved aerobic fitness (main effects of time, $p < 0.001$, $\eta_p^2 \geq 0.580$), with no differences between groups. CONT decreased the number of PCs from two to one at intensities both below and above the lactate turnpoint; PC_1 eigenvalues increased after CONT both below ($Z = 2.08$; $p = 0.04$; $d = 0.94$) and above the lactate turnpoint ($Z = 2.10$; $p = 0.04$; $d = 1.37$). HIIT decreased the number of PCs from two to one after the lactate turnpoint only; PC_1 eigenvalues increased after HIIT above the lactate turnpoint ($Z = 2.31$; $p = 0.02$; $d = 0.42$).

Conclusions Although CONT and HIIT improved aerobic fitness to a similar extent, there were different patterns of change for cardiorespiratory coordination. These changes appear training-intensity specific and could be sensitive to investigate the individual response to endurance training.

Keywords Endurance training · High-intensity interval training · Moderate-intensity continuous training · Coordinative variables · Principal component analysis

Introduction

High-intensity interval training (HIIT) provides similar or even greater improvements in aerobic fitness than moderate-intensity continuous training (CONT), despite a shorter training time commitment (Meyer et al. 2013; Jelleyman et al. 2015; Ramos et al. 2015). There is no clear consensus as to whether HIIT or CONT is most efficacious in improving aerobic fitness (Jiménez-Pavón and Lavie 2017; Viana et al. 2018) likely due to, in part, differences between studies with regard to the training protocols and outcome measures employed. When looking at individual data, at least 20–50% of participants undergoing various HIIT or CONT protocols reveal non-significant changes in at least one outcome variable, including $\dot{V}O_{2max}$ (Astorino and Schubert 2014; Gurd et al. 2016; Astorino et al. 2018). These results suggest that the commonly utilised markers of aerobic fitness may not be sensitive enough to reveal the early specific training adaptations (Balagué et al. 2016) and that the training

Communicated by I. Mark Olfert.

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response might be highly individual (Astorino et al. 2018). Our research hypothesis is centred on these issues.

A feasible explanation for the lack of sensitivity of $\dot{V}O_{2max}$ and other commonly utilised maximal physiological and performance variables may stem from the fact that they provide little information on the nonlinear dynamic interactions among physiological systems (Bartsch et al. 2015; Ivanov et al. 2016). More specifically, maximal physiological and performance values cannot inform about the qualitative synergetic reconfigurations that the cardiovascular and respiratory systems undertake to adjust the individual response to the exercise requirements (Balagué et al. 2016). These qualitative cardiorespiratory reconfigurations probably precede the quantitative changes assessed by the commonly utilised markers, which may be in this sense less sensitive. Therefore, to capture the specific training adaptations, the time series analysis and the detection of coordinative variables seem a recommendable strategy (Schulz et al. 1997).

Cardiorespiratory coordination is a novel method of measuring co-variation of cardiorespiratory variables during exercise testing (Balagué et al. 2016; Esquius et al. 2019; Garcia-Retortillo et al. 2017). It is estimated through principal component analysis (PCA) performed on the time series of selected cardiovascular and respiratory outcomes. PCA identifies how much the increase and/or decrease of time patterns from different physiological responses are synchronised from a statistical perspective, therefore, reflecting the extent to which time patterns of physiological responses co-vary. The co-variation, across time, of two or more cardiorespiratory variables reflects the mutual information that they share; this common variance and mutual information enable the representation of time patterns of single cardiorespiratory variables through fewer principal components (PCs). PCs are extracted in decreasing order of importance and represent the maximum possible fraction of the variability from the original data, so that the total number of PCs reflects the degree of coordination among different cardiorespiratory variables. More specifically, as stated by Balagué et al. (2016), the dimension reduction is a hallmark of the formation of coordinative structures (Haken 2000), and the decrease in the number of PCs and/or the increase in PC eigenvalues can be interpreted as an improvement in the efficiency of cardiorespiratory coordination. Cardiorespiratory coordination has recently shown a higher responsiveness to training (Balagué et al. 2016), training load (Garcia-Retortillo et al. 2017), and nutritional interventions (Esquius et al. 2019) than $\dot{V}O_{2max}$ and other markers of aerobic fitness. The training-induced improvement of cardiorespiratory coordination may be attributed to a known property of biological systems: the ability to efficiently re-allocate their resources under immediate organismic or environmental constraints (Latash 2008; Scholz and Schöner 1999). Therefore, the measurement of cardiorespiratory coordination through PCA may enrich the information provided by the conventionally assessed markers of aerobic fitness while displaying the following advantages: (a) reduction in the initial high dimensionality of the system under analysis (from several cardiorespiratory variables to one or two PCs) making it easier to model, (b) information on the level of co-relatedness among cardiovascular and respiratory variables, and (c) information on the efficiency of the adaptations produced by specific interventions.

Accordingly, the aim of the present research was to compare the effects of HIIT and CONT, matched for total work, on cardiorespiratory coordination. This study involves a re-analysis of cardiorespiratory data from a previous training study (O'Leary et al. 2017a, b). We hypothesised that HIIT and CONT would display training-specific cardiorespiratory coordination adaptations despite similar improvements in lactate threshold, lactate turnpoint, $\dot{V}O_{2max}$, and peak power output (W_{max}).

Methods

Twenty healthy adults (four women; age 27 ± 6 years, height 1.75 ± 0.10 m, mass 79.0 ± 13.2 kg) volunteered to participate in this two-arm parallel group single-blind randomised study. The study was approved by Oxford Brookes University institutional ethics review board. Each participant completed health history questionnaires and provided written informed consent before taking part. All participants were non-smokers, not taking any medications and were not engaged in endurance training (≤ 30 min per session, ≤ 2 sessions per week). After completing the pre-training experimental trials, participants were randomised (1:1) into either a HIIT group or a group completing work-matched CONT, stratified according to the lactate threshold and $\dot{V}O_{2max}$ (HIIT $n = 10$ (8 men/2 women), $\dot{V}O_{2max}$ 44.5 ± 5.4 ml kg^{-1} min^{-1}, LT $52 \pm 8\%$ $\dot{V}O_{2max}$; CONT $n = 10$ (8 men/2 women), $\dot{V}O_{2max}$, 43.5 ± 5.9 ml kg^{-1} min^{-1}, LT $52 \pm 9\%$ $\dot{V}O_{2max}$). The list was held by an investigator who supervised the training interventions. Participants were naïve to the study hypotheses and no intervention was presented to be superior. Group allocation was concealed from the assessor during the experimental trials until the end of the study, and participants were instructed to refrain from discussing their training programme. All experimental trials were, therefore, completed by a blinded assessor.

Each participant completed three experimental trials, all performed at the same time of day, before and after 6 weeks of either HIIT or CONT (see O'Leary et al. 2017a, b); the data in this current study concern the first visit completed at the pre-training and post-training time points only. Each participant was instructed to arrive at the laboratory 2 h

postprandial and after abstaining from caffeine (12 h), alcohol (24 h) and exhaustive exercise (48 h). During this first visit at each time point, participants completed submaximal and maximal exercise tests for the determination of the lactate threshold, lactate turnpoint and $\dot{V}O_{2max}$. At follow-up, the submaximal and maximal exercise tests were repeated within 2–4 days of completing the training interventions.

The exercise test was completed on an electromagnetically braked cycle ergometer (Excalibur Sport, Lode, Netherlands) at a self-selected cadence above 60 rpm. Heart rate and expired gases were monitored using online telemetry (T31, Polar, Finland) and an online gas analyser (Metalyzer 3B, Cortex, Germany), respectively. Blood lactate concentrations ($[La^-]$) were measured from whole blood finger-tip capillary samples (Lactate Pro, Arkray, Japan). Perceived exertion (RPE) was determined using the Borg Scale (6–20).

Participants first completed a submaximal exercise test for aerobic capacity by the determination of the lactate threshold and lactate turnpoint. The submaximal exercise test started at 50 W for men and 30 W for women with the intensity increased by 20 W every 4 min. $[La^-]$ was measured at the end of each stage and the test was terminated once $[La^-]$ reached ≥ 4 mmol·l^{-1}. The lactate threshold and lactate turnpoint were determined by visual inspection of the power output and $[La^-]$ relationship by two blinded independent reviewers. The lactate threshold was defined as the first sudden and sustained increase in $[La^-]$ and the lactate turnpoint was defined as the appearance of a second sudden increase in $[La^-]$ between the lactate threshold and $\dot{V}O_{2max}$. This method of detection is supported by work from numerous studies (Carter et al. (2000); Goodwin et al. (2007)) and data from our laboratory report coefficient of variation of 2.9% and 3.2% for lactate threshold and lactate turnpoint detection, respectively. Following a 20-min rest, a maximal ramp test was completed for the determination of aerobic power as measured by $\dot{V}O_{2max}$. The maximal test began with cycling for 1 min at 100 W for men and 50 W for women, followed by a ramp increase of 25 W min^{-1} for men and 20 W min^{-1} for women until 60 rpm could no longer be maintained. Expired gases and HR were measured throughout. W_{max} was taken as the highest 30 s average of the recorded power output, whilst $\dot{V}O_{2max}$ was recorded as the highest 30 s average meeting the criteria of Midgley et al. (2007) (end $[La^-] \geq 8$ mmol/L^{-1}, peak RER ≥ 1.15, end RPE ≥ 19, peak HR $\geq 90\%$ age-predicted maximum and volitional exhaustion). All participants met these criteria.

All training sessions were completed on a cycle ergometer (either Excalibur Sport or Corival, Lode, Netherlands) and supervised by an investigator. Both the HIIT and CONT training groups completed three training sessions per week for 6 weeks (18 sessions total) with each session separated by a minimum of 24 h. An adapted HIIT protocol was used (Weston et al. 1997), which involved six repeats of 5-min cycling at an intensity equivalent to halfway between the lactate threshold and $\dot{V}O_{2max}$ (50%Δ), each separated by 1-min rest. The number of repeats was progressed to eight during weeks 4–6. The CONT protocol involved continuous cycling at 90% of the power output at lactate threshold. The duration was prescribed so that the same volume of work (kJ) that would have been completed in the HIIT protocol was reached at the power output equal to 90% of lactate threshold. HR and RPE were measured at 5-min intervals throughout each training session with the training intensity re-assessed every 2 weeks (sessions 7 and 13) and increased if necessary to ensure HR and RPE were consistent with baseline values. The full characteristics of the training interventions have been reported in a previous publication (O'Leary et al. 2017a, b).

Statistical analyses were completed in SPSS (v.23, SPSS Inc., USA). All data were tested for normality. To study cardiorespiratory coordination, a PCA was carried out on the time series of selected cardiorespiratory variables in all participants, in both pre- and post-training maximal tests: end-tidal partial pressure of oxygen ($PetO_2$), end-tidal partial pressure of carbon dioxide ($PetCO_2$), ventilation (VE), and HR. Oxygen pulse, oxygen consumption, respiratory equivalents (VE/VO_2, VE/VCO_2, respiratory exchange ratio), and other frequently recorded parameters during cardiorespiratory testing were not included in the analysis given their known deterministic mathematical relation with the aforesaid variables (Balagué et al. 2016; Garcia-Retortillo et al. 2017). Continuous blood pressure monitoring could not be provided in this study; however, recently published work has shown similar results while analysing cardiorespiratory coordination with and without continuous blood pressure measurement (Esquius et al. 2019). Bartlett's sphericity test and the Kaiser–Meyer–Olkin (KMO) index (Denis 2016) were computed to evaluate the suitability of the application of the PCA. The number of PCs was defined by the Kaiser–Guttman criterion, which recognises PCs with eigenvalues $\lambda \geq 1.00$ as significant (Jolliffe 2002; Balagué et al. 2016). Since eigenvalues of the first PC (PC_1) contain the largest amount of the data variance, PC_1 eigenvalues and the loadings of selected cardiorespiratory variables onto PC_1 were also calculated and compared within and between groups, by means of a Wilcoxon matched-pair test and Mann–Whitney *U* test, respectively. The same procedure was repeated before and after lactate turnpoint with the aim of accurately analysing cardiorespiratory coordination.

Total training volume and baseline measures of aerobic fitness were compared between groups with independent samples *t* tests. A series of 2 × 2 (group [HIIT and CONT] × time [pre-training and post-training]) mixed-design ANOVAs were used to compare training interventions for changes in aerobic fitness. Where the assumption of sphericity was violated, Greenhouse–Geisser corrections

were applied. Where an ANOVA revealed a significant main effect or interaction, post hoc contrasts and *t* tests were used to test for differences within and between groups where appropriate. Effect sizes (Cohen's d) were computed to demonstrate the magnitude of standardised mean differences and an alpha level was set at 0.05 for all statistical tests. Cohen's conventions (Cohen 1988) were adopted for interpretation of effect size, where < 0.2, 0.2–0.5, > 0.5–0.8 and > 0.8 were considered as trivial, small, moderate, and large, respectively.

Results

Bartlett's sphericity test ($p < 0.001$) and the KMO index ($M = 0.70$; SD = 0.11) showed a good sampling adequacy for the application of the PCA, in both CONT and HIIT.

Within CONT

Four participants decreased the number of PCs (from two PCs to one PC) at intensities below and above lactate turnpoint from pre- to post-training (see Table 1), indicating a larger degree of co-variation among selected cardiorespiratory variables post-training. At intensities below the lactate turnpoint, while PC_1 was formed by VE, $PetCO_2$ and HR, PC_2 was mainly formed by $PetO_2$. However, at intensities above the lactate turnpoint, PC_1 was loaded by VE, $PetO_2$ and HR, and PC_2 was mainly formed by $PetCO_2$ (see Table 1 and Fig. 1). All participants (even those with no changes in the number of PCs) significantly increased PC_1 eigenvalues after the training period both before ($Z = 2.08$; $p = 0.04$; $d = 0.94$) and after LT ($Z = 2.10$; $p = 0.04$; $d = 1.37$; see Table 1).

Within HIIT

Three participants decreased the number of PCs (from two PCs to one PC) at intensities above the lactate turnpoint from pre- to post-training (see Table 1), indicating a higher degree of co-variation among physiological variables specifically after the lactate turnpoint. At intensities below the lactate turnpoint, whereas PC_1 was formed by VE, $PetCO_2$ and HR, PC_2 was formed by $PetO_2$. However, at intensities above the lactate turnpoint, PC_1 was loaded by VE, $PetO_2$ and HR, and PC_2 was mainly formed by $PetCO_2$ (see Table 1 and Fig. 2). PC_1 eigenvalues significantly increased after the training period (even in those participants with no changes in the number of PCs), but only at intensities above the lactate turnpoint ($Z = 2.31$; $p = 0.02$; $d = 0.42$; see Table 1). No significant differences were found in PC_1 eigenvalues below the lactate turnpoint, when comparing pre- and post-training ($Z = 0.42$; $p = 0.68$).

Table 1 Means (standard deviations) of PC_1 and PC_2 eigenvalues and projection of the selected cardiovascular and cardiorespiratory variables onto PC_1, and PC_2, before and after lactate turnpoint in both pre- and post-training tests

		Before lactate turnpoint								After LTP							
		Pre-training					Post-training					Pre-training					Post-training		
		Par	PC EV	VE	HR	$PetO_2$	$PetCO_2$	Par	PC EV	VE	HR	$PetO_2$	$PetCO_2$	Par	PC EV	VE	HR	$PetO_2$	$PetCO_2$
CONT	PC1	1	2.55	0.92	0.93	0.45	0.73	4	2.56	0.87	0.95	0.53	0.91	5	2.85	0.89	0.82	0.92	0.40	6	3.08	0.96	0.95	0.95	0.52
			(0.32)	(0.03)	(0.04)	(0.26)	(0.17)		(0.50)	(0.09)	(0.01)	(0.25)	(0.08)		(0.32)	(0.11)	(0.24)	(0.07)	(0.29)		(0.19)	(0.01)	(0.06)	(0.04)	(0.29)
	PC2	9	1.25	0.23	0.17	0.81	0.60	6	1.17	0.25	0.19	0.25	0.94	5	1.17	0.47	0.19	0.86	0.28	4	1.01	0.04	0.06	0.15	0.98
			(0.27)	(0.15)	(0.17)	(0.24)	(0.23)		(0.12)	(0.29)	(0.15)	(0.19)	(0.09)		(0.12)	(0.15)	(0.03)	(0.15)	(0.11)		0.02	(0.03)	(0.05)	0.05	(0.02)
HIIT	PC1	2	2.73	0.86	0.93	0.45	0.93	3	2.65	0.91	0.95	0.34	0.87	1	2.79	0.96	0.89	0.94	0.36	6	2.93	0.97	0.92	0.95	0.43
			(0.29)	(0.13)	(0.06)	(0.22)	(0.04)		(0.27)	(0.07)	(0.05)	(0.21)	(0.10)		(0.38)	(0.02)	(0.14)	(0.04)	(0.21)		(0.27)	(0.02)	(0.11)	(0.04)	(0.19)
	PC2	7	1.18	0.41	0.30	0.88	0.30	6	1.02	0.12	0.19	0.22	0.92	8	1.21	0.33	0.21	0.91	0.41	3	1.04	0.05	0.28	0.09	0.99
			(0.22)	(0.21)	(0.16)	(0.12)	(0.11)		(0.02)	(0.10)	(0.10)	(0.18)	(0.07)		(0.23)	(0.14)	(0.12)	(0.10)	(0.20)		(0.04)	(0.04)	(0.02)	(0.03)	(0.00)

CONT moderate-intensity continuous training, *HIIT* high-intensity interval training, *PC* principal component, *EV* eigenvalue, *Par* number of participants with one or two PCs, *VE* expired minute volume, $PetO_2$ end-tidal partial pressure of oxygen, $PetCO_2$ end-tidal partial pressure of carbon dioxide, *HR* heart rate

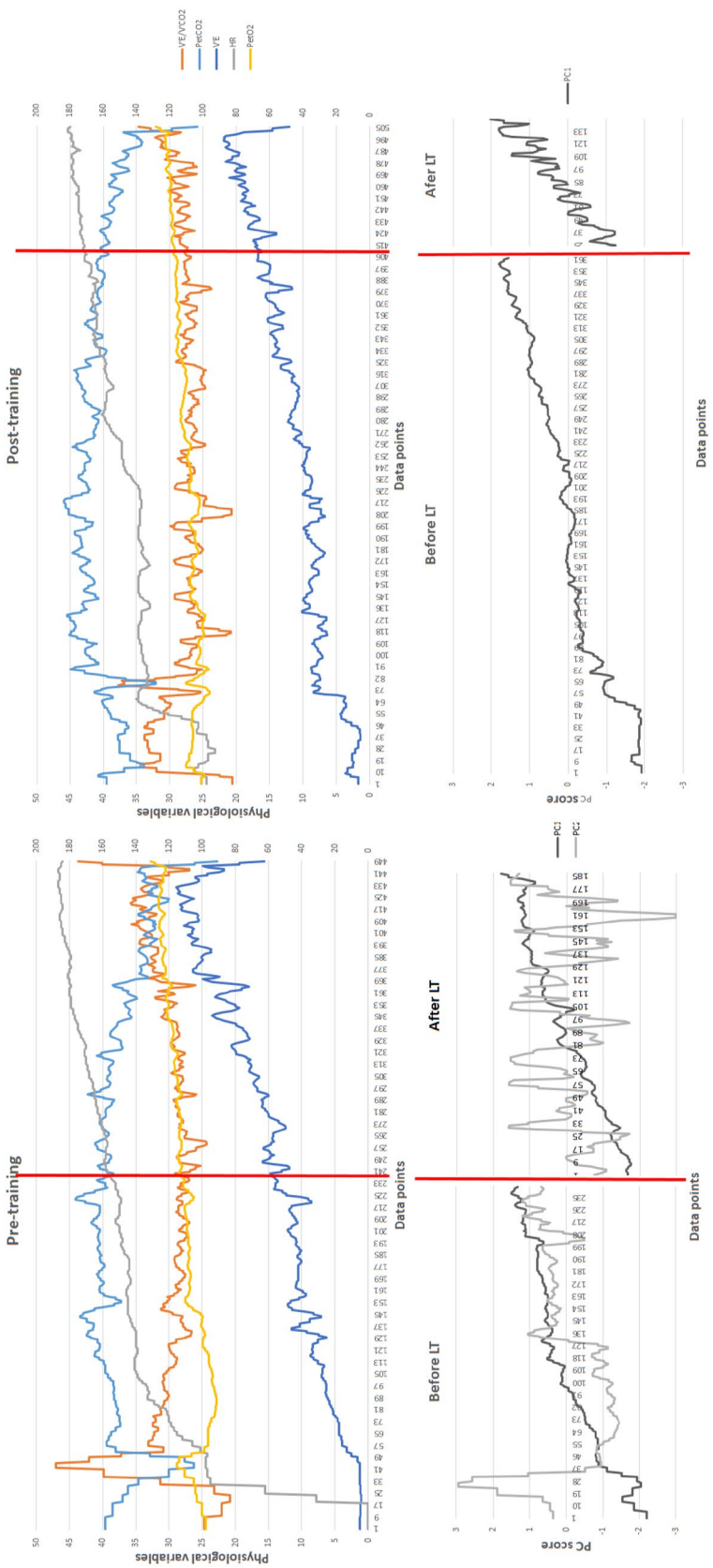

Fig. 1 Example (CONT) of the creation of time series of coordination variables, expressed through PCs from cardiorespiratory variables in pre- and post-training tests. This figure represents a decrease in the number of PCs (from 2 to 1) before and after lactate turnpoint post-training. Top graphs: time series of four cardiorespiratory variables corresponding to pre- and post-training tests. Bottom graphs: time series of the PC scores for pre- and post-training tests, with standardised z values in the space spanned by PCs. Following PC-based dimension reduction, the initial four time series lead to two time series or one time series in pre-training and post-training, respectively. The average trend is calculated by weighted least squares method and graphically plotted in the black and grey lines shown, whereas the red line corresponds to the occurrence of lactate turnpoint. Data points along the axis of abscissae represent the number of measurements registered throughout the test

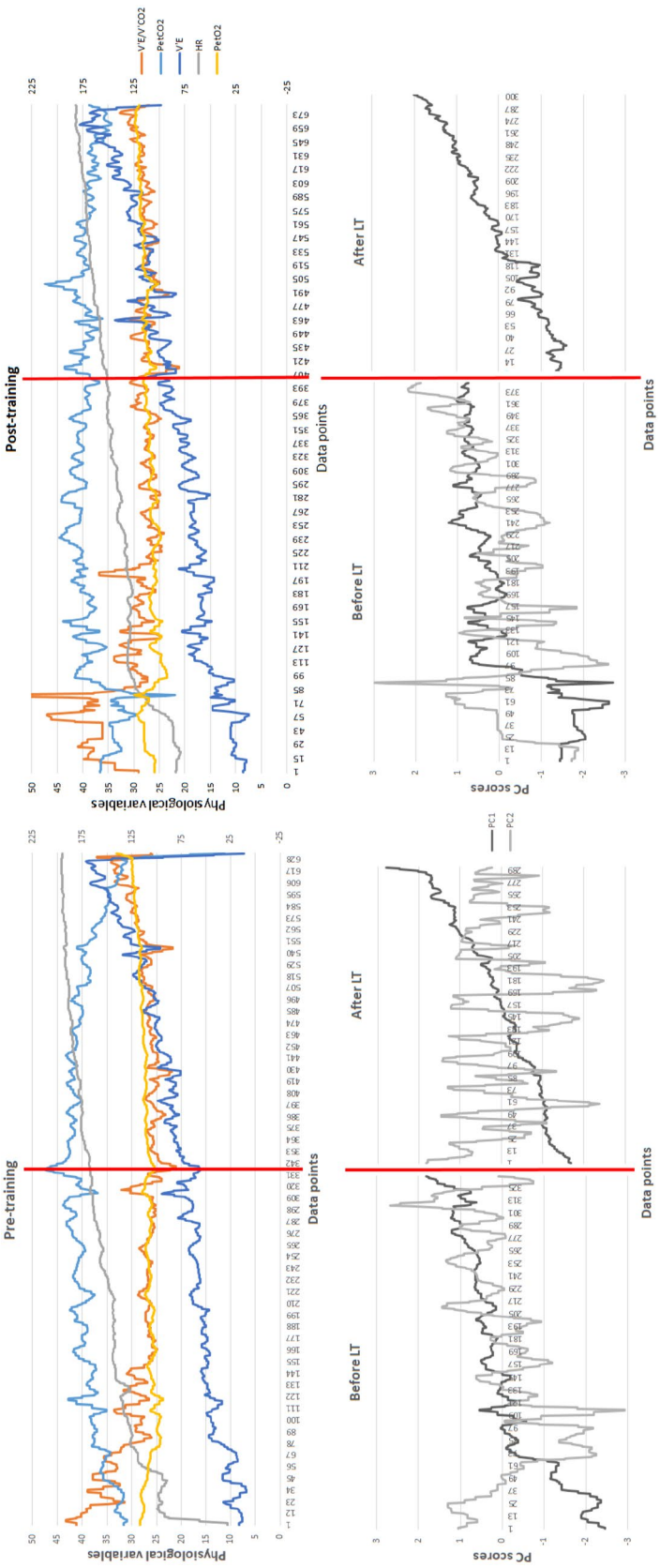

Fig. 2 Example (HIIT) of the creation of time series of coordination variables, expressed through PCs from cardiorespiratory variables in pre- and post-training tests. This figure represents a decrease in the number of PCs (from two to one) after lactate turnpoint post-training. Top graphs: time series of four cardiorespiratory variables corresponding to pre- and post-training tests. Bottom graphs: time series of the PC scores for pre- and post-training tests, with standardised *z* values in the space spanned by PCs. Following PC-based dimension reduction, the initial four time series lead to two time series (pre-training: before and after lactate turnpoint; post-training: before lactate turnpoint) or one time series (post-training: after lactate turnpoint). The average trend is calculated by weighted least squares method and graphically plotted in the black and grey lines shown

Between groups (post-training)

Below the lactate turnpoint, five participants had one PC in CONT, but only one participant showed one PC in HIIT (Table 1), revealing a higher degree of co-variation following CONT below the lactate turnpoint. However, above the lactate turnpoint, six participants in both CONT and HIIT showed one PC, demonstrating a similar degree of co-variation between groups above the lactate turnpoint. There were no significant differences when comparing PC_1 eigenvalues or the loadings of physiological variables between groups, neither before ($U = 38.00$; $p = 0.86$) nor after LT ($U = 72.00$; $p = 0.26$; see Table 1).

There were no differences between groups for training-induced changes in aerobic fitness parameters: lactate threshold (HIIT: pre 112 ± 36 W vs post 138 ± 43 W; CONT: pre 106 ± 37 W vs post 128 ± 39 W), lactate turnpoint (HIIT: pre 158 ± 38 W vs post 186 ± 35 W; CONT: pre 158 ± 38 W vs post 174 ± 40 W), $\dot{V}O_{2max}$ (HIIT: pre 3.52 ± 0.71 L/min vs post 3.80 ± 0.75 L/min; CONT: pre 3.33 ± 0.92 L/min vs post 3.62 ± 0.99 L/min) (group × time interactions, all $p \geq 0.081$, $\eta_p^2 \leq 0.159$). Both HIIT and CONT increased the power at lactate threshold, power at lactate turnpoint, W_{max} and $\dot{V}O_{2max}$ (l min^{-1}) (main effects of time, $p < 0.001$, $\eta_p^2 \geq 0.580$) with the $\dot{V}O_2$ (%$\dot{V}O_{2max}$) at LT and lactate turnpoint demonstrating a similar pattern of change.

Discussion

This study utilised a novel approach to analyse the effect of HIIT and CONT on cardiorespiratory coordination. All participants from the CONT group improved cardiorespiratory coordination at intensities above and below the lactate turnpoint, whereas following HIIT, cardiorespiratory coordination increased at intensities above the lactate turnpoint only. Since a dimension reduction (i.e. reduction in the number of PCs) is a hallmark of formation of coordinative structures (Haken 2000), these changes suggest that a coordinative, nonlinear reconfiguration occurred following training (Balagué et al. 2016). This adaptation may represent a reallocation of biological resources under immediate environmental and/or organismic constraints (Scholz and Schöner 1999; Latash 2008). Despite the different patterns of change at the level of organic coordination (i.e. cardiorespiratory coordination), specifically below the lactate turnpoint, both groups increased aerobic fitness ($\dot{V}O_{2max}$, lactate threshold, and lactate turnpoint) to a similar extent, in agreement with previous work-matched studies (Balagué et al. 2016; Esquius et al. 2019; Garcia-Retortillo et al. 2017). These observations suggest that changes in cardiorespiratory coordination might be specific for each training intervention and reinforces the idea that cardiorespiratory coordination analysis could be a sensitive tool to investigate the individual cardiorespiratory response to exercise training (Balagué et al. 2016; Esquius et al. 2019; Garcia-Retortillo et al. 2017).

Although HIIT improved the lactate threshold, in agreement with previous research (Edge et al. 2006; Ní Chéilleachair et al. 2017), no improvements were observed in cardiorespiratory coordination before the lactate turnpoint. At exercise intensities below the lactate turnpoint, the variance of the selected cardiorespiratory variables was mostly captured by two PCs pre-training for both the CONT and HIIT groups (Table 1). While PC_1 was formed by VE, $PetCO_2$, and HR, only $PetO_2$ was aligned with PC_2. The lack of co-variation and the subsequent setup of PC_2 may be as a result of the particular dynamics of $PetO_2$, which decreases at exercise onset and progressively increases thereafter, whereas the variables forming PC_1 demonstrate an increase from the onset of exercise (Garcia-Retortillo et al. 2017). The decrease of $PetO_2$ at exercise onset was nonetheless insufficient in most of the participants post-training to form a new PC_2 in CONT (see Fig. 1). As suggested by Balagué et al. (2016), an attenuated decrease in the data series for similar or higher workloads (the decrease would, therefore, affect fewer data points) suggests better ventilation and/or buffering. It could, therefore, be interpreted that there was an attenuated phase of falling $PetO_2$ at submaximal intensities following CONT since there was a lower O_2 uptake at test onset due to an increase in the efficiency of gas exchange. It should be noted that participants who did not decrease the number of PCs before lactate turnpoint, significantly increased PC_1 eigenvalues, which is also indicative of an increase in the degree of co-variation and, thus, an improvement on cardiorespiratory coordination. A feasible interpretation for the lack of improvements in cardiorespiratory coordination below the lactate turnpoint following HIIT may be related to the specificity of training intensity and, therefore, HIIT could have been less likely to improve gas exchange efficiency at lower exercise intensities.

During exercise intensities higher than lactate turnpoint, PC_1 was loaded by VE, $PetO_2$, and HR, and PC_2 was mainly formed by $PetCO_2$ (Table 1). The distinct behaviour of $PetCO_2$ above lactate turnpoint (i.e. dominantly decreasing while the other variables increases), due to the non-proportional increase in ventilation compared to $\dot{V}CO_2$ as a result of the rise in H^+ production (Binder et al. 2008) was responsible for the formation of PC_2. However, the $PetCO_2$ decreasing phase was not long enough (i.e. affected fewer data points) following either CONT or HIIT to form a new PC_2 in most of participants, potentially as a result of improved bicarbonate buffering efficiency during higher exercise intensities. The improvement of CRC above LTP was not initially expected. This result may be explained by

the review of Granata et al. (2018), where the importance of both training intensity and volume is discussed in relation to mitochondrial biogenesis. Training volume was highlighted as a more important factor than intensity for increases in mitochondrial content (an effect driven by training duration) and, given the greater training time in the CONT group in this current study, this may explain the improved CRC both above LTP.

The results in this study do not address whether CONT or HIIT is most efficacious at improving aerobic fitness; however, as suggested by Astorino et al. (2018), the "one size fits all" approach, in which an identical protocol is applied to each individual, may not be appropriate since individual responses to training might occur. The lack of between-group differences in improvements in markers of aerobic fitness (Edge et al. 2006; Bishop et al. 2014; O'Leary et al. 2017a, b) and the high incidence of non-responders (Gurd et al. 2016; Astorino et al. 2018) may be related to the fact that the acute physiological response to a training session (and the likely forthcoming adaptions) is determined by a wide range of variables and, subsequently, a myriad of metabolic and neuromuscular subsystems is affected simultaneously (Buchheit and Laursen 2013). Thus, since the coordination and network interactions among such subsystems are a hallmark of physiologic state and function (Ivanov et al. 2016) and given that changes in cardiorespiratory coordination might be specific for each training intervention, the use of cardiorespiratory coordination alongside other performance parameters could help to precisely analyse physiological adaptations after different CONT and HIIT interventions, and may assist coaches with the selection of the most appropriate training session to apply. However, further research is required to elucidate the effects of different HIIT (e.g. short or long intervals) and CONT protocols on cardiorespiratory coordination.

From a practical point of view, the evaluation of cardiorespiratory coordination together with commonly utilised maximal performance and cardiorespiratory variables could assist in the assessment of different training interventions on health and fitness, and improve the interpretation of cardiorespiratory exercise testing. Since cardiorespiratory coordination could be more sensitive to training than W_{max}, $\dot{V}O_{2max}$, or lactate turnpoint, the tracking of changes in cardiorespiratory coordination may offer an alternative approach to the assessment of variability (Bonafiglia et al. 2016) and 'non-responders' to exercise training programmes (Gurd et al. 2016; Astorino et al. 2018). Participants reporting no improvement in quantitative aerobic parameters in previous studies could indeed have qualitatively increased their degree of cardiorespiratory coordination after the training period. Furthermore, given the existing strong relationship between cardiorespiratory coupling and neuroautonomic regulation (Bartsch et al. 2015), cardiorespiratory coordination might also contribute to the evaluation of certain conditions characterised by an increased sympathetic adrenal activity, such as myocardial infarcts (Leder et al. 2000), advanced age (Bartsch et al. 2015), or some sleep stages (Bartsch et al. 2014), in which a pronounced decreased cardiorespiratory coupling has been shown. However, further research is warranted to elucidate such interactions.

Our results should be discussed in the light of some methodological limitations. First, when comparing PC_1 eigenvalues or the loadings of physiological variables between groups, no significant differences were found, either below or above the lactate turnpoint. A logical explanation stems from the fact that cardiorespiratory coordination is an intra-subject measure (Cysarz et al. 2004) and its performance is not methodologically adequate between groups since it tracks the nearness of an individual to the optimal cardiorespiratory coordination level (a participant could, subsequently, show low levels of cardiorespiratory coordination despite achieving high athletic performances). Second, the study design does not consider the accurate moment in which the PC changes for each one of the participants, which could lead to the establishment of patterns of cardiorespiratory coordination and would help to better capture the general picture of change across the continuum of exercise intensity. The intention was nonetheless to compare the improvements at the level of organic coordination (i.e. cardiorespiratory coordination) between training interventions.

Conclusion

In conclusion, 6 weeks of CONT and HIIT showed different patterns of change on cardiorespiratory coordination, despite improving markers of aerobic fitness to a similar extent. Therefore, changes in cardiorespiratory coordination may be specific for each training intervention and its evaluation appears as a sensitive tool to investigate the individual cardiorespiratory response to exercise training, alongside traditional measures of aerobic fitness.

Practical implications

- The evaluation of cardiorespiratory coordination alongside commonly utilised maximal performance and cardiorespiratory variables may improve the interpretation of cardiorespiratory exercise testing.
- The evaluation of cardiorespiratory coordination could help to precisely analyse specific physiological adaptations after different training interventions, and may assist coaches with selection of the most appropriate training session to apply.

- Cardiorespiratory coordination might offer an alternative approach to the assessment of variability and 'non-responders' to exercise training programmes across a range of populations.

Acknowledgements The authors wish to express gratitude to all research participants. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Author contribution All authors contributed to study design, data analysis and manuscript preparation.

Compliance with ethical standards

Conflict of interest The authors declare that they have no competing interests.

References

Astorino TA, Schubert MM (2014) Individual responses to completion of short-term and chronic interval training: a retrospective study. PLoS One 9:5

Astorino TA, deRevere J, Anderson T et al (2018) Change in $\dot{V}O_{2max}$ and time trial performance in response to high-intensity interval training prescribed using ventilatory threshold. Eur J Appl Physiol 118(9):1811–1820

Balagué N, González J, Javierre C et al (2016) Cardiorespiratory coordination after training and detraining. A principal component analysis approach. Front Physiol 7:35

Bartsch RP, Liu KK, Ma QD et al (2014) Three independent forms of cardio-respiratory coupling: transitions across sleep stages. Comput Cardiol 41:781–784

Bartsch RP, Liu KK, Bashan A et al (2015) Network physiology: how organ systems dynamically interact. PLoS One 10:11

Binder RK, Wonisch M, Corra U et al (2008) Methodological approach to the first and second lactate threshold in incremental cardiopulmonary exercise testing. Eur J Cardiovasc Prev Rehabil 15(6):726–734

Bishop DJ, Granata C, Eynon N (2014) Can we optimise the exercise training prescription to maximise improvements in mitochondria function and content? Biochim Biophys Acta 1840(4):1266–1275

Bonafiglia JT, Rotundo MP, Whittall JP et al (2016) Inter-individual variability in the adaptive responses to endurance and sprint interval training: a randomized crossover study. PLoS One 11:12

Buchheit M, Laursen PB (2013) High-intensity interval training, solutions to the programming puzzle. Sports Med 43(10):927–954

Carter H, Jones AM, Barstow TJ, Burnley M, Williams CA, Doust JH (2000) Oxygen uptake kinetics in treadmill running and cycle ergometry: a comparison. J Appl Physiol 89:899–907

Cohen J (1988) Statistical power analysis for the behavioral sciences. Laurence Erlbaum Associates, Publishers, Hillsdale

Cysarz D, Bettermann H, Lange S et al (2004) A quantitative comparison of different methods to detect cardiorespiratory coordination during night-time sleep. Biomed Eng Online 3(1):44

Denis DJ (2016) Applied univariate, and multivariate statistics bivariate. Wiley, Hoboken

Edge J, Bishop D, Goodman C (2006) The effects of training intensity on muscle buffer capacity in females. Eur J Appl Physiol 96:97–105

Esquius L, Garcia-Retortillo S, Balagué N et al (2019) Physiological- and performance-related effects of acute olive oil supplementation at moderate exercise intensity. J Int Soc Sports Nutr 16:2

Garcia-Retortillo S, Javierre C, Hristovski R et al (2017) Cardiorespiratory coordination in repeated maximal exercise. Front Physiol 8:387

Goodwin ML, Harris J, Hernández A et al (2007) Blood lactate measurements and analysis during exercise: a guide for clinicians. J Diabetes Sci Technol 4:558–569

Granata C, Jamnick NA, Bishop DJ (2018) Training-induced changes in mitochondrial content and respiratory function in human skeletal muscle. Sports Med 48:1809–1828

Gurd BJ, Giles MD, Bonafiglia JT et al (2016) Incidence of non- response and individual patterns of response following sprint interval training. Appl Physiol Nutr Metab 41(3):229–234

Haken H (2000) Information and self-organization. A macroscopic approach to complex systems. Springer, New York

Ivanov PC, Liu KK, Bartsch RP (2016) Focus on the emerging new fields of network physiology and network medicine. New J Phys 18(10):100201

Jelleyman C, Yates T, O'Donovan G et al (2015) The effects of high-intensity interval training on glucose regulation and insulin resistance: a meta-analysis. Obes Rev 16:942–961

Jiménez-Pavón D, Lavie CJ (2017) High-intensity intermittent training versus moderate-intensity intermittent training: is it a matter of intensity or intermittent efforts? Br J Sports Med 51(18):1319–1320

Jolliffe I (2002) Principal component analysis. Springer, New York

Latash ML (2008) Synergy. Oxford University Press, New York

Leder U, Hoyer D, Sommer M et al (2000) Cardiorespiratory desynchronization after acute myocardial infarct. Z Kardiol 89:630–637

Meyer P, Gayda M, Juneau M et al (2013) High-intensity aerobic interval exercise in chronic heart failure. Curr Heart Fail Rep 10:130–138

Midgley A, McNaughton LR, Polman R, Marchant D (2007) Criteria for determination of maximal oxygen uptake: a brief critique and recommendations for future research. Sports Med 37:1019–1028

Ní Chéilleachair NJ, Harrison AJ, Warrington GD (2017) HIIT enhances endurance performance and aerobic characteristics more than high-volume training in trained rowers. J Sports Sci 35(11):1052–1058

O'Leary TJ, Collett J, Howells K (2017a) Endurance capacity and neuromuscular fatigue following high vs moderate- intensity endurance training: a randomised trial. Scand J Med Sci Sports 27(12):1648–1661

O'Leary T, Collett J, Howells K et al (2017b) High but not moderate-intensity endurance training increases pain tolerance: a randomised trial. Eur J Appl Physiol 117:2201–2210

Ramos JS, Dalleck LC, Tjonna AE et al (2015) The impact of high-intensity interval training versus moderate- intensity continuous training on vascular function: a systematic review and meta-analysis. Sports Med 45:679–692

Scholz JP, Schöner G (1999) The uncontrolled manifold concept: identifying control variables for a functional task. Exp Brain Res 126:289–306

Schulz S, Adochiei F, Edu I et al (1997) Cardiovascular and cardiorespiratory coupling analyses: a review. Philos Trans A Math Phys Eng Sci 2013(371):20120191

Viana RB, Barbosa de Lira CA, Araújo Naves JP et al (2018) Can we draw general conclusions from interval training studies? Sports Med 48(9):2001–2009

Weston AR, Myburgh KH, Lindsay FH et al (1997) Skeletal muscle buffering capacity and endurance performance after high-intensity interval training by well-trained cyclists. Eur J Appl Physiol 75:7–13