Cardiorespiratory coordination reveals training-specific physiological adaptations

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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 Two-arm parallel group single-blind randomised study. Twenty adults were randomly assigned to 6 weeks of HIIT or volume-matched CONT. Participants completed a progressive maximal cycling test before and after the training. Principal component (PC) analysis was performed on the series of cardiorespiratory variables to evaluate dimensionality of cardiorespiratory coordination, before and after lactate turnpoint. PC1 eigenvalues were compared. Results Both HIIT and CONT improved aerobic fitness (main effects of time, $p < 0.001$, $\eta p2 \geq 0.580$), with no differences between groups. CONT decreased the number of PCs from 2 to 1 at intensities both below and above the lactate turnpoint; PC1 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 2 to 1 after the lactate turnpoint only; PC1 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. Changes in cardiorespiratory coordination appear training-intensity specific and could be a sensitive tool to investigate the individual cardiorespiratory response to endurance training.
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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: Two-arm parallel group single-blind randomised study. Twenty adults were randomly assigned to 6 weeks of HIIT or volume-matched CONT. Participants completed a progressive maximal cycling test before and after the training. 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, $p < 0.001$, $\eta p2 \geq 0.580$), with no differences between groups. CONT decreased the number of PCs from 2 to 1 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 2 to 1 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. Changes in cardiorespiratory coordination appear training-intensity specific and could be a sensitive tool to investigate the individual cardiorespiratory response to endurance training.

Keywords: endurance training; high-intensity interval training; moderate-intensity continuous training; coordinative variables; principal component analysis.

i. 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 are most efficacious in improving aerobic fitness (Jiménez-Pavón and Lavie 2017; Viana et al. 2018) likely due to, in part, to differences between studies with regards to the training protocols and outcome measures employed. Aerobic fitness has been assessed with markers including maximal oxygen consumption ($\dot{V}O_{2max}$), lactate thresholds, and anaerobic performance indices (Racil et al. 2013; Nalcakan 2014; O'Leary et al. 2017), but with varying results. When looking at individual data, at least 20-50% of participants undergoing various HIIT or CONT protocols reveal non-response 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 registered markers of aerobic training are not sensitive enough to capture the specific training adaptations (Balagué et al. 2016) or the optimal endurance training intervention might be specific to each individual depending on sensitivity to training (Astorino et al. 2018). Our research hypothesis is centred on these issues.

Previous work has shown that $\dot{V}O_{2max}$ and other commonly registered maximal physiological and performance variables may not be sensitive enough to detect specific physiological adaptations occurring after different types of training (Balagué et al. 2016). A feasible explanation may stem from the fact that they provide little information on the specific nonlinear dynamic interactions between organic subsystems (Bartsch et al. 2015; Ivanov et al. 2016). The study of time series of coordinative variables (Schulz et al. 2013) and the application of nonlinear models (Goushcha et al. 2014) may detect these specific interactions. This research approach will enable the measurement of quantitative (e.g., $VO2_{max}$) and qualitative adaptations (e.g., in the cardiorespiratory coordination), and may be more sensitive in evaluating the effects of different types of endurance training.

Cardiorespiratory coordination is a novel method of measuring co-variation of cardiorespiratory variables during exercise testing (Balagué et al. 2016; Garcia-Retortillo et al. 2017). It is estimated through principal component analysis (PCA), performed on the time series of selected cardiovascular and respiratory outcomes. In contrast to isolated cardiorespiratory outcomes, the cardiorespiratory response to exercise can be represented, through PCA, by a short set of principal components (PCs) extracted in decreasing order of importance. Principal components 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 (high number of PCs entail low coordination, whereas low number of PCs imply high coordination; see Balagué et al. 2016 for a detailed explanation). Cardiorespiratory coordination has recently shown a higher responsiveness to training (Balagué et al. 2016) and training load (Garcia-Retortillo et al. 2017) than $\dot{V}O_{2max}$ and other markers of aerobic fitness. The training-induced changes in cardiorespiratory coordination represent the ability of biological systems to optimise their response by means of an efficient reallocation of their resources under immediate environmental and/or organismic constraints (Scholz and Schöner 1999; Latash 2008).

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. 2017). 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}).

ii. 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 $\dot{V}O_{2max}$. 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, 2017b); the data in this current study concerns 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 a submaximal and maximal exercise test 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 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 $mmol \cdot l^{-1}$. 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 $\dot{V}O_{2max}$. Following 20 min rest, a maximal ramp test was completed for the determination of $\dot{V}O_{2max}$. 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 $W \cdot min^{-1}$ for men and 20 $W \cdot min^{-1}$ for women until 60 rpm could no longer be maintained. Expired gases and HR were measured throughout. $\dot{V}O_{2max}$ and $\dot{W}_{max}$ were taken as the highest 30 s average of the recorded VO_2 and power output, respectively.

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 3 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 6 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 8 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 (session 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. 2017).

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, non-published results of our lab have shown similar results while analysing cardiorespiratory coordination with and without continuous blood pressure measurement. Bartlett's sphericity test and the Kaiser-Mayer-Olkin (KMO) index (Denis 2016) were computed in order to evaluate the suitability of the application of the PCA. The number of PCs was defined by the Kaiser-Gutmann criterion, which recognizes 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 pairs 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 standardized mean differences and an alpha level was set at 0.05 for all statistical tests.

iii. 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 2 PCs to 1 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 Figure 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 2 PCs to 1PC) 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 Figure 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).

Between groups (post-training). Below the lactate turnpoint five participants had 1 PC in CONT, but only one participant showed 1 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 1 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).

As previously reported (O'Leary et al. 2017a, 2017b) there were no differences between groups for training-induced changes in aerobic fitness parameters: lactate threshold, lactate turnpoint, $\dot{V}O_{2max}$ or $\dot{W}_{max}$ (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, $\dot{W}_{max}$ and $\dot{V}O_{2max}$ ($l \cdot min^{-1}$) (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.

iv. 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 (Kelso 1995), 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 CONT and HIIT studies (Balagué et al. 2016; 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; 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 covariation and the subsequent set-up 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 participants post-training to form a new PC_2 in CONT (see Figure 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 $PetO_2$ following CONT, since there were lower O_2 demands at test onset due to an increase in the efficiency of gas exchange (Ben-Tal et al. 2012). 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^+ (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 results in this study do not address whether CONT or HIIT are 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-groups differences in improvements in makers of aerobic fitness (Edge et al. 2006; Bishop et al. 2014; O’Leary et al. 2017) 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 2014). Thus, since the coordination and network interactions among such subsystems is 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 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 registered 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, cardiorespiratory coordination may also contribute to the early detection and, furthermore, to the implementation of preventative programs on fatigue effects induced by exercise at different time-scales (Noon et al. 2015). Symptoms derived from overreaching states or overtraining syndromes may result from a deficient and poor coupling between or amongst the different physiological subsystems involved (Kreher 2016) and common physiological tests are inadequate for their detection (Meeusen et al. 2012).

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, neither below nor above the lactate turnpoint. A logical explanation stems from the fact that cardiorespiratory coordination is an intra-subject measure (Cysarz 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.

v. 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.

vi. Practical Implications

- The evaluation of cardiorespiratory coordination alongside commonly registered 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 assessment may contribute to prevention and early detection of exercise-induced fatigue effects, and might offer an alternative approach to the assessment of variability and 'non-responders' to exercise training programmes across a range of populations.

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viii. References

American Thoracic Society. ATS/ACCP statement on cardiopulmonary exercise testing. Am J Respir Crit Care Med 2003; 167:211–277.

Astorino TA, deRevere J, Anderson T et al. Change in VO2max and time trial performance in response to high-intensity interval training prescribed using ventilatory threshold. Eur J Appl Physiol 2018; 1-10.

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

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

Bartsch RP., Liu KK, Bashan A et al. Network physiology: how organ systems dynamically interact. PloS one 2015, 10:11.

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

Ben-Tal A., Shamailov SS, Paton JFR. Evaluating the physiological significance. J Physiol 2012; 590:1989–2008.

Bishop DJ, Granata C, Eynon N. Can we optimise the exercise training prescription to maximise improvements in mitochondria function and content? Biochim Biophys Acta 2014; 1840(4):1266–75.

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

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

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

Denis DJ. Applied Univariate, Bivariate, And Multivariate Statistics. Hoboken, Wiley, 2016

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

Foster C, Farland CV, Guidotti F et al. The effects of high intensity interval training vs steady state training on aerobic and anaerobic capacity. J Sports Sci Med 2015; 14(4):747-755.

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

Goushcha AO, Hushcha TO, Christophorov LN. Self-organization and coherency in biology and medicine. Open J Biophys 2014; 4:119–146.

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

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

Haken H. Information and Self-Organization. A Macroscopic Approach to Complex Systems. New York, Springer, 2000

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

Jelleyman C, Yates T, O'Donovan G et al. The effects of high-intensity interval training on glucose regulation and insulin resistance: a meta-analysis. Obes Rev 2015;16:942–61.

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

Jolliffe I. Principal Component Analysis. New York, Springer, 2002

Kreher J. Diagnosis and prevention of overtraining syndrome: an opinion on education strategies. Open Access J Sports Med 2016; 8:115–122.

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

Mann TN, Lamberts RP, Lambert MI. High responders and low responders: factors associated with individual variation in response to standardized training. Sports Med 2014; 44(8):1113–1124.

McKay BR, Paterson DH, Kowalchuk JM. Effect of short-term high-intensity interval training vs. continuous training on O2 uptake kinetics, muscle deoxygenation, and exercise performance. J Appl Physiol 2009; 107(1):128–38.

Meeusen R, Duclos M, Foster et al. Prevention, diagnosis, and treatment of the overtraining syndrome: joint consensus statement of the European College of Sport Science and the American College of Sports Medicine. Med Sci Sports Exerc 2012; 45:186–205.

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

Milanović Z, Sporiš G, Weston M. Effectiveness of high-intensity interval training (HIT) and continuous endurance training for VO2max improvements: a systematic review and meta-analysis of controlled trials. Sports Med 2015; 45(10):1469-81.

Nalcakan GR. The effects of sprint interval vs. continuous endurance training on physiological and metabolic adaptations in young healthy adults. J Hum Kinet 2014; 44:97-109.

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

Noon MR, James RS, Clarke ND et al. Perceptions of well-being and physical performance in English elite youth footballers across a season. J Sports Sci 2015; 33(20):2106-2115.

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

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

Racil G, Ben Ounis O, Hammouda O et al. Effects of high vs. moderate exercise intensity during intrval training on lipids and adiponectin levels in obese young females. Eur J Appl Physiol 2013; 113:2531–2540.

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

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

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

Viana RB, Barbosa de Lira CA, Araújo Naves JP et al. Can we draw general conclusions from interval training studies? Sports Med 2018; 1-9.

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

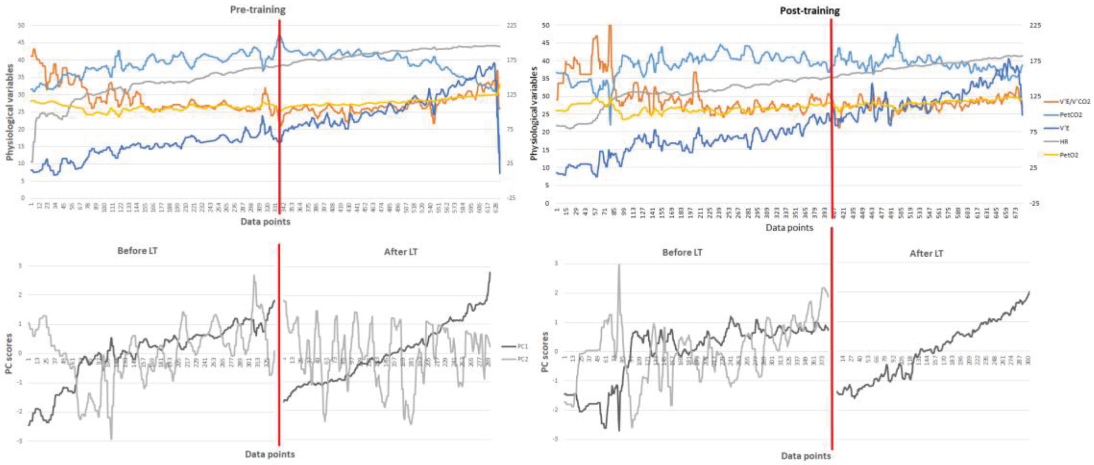

Figure 2. Example (HIIT) of the creation of time-series of coordination variables, expressed through PCs from cardiorespiratory variables in pre and post-training tests. This figure represents a decrease in the number of PCs (from 2 to 1) after LT post-training. Top Graphs: Time-series of four cardiorespiratory variables corresponding to pre and post-training tests. Bottom Graphs: Time-series of the PC scores for pre and post-training tests, with standardized z-values in the space spanned by PCs. Following PC-based dimension reduction, the initial four time-series lead into two time-series (pre-training: before and after LT; post-training: before LT) or one time series (post-training: after LT). The average trend is calculated by weighted least squares method and graphically plotted in the black and grey lines shown.

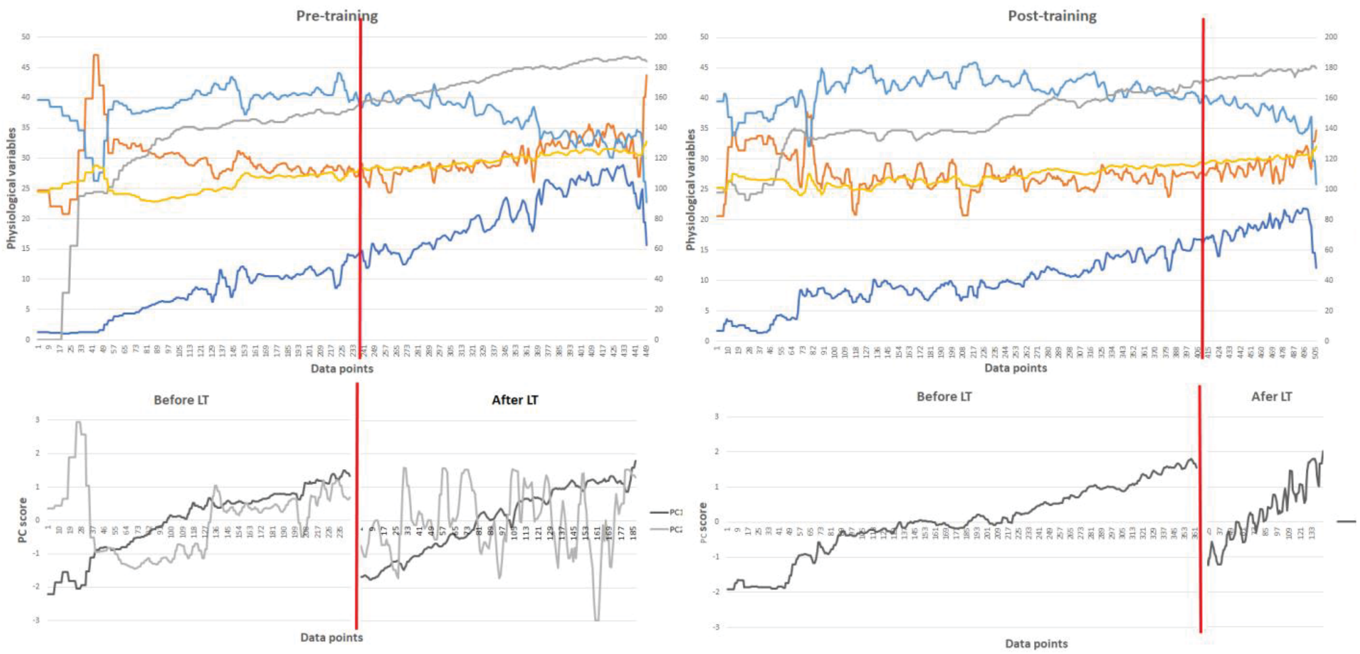

Figure 1. Example (CONT) of the creation of time-series of coordination variables, expressed through PCs from cardiorespiratory variables in pre and post-training tests. This figure represents a decrease in the number of PCs (from 2 to 1) before and after LTP post-training. Top Graphs: Time-series of 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 standardized z-values in the space spanned by PCs. Following PC-based dimension reduction, the initial four time-series lead into 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 LTP. Data points along the axis of abscissae represent the number of measurements registered throughout the test.

i. Tables

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 LTP in both pre and post-training tests.

Before LTP

		Pre-training						Post-training					
		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
			(0.32)	(0.03)	(0.04)	(0.26)	(0.17)		(0.50)	(0.09)	(0.01)	(0.25)	(0.08)
	PC2	9	1.25	0.23	0.17	0.81	0.60	6	1.17	0.25	0.19	0.25	0.94
			(0.27)	(0.15)	(0.17)	(0.24)	(0.23)		(0.12)	(0.29)	(0.15)	(0.19)	(0.09)
HIIT	PC1	2	2.73	0.86	0.93	0.45	0.93	3	2.65	0.91	0.95	0.34	0.87
			(0.29)	(0.13)	(0.06)	(0.22)	(0.04)		(0.27)	(0.07)	(0.05)	(0.21)	(0.10)
	PC2	7	1.18	0.41	0.30	0.88	0.30	6	1.02	0.12	0.19	0,22	0.92
			(0.22)	(0.21)	(0.16)	(0.12)	(0.11)		(0.02)	(0.10)	(0.10)	(0.18)	(0.07)

After LTP

		Pre-training						Post-training					
		Par	PC EV	VE	HR	$PetO_2$	$PetCO_2$	Par	PC EV	VE	HR	$PetO_2$	$PetCO_2$
CONT	PC1	5	2.85	0.89	0.82	0.92	0.40	6	3.08	0.96	0.95	0.95	0.52
			(0.32)	(0.11)	(0.24)	(0.07)	(0.29)		(0.19)	(0.01)	(0.06)	(0.04)	(0.29)
	PC2	5	1.17	0.47	0.19	0.86	0.28	4	1.01	0.04	0.06	0.15	0.98
			(0.12)	(0.15)	(0.03)	(0.15)	(0.11)		0.02	(0.03)	(0.05)	0.05	(0.02)
HIIT	PC1	1	2.79	0.96	0.89	0.94	0.36	6	2.93	0.97	0.92	0.95	0.43
			(0.38)	(0.02)	(0.14)	(0.04)	(0.21)		(0.27)	(0.02)	(0.11)	(0.04)	(0.19
	PC2	8	1.21	0.33	0.21	0.91	0.41	3	1.04	0.05	0.28	0.09	0.99
			(0.23)	(0.14)	(0.12)	(0.10)	(0.20)		(0.04)	(0.04)	(0.02)	(0.03)	(0.00)

LTP, lactate turnpoint; CONT, moderate-intensity continuous training; HIIT, high-intensity interval training; PC, principal component; EV, eigenvalue; Par, number of participants with 1 or 2 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.

Author contribution

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