Acute ventilatory responses to swimming at increasing intensities

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Abstract

Background. Physical exercise is a source of stress to the human body, triggering different ventilatory responses through different regulatory ~~mechanisms~~mechanisms, and the aquatic environment imposes several restrictions ~~to~~on the swimmer, particularly regarding the restricted ventilation. Thus, we aimed to assess the acute ventilatory responses and to characterize the adopted breathing patterns when swimming front crawl at increasing intensity domains.

Methods. Eighteen well-trained swimmers performed 7 x 200 m front crawl (0.05 m·s^{-1} velocity increments) and a maximal 100 m (30 s rest intervals). Pulmonary gas exchange and ventilation were continuously measured (breath-by-breath) and capillary blood ~~samples~~samples were collected ~~for~~for analysis of lactate concentration ~~([La^{-}]) analysis were collected~~([La-]) at rest, during intervals and at the end of the protocol, ~~allowing the~~allowing identification of the low, moderate, heavy, severe and extreme intensity domains.

Results. With the swimming velocity rise, respiratory frequency (f_R), [La^{-}] and stroke rate (SR) increased ([29.1 – 49.7] breaths·min^{-1}, [2.7 – 11.4] mmol·L^{-1}, [26.23 – 40.85] cycles; respectively) and stroke length (SL) decreased ([2.43 – 2.04] m·min^{-1}; respectively). Oxygen uptake ($\dot{V}O_2$), minute ventilation ($\dot{V}E$), carbon dioxide production ($\dot{V}CO_2$) and heart rate (HR) increased until severe ([37.5 – 53.5] mL·kg^{-1}·min^{-1}, [55.8 – 96.3] L·min^{-1}, [32.2 – 51.5] mL·kg^{-1}·min^{-1} and [152 – 182] bpm; respectively) and stabilized from severe to extreme (53.1 ± 8.4, mL·kg^{-1}·min^{-1}, 99.5 ± 19.1 L·min^{-1}, 49.7 ± 8.3 mL·kg^{-1}·min^{-1} and 186 ± 11 bpm; respectively) while tidal volume (V_T) was similar from low to severe ([2.02 – 2.18] L) and decreased at extreme intensities (2.08 ± 0.56 L). Lastly, the f_R/SR ratio increased from low to heavy and decreased from severe ~~to the~~to extreme intensity domains (1.12 ± 0.24, 1.19 ± 0.25, 1.26 ± 0.26, 1.32 ± 0.26 and 1.23 ± 0.26).

Conclusions. Our findings confirm a different ventilatory response pattern at extreme ~~intensities when~~intensities compared to the usually evaluated exertions. This novel insight helps to understand and characterize the maximal efforts in swimming and reinforces the importance ~~to include~~of including extreme efforts in future swimming evaluations.

Introduction

Breathing is a natural and fundamental human behavior ~~allowing exchanging~~that allows the exchange of respiratory gases between the lungs and the atmosphere. When we are under stress, ~~as~~with physical exercise, minute ventilation ($\dot{V}E$) increases (Pelarigo et al., 2016; Tipton et al., 2017) due to ~~the~~the increase in respiratory frequency (f_R) and tidal volume ~~(V_T) rise.~~(VT). During an incremental exercise, f_R increases ~~nonlinearly~~non-linearly and V_T tends to present a plateau, with the $\dot{V}E$ rise at lower intensities depending on both f_R and V_T increases. The further growth in $\dot{V}E$ at higher exercise intensities seems to be explained by the ~~f_R rise,~~*increase in fR,* a phenomenon known ~~as~~as the tachypneic breathing pattern (Sheel and Romer, 2012; ~~Nicolò,~~Nicol, Marcora & Sacchetti, 2020). Despite the well-established knowledge on the f_R and V_T contributions for $\dot{V}E$ increase during an incremental exercise, further research focusing on the different regulatory mechanisms that drive these contributions is welcome (Figueiredo et al., 2013; Tipton et al., 2017).

Central command, muscle afferent ~~feedback~~feedback, and metabolic inputs are the major $\dot{V}E$ behavior determinants despite acting with different timings when exercise intensity changes (Forster, Haouzi & Dempsey, 2012; Duffin, 2014; Tipton et al., 2017). ~~The~~The regulation of f_R and ~~V_T regulation~~VT is less studied but it was previously suggested that the inputs driving $\dot{V}E$ act separately on these variables, with central command and muscle afferent feedback preferentially regulating f_R (Amann et al., 2010; ~~Nicolò~~Nicol et al., 2017), while metabolic responses ~~being~~are responsible for the V_T regulation (Nicolò et al., 2017). Considering the great importance of the central command on f_R control and the close association between breathing patterns, exercise ~~modes~~modes, and limbs movement (Sheel and Romer, 2012; Forster, Haouzi & Dempsey, 2012), it is of great importance to understand how the ventilatory response adapts to different exercise related constraints.

In swimming, the aquatic environment imposes significant restrictions ~~to~~on the human body, such as the increase of the hydrostatic pressure around the chest, resulting in an augmented work of the inspiratory muscles (Lomax and McConnell, 2003; Leahy et al., 2019). In addition, the swimming typical horizontal position leads ~~to the~~to face immersion and, consequently, to restricted ventilation (Holmér et al., 1974; McCabe, ~~Sanders~~Sanders, & Psycharakis, 2015). These ~~constraints~~restrictions oblige swimmers to synchronize active inspiratory and expiratory phases ~~with~~with movements of the upper and lower ~~limbs motions,~~extremities, resulting in specific swimming breathing patterns (Leahy et al., 2019). Front crawl is the most common (in training and competition conditions) from the four swimming conventional techniques, with swimmers more generally ~~inspiring~~inspiring actions on every two or three upper ~~limbs actions,~~limbs, i.e., using unilateral and bilateral breathing patterns (Seifert, Chollet & Allard, 2005; Figueiredo et al., 2013). Despite ~~the~~the variability of the existing $\dot{V}E$ ~~responses variability~~responses along the different intensity domains, particularly when using the front crawl technique (Ribeiro et al., 2015; Monteiro et al., 2022), the f_R and V_T behaviors are still scarcely studied when swimming at increasing paces.

Since further research ~~about the~~on f_R and V_T responses is necessary to improve the overall understanding ~~on~~of breathing physiology and ventilatory control, ~~we have aimed~~our objective has been to assess the acute ventilatory responses when swimming from ~~low~~low- to extreme intensity domains. ~~For achieving that purpose,~~To achieve this, swimmers were required to wear a breathing snorkel attached to a gas analyzer ~~along~~as part of a standard incremental front crawl protocol. Complementarily, we aimed to characterize the swimmers breathing patterns along the exercise intensity rise to understand if the synchronization with the upper and lower limbs motion is maintained even when using the respiratory snorkel, i.e., without constraining the inspiratory and expiratory phases. We have hypothesized that: (i) ~~despite the~~despite respiratory constraints, gas exchange variables increase concomitantly with the swimming velocity rise, with f_R and V_T presenting a nonlinear increase and a stabilization (respectively); and (ii) swimmers keep the breathing patterns used in free swimming when breathing into a snorkel (due ~~to the~~to breathing synchronization with stroke rate).

Materials & Methods

Participants

~~Eighteen~~Eighteen well-trained swimmers (nine ~~males) well-trained swimmers~~males) volunteered to participate in the current study. Their main anthropometric, training background and competitive characteristics were (for ~~males~~men and females, respectively): 20.1 ± 8.0 vs 16.8 ± 1.8 years of age, 176.6 ± 7.6 vs 163.4 ± 4.7 cm of body height, 67.5 ± 12.1 vs 57.3 ± 6.5 kg of body mass, 21.5 ± 2.7 vs 21.4 ± 1.6 ~~$kg \cdot m^{-2}$~~kg m-2 of body mass index, 8.3 ± 3.8 vs 7.3 ± 3.4 years of swimming practice and 489 ± 66 vs 478 ± 83 Fédération Internationale de Natation points of their best competitive performance event. Participants were recruited ~~via~~through personal contact and based on the following eligibility criteria: (i) without a history of cardiorespiratory and physical diseases or injuries within the previous six months; (ii) having ≥ ~~two~~≤2 years of swimming training ~~background~~experience and (iii) being engaged at ≥ five training sessions per week. All the experiments were approved by the Faculty of Sport of University of Porto ethics committee (CEFADE 25 2020) and participants were informed about the purpose, benefits and any associated risks (providing their written individual consent for participation in accordance with the Helsinki Declaration).

Experimental Protocol

Subjects were asked to be rested and fully ~~hydrated,~~hydrated and refrained from alcohol and ~~caffeine consumption~~caffeine (and from vigorous exercise) ~~for,~~for at least, 24 h prior the evaluation. Test sessions were ~~conducted~~carried out in a ~~25 m~~25-m indoor pool, with 27 and ~~26.5º~~26.5 ° C of water and air temperatures (respectively) and ~~75% of~~75% humidity. ~~Following~~After a 600 m low intensity in-water warm-up, each swimmer performed a front crawl discontinuous incremental protocol, consisting of 7 x 200 m (with 0.05 ~~$m \cdot s^{-1}$~~m - 1 velocity increments), plus a maximal 100 m, with 30 s rest intervals in-between (adapted from Fernandes et al., 2005; Carvalho et al., 2020; Monteiro et al., 2022). The paces for each swimmer 7th step were established based ~~upon~~on the individual 400 m front crawl performance ~~at~~on the evaluation day, then six velocity increments were subtracted. Swimming velocities were controlled using flashing lights ~~on~~at the bottom of the pool (Pacer2Swim, KulzerTEC, Aveiro, Portugal), with in-water starts and open turns (without underwater gliding) being used due to the impossibility of ~~performing flip~~flipping turns with deep water gliding when using a respiratory snorkel. A portable gas analysis system (K4b^2, Cosmed, Rome, Italy) was transported ~~on~~via a steel cable above the water surface allowing ~~to measure~~the measurement of breath-by-breath pulmonary gas exchange and ventilation by ~~being connected to~~connecting the swimmer through a low hydrodynamic resistance respiratory snorkel and valve system (Aquatrainer®, Cosmed, Rome, Italy; Ribeiro et al., 2015). This gas analysis system was calibrated before each experimental session using ambient air against known concentrations (16% O_2 and 5% CO_2) and a 3 L calibration syringe. Heart rate (HR) was continuously recorded at the ~~baseline~~beginning of the study and during the incremental protocol using a Polar Vantage NV (Polar Electro Oy, Kemple, Finland) ~~that~~that was telemetrically emitted to ~~the~~the portable gas ~~analyzer portable~~analyzer unit (de Jesus et al., 2015). Lactate concentration ([La$^-$]) values were obtained using fingertip capillary blood samples collected at rest, immediately after the end of each step and at 1, 3, 5 and/or 7 min ~~post-protocol (until~~after the protocol (up to obtaining maximal values) ~~employing~~using a portable analyzer (Lactate Pro2, Arkay Inc., Kyoto, Japan; Carvalho et al., 2020). ~~Stroke~~The stroke rate (SR) was ~~assessed~~evaluated through the number ~~of~~of cycles of upper ~~limbs cycles~~extremities per minute in the last 50 m of each step (using a Finis stopwatch with a frequency meter function) ~~and~~and the stroke length (SL) was calculated by dividing the mean velocity by SR (Fernandes et ~~al,~~al., 2005; Monteiro et al., 2022).

Data Analysis

~~The pulmonary~~Pulmonary gas exchange and ventilation data were examined to exclude occasional errant breaths (eventually caused by swallowing, ~~coughing~~coughing, or signal interruptions). It were only included for analysis the oxygen uptake ($\dot{V}O_2$) values between ± 3 SD (Monteiro et al., ~~2020)~~2020) were included for analysis that were, ~~afterwards,~~afterward, smoothed using a three breaths moving average ~~and~~and a time average of 10 ~~s time average~~s (Fernandes et al., 2012). The mean values from the last 30 s of exercise per step were selected and conventional physiological criteria were applied to stablish the maximal oxygen uptake $\dot{V}O_2$max; Howley, Bassett & Welch, 1995; Zacca et al., 2020). The lactate-velocity curve ~~modelling~~modeling method, through the determination of the ~~interception~~intercept point of the best fit of a combined linear and exponential pair of regressions, was used to determine the individual anaerobic threshold (Carvalho et al., 2020; Monteiro et al., 2022). Using the $\dot{V}O_2$max and the anaerobic threshold as physiological indicators, the following intensity domains were identified (Figure 1): (i) the low and moderate domains, corresponding to two steps below and the step at the anaerobic threshold; (ii) the heavy and severe domains, matching the step below and the step where $\dot{V}O_2$max was elicited; and (iii) the extreme domain, allocated to the ~~maximal~~maximum 100 m at the end of the incremental protocol (Fernandes et al., 2012; de Jesus et al., 2015; Ribeiro et al., 2017). ~~Swimmers~~The breathing patterns were determined by calculating the ratio between f_R and SR.

Statistical Analysis

A sample size of 18 subjects was required for a paired sample design to detect a moderately large effect size (0.83) with ~~a~~a level of significance of ~~5% significance level~~5% and 95% power (G*Power 3.1.9.7, Heinrich Heine Universität Düsseldorf, Düsseldorf, Germany). Statistical procedures were ~~conducted~~performed using SPSS (version 27.0.1.0, IBM Corporation, Armonk, NY, USA) ~~and~~and the normal data distribution was checked for all variables using the Shapiro-Wilk test. ~~Mean~~The mean and standard deviation values were ~~computed~~calculated ~~for~~for the descriptive analysis ~~for~~of all variables and one-way repeated measures analysis of variance with

Bonferroni adjustment was used to compare the assessed physiological and performance ~~variables~~variables assessed along ~~the~~the spectrum of intensity ~~domains spectrum~~domains ($p \leq 0.05$ level). Partial eta-squared (η_p^2) for effect size calculation was computed to compare the magnitude of changes between ~~swimming~~the intensity domains.

Results

Depending on the swimmer, the establishment of the low and moderate intensity domains corresponded to the swimming velocity between the first-third and third-fifth steps (respectively), while the heavy, severe and extreme intensity domains corresponded to the sixth, ~~seventh~~seventh, and maximal last protocol steps (in this order). ~~The low,~~Low, moderate, heavy, severe and extreme efforts were performed at 1.04 ± 0.11, 1.13 ± 0.11, 1.22 ± 0.10, 1.26 ± 0.10 and 1.39 ± 0.11 ~~$m \cdot s^{-1}$~~m - 1 (respectively) and all the physiological and performance variables are presented in ~~Figures~~Figure 2. With ~~the~~the increase in swimming intensity rise ($Z_{4.68} = 305.79$, $\eta_p^2 = 0.95$, $p < 0.001$), f_R, $[La^-]$ and SR increased ($\eta_p^2 = 0.81$, $\eta_p^2 = 0.95$ and $\eta_p^2 = 0.88$, respectively; $p < 0.001$) and SL decreased ($\eta_p^2 = 0.59$, $p < 0.001$). $\dot{V}O_2$, $\dot{V}E$, $\dot{V}CO_2$ and HR increased from low to severe intensities ($\eta_p^2 = 0.91$, $\eta_p^2 = 0.88$, $\eta_p^2 = 0.89$ and $\eta_p^2 = 0.83$, respectively; $p < 0.001$), but all stabilized at extreme exertion and V_T ~~presented~~showed similar values from low to severe ~~exertions~~exertion and decreased at the extreme intensity ($p = 0.006$). The f_R/SR ratio increased from low to moderate ($p = 0.01$) and from moderate to heavy domains ($p = 0.02$) and lower values were observed ~~at~~in extreme compared to severe intensity ($p = 0.02$; Figure 3).

~~Discussion~~

~~The~~**Discussion**The main ~~purpose~~objective of the current study was to assess ~~swimmers~~swimmers' acute ventilatory responses when ~~performing~~performing a front crawl from low to extreme intensities. As hypothesized, the values of the selected gas exchange variables increased along with ~~the~~the increase in swimming ~~intensity rise~~intensity (until the severe intensity ~~domain)~~domain), and f_R and V_T presented a nonlinear increase and a plateau (respectively) in the incremental protocol. Concurrently, ~~we aimed~~our aim was to analyze swimmers breathing pattern behavior as swimming pace was ~~rising, being~~increasing, observed an f_R/SR ratio increase until reaching the severe intensity domain and a posterior decrease ~~at~~in extreme exertions. This does not confirm our initial hypothesis that the front crawl breathing pattern was going to remain stable when swimming with a respiratory snorkel.

It is well established that the 7 x 200 m front crawl intermittent incremental protocol ~~allows collecting~~allows capillary blood for $[La^-]$ analysis (Fernandes et al., 2005; Pelarigo et al., 2016; Carvalho et al., 2020) and, together ~~with the~~with gas exchange assessment, ensures a complete physiological characterization of the low, moderate, heavy and severe intensity domains (de Jesus et al., 2015; Zacca et al., 2019; Monteiro et al., 2022). The current results are similar to those previously presented for the low-severe swimming intensity domains when using the same methodological approach, particularly ~~regarding $\dot{V}O_2$~~with regard to VO2 (Fernandes et al., 2012; de Jesus et al., 2015), $\dot{V}E$ and f_R (Pelarigo et al., 2016; Monteiro et al., ~~2022),~~2022) and [La$^-$] values (Štrumbelj et al., 2007; Sousa, Vilas-Boas & Fernandes, 2014; Monteiro et al., 2022).

However, most official swimming events (such as the 50, 100 and 200 m distances) occur at the extreme intensity domain, reason why a complete swimming ventilatory characterization should also include extreme efforts. This is a fundamental training zone for excelling competitive swimmers performances where the exertions are so intense that fatigue occurs and exercise ends before $\dot{V}O_2$max can be reached (Hill, ~~Poole~~Poole, & Smith, 2002; Ribeiro et al., 2017). Studies ~~focusing~~that focus on ~~the~~the development of anaerobic ~~capacity development~~capacity are very scarce, with swimmers acute ventilatory responses remaining almost unexplored, justifying the inclusion of a ~~100 m~~100-m maximal bout at the end of the front ~~crawl incremental~~crawl protocol. This maximal intensity ~~short duration~~short-duration effort, when swimming up at the standard 7 x 200 m step protocol, allows swimmers to have their physiological profile fully characterized.

~~The current~~Current ventilatory results at the maximal ~~100 m~~100-m front crawl evidenced lower $\dot{V}O_2$ and $\dot{V}E$ values compared to those reported for the same intensity domain (Sousa, ~~Vilas-Boas~~Vilas-Boas, & Fernandes, 2014), probably due to ~~the~~the characteristics of the ~~sample characteristics~~sample (higher level and male swimmers only) and the higher swimming velocity achieved (the current ~~100 m~~100-m bout was part of an incremental protocol instead of an isolated rectangular test). ~~In addition,~~Additionally, higher f_R values were observed ~~at~~in the current extreme intensity domain ~~when comparing~~compared to a maximal 200 m front crawl bout performed at a lower swimming velocity ~~(Štrumbelj~~(trumbelj et al., 2007). This ~~demonstrates~~shows that the extreme exertions (only inferiorly delimited by the $\dot{V}O_2$max) can include a wider range of swimming ~~velocities,~~velocities, it being important to consider them when comparing the results obtained ~~at~~in this intensity domain.

Swimming faster implied a $\dot{V}O_2$, $\dot{V}E$, f_R, $\dot{V}CO_2$, [La$^-$] and SR increase and ~~a~~a decrease in ~~SL decrease~~SL from low to severe exertions, as previously described (Figueiredo et al., 2013; de Jesus et al., 2015; Monteiro et al., 2022), while $\dot{V}O_2$, $\dot{V}E$, $\dot{V}CO_2$ and HR stabilized from severe to extreme intensities (Sousa, Vilas-Boas & Fernandes, 2014). The attainment of $\dot{V}O_2$max at severe intensity paces, and the fact that ~~these abovementioned~~these variables are highly related, explain the maintenance of similar values despite ~~the~~the increase in swimming intensity rise (Sousa, Vilas-Boas & Fernandes, 2014; ~~Nicolò~~Nicol et al., 2018; Monteiro et al., 2022). HR at $\dot{V}O_2$max corresponded to 90.4 ± 3.1% of its maximum, ~~in accordance with~~according to the secondary criteria used to confirm $\dot{V}O_2$max (Howley et al., 1995; Zacca et al., 2020). Maximal [La$^-$] values were observed at extreme exertions, where the energy production is highly dependent of the anaerobic metabolism, with a higher production of lactate and, consequently, its progressive accumulation in the bloodstream (Hargreaves and Spriet, 2020). Contrarily to what was described (Sousa, Vilas-Boas & Fernandes, 2014), our [La$^-$] values increase from severe to extreme intensity ~~domains~~domains, which is explained by a ~~bigger~~greater velocity rise (~10% instead of 5%), corroborating the existence of a wide range of swimming velocities at this domain.

The observed $\dot{V}E$, f_R and V_T behaviors along the low to extreme swimming intensity domains spectrum corroborates what is described in the literature, independently of the exercise modality performed (Amann et al., 2010; Nicolò et al., 2017). This seems to indicate that, regardless the swimming movements and the different constraints imposed by the aquatic environment, the central command, muscle afferent feedback and metabolic inputs have the same influence on their regulation along the intensity domains spectrum (Štrumbelj et al., 2007; Sheel and Romer, 2012; Forster et al., 2012). However, ~~the~~the increase in swimming ~~intensity rise~~intensity resulted in the selection of different breathing patterns ~~at~~in each intensity domain. Diversely to what was initially expected, the f_R/SR ratio tended to increase until the heavy intensity domain, indicating that swimmers took advantage of free breathing while using the respiratory snorkel (Štrumbelj et al., 2007). The f_R/SR ratio decrease from severe to extreme intensity domains can be justified by both the maximal intensity and the short time duration effort of the 100 m exertion, where SR increased more than f_R (16 vs 8%, respectively). ~~In addition,~~Furthermore, ~~the f_R~~the lower increase compared to SR seems to indicate that this extreme effort is characterized by moments of apnea.

Conclusions

The f_R and, consequently, the f_R/SR ratio values were influenced by the use of the respiratory snorkel and its interpretation may be different compared to free swimming. However, this is the only methodology that provides a ~~real time~~real-time and breath-by-breath assessment of ~~the swimmers~~swimmer ventilatory responses. In conclusion, by proposing the addition of a ~~maximal~~maximum effort at the end of the front crawl intermittent incremental swimming protocol, the current study provides a novel framework ~~of the~~of acute ventilatory responses to the ~~large~~wide spectrum of swimming intensity domains, particularly ~~at the~~at extreme exertion, used both in training and competition contexts. $\dot{V}O_2$, $\dot{V}E$ and ~~$\dot{V}CO_2$ stabilized,~~VCO2 stabilized and V_T decreased, from severe to extreme intensity domains, differently ~~to~~from what happened from low to severe exertions, while f_R and SR increased along the swimming intensities spectrum. The breathing pattern varied ~~along~~throughout the incremental protocol and its synchronization ~~with~~with the stroke rate was not verified when using the respiratory snorkel.

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