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Respiratory muscle endurance, oxygen saturation index in vastus lateralis and performance during heavy exercise

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ABSTRACT

The purpose of this study was to investigate the relationships between respiratory muscle endurance, tissue oxygen saturation index dynamics of leg muscle (TSI) and the time to exhaustion (TTE) during high intensity exercise. Eleven males performed a respiratory muscle endurance test, a maximal incremental running field test ($8\,\text{km}\,\text{h}^{-1} + 0.5\,\text{km}\,\text{h}^{-1}$ each 60 s) and a high-intensity constant speed field test at 90% $\text{VO}_{2\text{max}}$. The TSI in vastus lateralis was monitored with near-infrared spectroscopy. The TSI remained steady between 20 and 80% of TTE. Between 80 and 100% of TTE (7.5 ± 6.1%, $p < 0.05$), a significant drop in TSI concomitant with a minute ventilation increase ($16 \pm 10\,\text{l}\,\text{min}^{-1}$) was observed. Moreover, the increase of ventilation was correlated to the drop in TSI ($r = 0.70$, $p < 0.05$). Additionally, respiratory muscle endurance was significantly correlated to TSI time plateau (20–80% TTE) ($r = 0.83$, $p < 0.05$) and to TTE ($r = 0.95$, $p < 0.001$). The results of the present study show that the tissue oxygen saturation plateau might be affected by ventilatory work and that respiratory muscle endurance could be considered as a determinant of performance during heavy exercise.

1. Introduction

Respiratory muscle exhibit continuous, phasic contractile activity and are known to be characterized by a high oxidative capacity and capillary density (Dempsey et al., 2006). It is well documented that respiratory muscle work can affect exercise performance at high intensities (~>85% of maximal oxygen uptake, $\text{VO}_{2\text{max}}$). This is related to the high metabolic demand of the respiratory muscle (8–16% $\text{VO}_{2\text{max}}$) to sustain exercise-induced hyperpnoea. Additionally, it should be noted that the respiratory muscle are susceptible to fatigue (Dempsey et al., 2006; Guenette et al., 2010; Katayama et al., 2012; Verges et al., 2007) which might enhance the so-called ‘respiratory steal phenomenon’ (Legrand et al., 2007a). In exercising humans, increases and decreases in the work of the respiratory muscle induced vasoconstriction and vasodilation in the exercising limb, respectively (Harms et al., 1997). Additionally to the change in limb blood flow, it has been shown that decreasing the respiratory muscle work (unloading by means of a proportional assist ventilation) resulted in a 14.4% increase in time to exhaustion for cycling at 90% $\text{VO}_{2\text{max}}$ (Harms et al., 2000), whereas increasing the respiratory muscle work (by adding breathing resistance) decreased time to exhaustion already at an intensity of 80% $\text{VO}_{2\text{max}}$ (Carra et al., 2003).

Respiratory muscle training has shown to improve performance (Bailey et al., 2010; Holm et al., 2004; McMahon et al., 2002; Verges et al., 2009) by reducing their solicitation level (McMahon et al., 2002), oxygen uptake (Bailey et al., 2010), and fatigue development (Verges et al., 2007). Therefore, it appears that respiratory muscle endurance strongly determines exercise tolerance. Despite the above mentioned studies it is currently unclear to which extent respiratory muscle endurance has an impact on locomotor muscle oxygenation during exercise. Measurements of muscle oxygenation (Legrand et al., 2007a) have pointed out that the accelerated fall in respiratory muscle oxygenation (i.e., deoxygenation) coincides with both the levelling-off in locomotor muscle deoxygenation (i.e., oxygenation level reaches a plateau) and the respiratory compensation point at an intensity of ~85% $\text{VO}_{2\text{max}}$, suggesting a competition between respiratory and locomotor muscle oxygenation.

Given the impact of respiratory muscle work and fatigue on blood flow to the exercising limbs (Harms et al., 1997), the positive impacts of inspiratory muscle training and the observed relationship between respiratory and locomotor muscle oxygenation (Legrand et al., 2007a), it can be suggested that respiratory muscle endurance is related to exercise tolerance (time to exhaustion) for

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a heavy-intensity exercise (>85% VO_{2max}) mediated by differences in the level of oxygenation at the exercising muscles. Recently, an incremental test was developed to evaluate respiratory muscle endurance (Verges et al., 2009; Villiot-Danger et al., 2011) in which the maximal sustainable ventilation is expressed as a fraction of the maximal voluntary ventilation (ATS/ERS, 2002). This technique allows to assess muscle oxygenation responses exactly when the respiratory muscles reach the maximal sustainable ventilation during heavy exercise.

In this concern, the objective of the present study was to assess the relationships between respiratory muscle endurance, exercise performance, changes in ventilation, and (de) oxygenation of the locomotor muscles during a field running exercise at heavy intensity to the limits of tolerance. It was hypothesized that subjects displaying a higher respiratory muscle endurance would have a longer time to exhaustion in combination with a higher amplitude of change in ventilation and locomotor muscle deoxygenation.

2. Material and methods

2.1. Subjects

Eleven healthy, active men (mean ± SD: age 23 ± 3 years, body weight 73 ± 12 kg, height 181 ± 7 cm) took part in this study. All participants were non-smokers and free of heart and lung diseases and had normal resting pulmonary function, as assessed by spirometry tests. This study was approved by the Ethics Committee of UHC Farhat-Hached Hospital and in accordance with the Declaration of Helsinki. The subjects were informed in detail about the experimental procedures and risks involved with the experimental methodology, and gave their informed consent. They were instructed not to engage in any physical activity and not to drink or eat any caffeinated meals on testing days.

2.2. Testing procedures

The experiment was performed over three separate sessions with at least 48 h between each session. Session 1 was devoted to a spirometry test and a maximal incremental running field test. The respiratory muscle endurance test and the constant-load exercise at 90% VO_{2max} were performed (in counterbalanced order) in sessions 2 and 3. The spirometry and respiratory muscle endurance test were performed in the laboratory at a mean ± SD temperature of 23 ± 2 °C and a relative humidity of 44 ± 3%. Maximal incremental running exercise and constant-load exercise were performed in a gymnasium at a temperature of 22 ± 2 °C and relative humidity of 42 ± 2%. The laboratory and the gymnasium did not differ significantly in terms of the atmospheric conditions. In each test, the participants were given verbal encouragements. To minimize circadian effects, all tests were performed at the same time of day. On a given day, all tests were performed under the same conditions and with the same equipment.

2.2.1. Spirometry test

Spirometry test was performed with the participant in the sitting position while breathing room air, with the nose being occluded by a clip. A breathing tube was inserted into the subject's mouth with the lips sealed around the mouthpiece. All testing was completed using a calibrated computerized spirometer Spirolab III (Medical International Research, Rome, Italy) by the same technician. The subjects were familiarized with the device and the procedure for each test demonstrated by the technician. The flow and volume measurement sensor is a digital turbine, based on the infrared interruption principal. This principal ensures the accuracy and the reproducibility of the measurements without requiring a periodic calibration. For an accurate and reliable calibration, the syringe volume must be at least 3 L. Each subject performed tests five times. Respiratory maneuvers were performed in accordance with the standards established by Miller et al. (2005).

2.2.2. Incremental running field test

The incremental running field test was performed in a gymnasium (110 m for a lap). The running speed was initially set at 8 km h^{-1} and was increased by 0.5 km h^{-1} each minute. The running speed was controlled using auditory signals ('sound beeps'). Throughout the test, the gas exchange was measured by means of a portable metabolic measurement system (Cosmed K^4b_2, Rome, Italy). The gas analyzer was calibrated before each test with a reference mixture (16% O_2 and 5% CO_2) and the pneumotachograph was calibrated by using a 3 L syringe (Cosmed, Rome, Italy). The heart rate (HR) was measured with a polar device (RS300, Polar Electro, Kempele, Finland). The test was terminated after two consecutive delays in achieving the target speed stage.

2.2.3. Respiratory muscle endurance test

The test was performed as previously described (ATS/ERS, 2002; Vergès et al., 2009). Subjects were seated and familiarized with the device (SpiroTiger, Idiag, Fehraltorf, Switzerland), which enabled partial rebreathing and voluntary normocapnic hyperpnea (Renggli et al., 2008; Villiot-Danger et al., 2011). The rebreathing bag was connected to two-way piston valve allowing the renewal of fresh inspired air into the bag to ensure a constant isocapnic end-tidal CO_2 fraction (Keramidas et al., 2011). The rebreathing bag was adjusted to 50% of the subject's slow vital capacity and the test was started at a target minute ventilation (V_E) corresponding to 20% of the maximum voluntary ventilation (12 s). V_E was increased by 10% of the maximum voluntary ventilation (by increasing the respiratory rate) every 3 min until the subject could no longer maintain the target respiratory rate and/or tidal volume. Lung volume and respiratory rate were controlled at each cycle by the device such that it remains unchanged.

2.2.4. The 90% VO_{2max} constant-load running field exercise

The participants performed the constant-load running exercise until exhaustion in a gymnasium (110 m for a lap). The running speed was controlled using auditory signals. The exercise was stopped after two consecutive delays in achieving the target speed. Since the subjects studied were well trained and familiarized with this type of effort minimizing the day to day variability, the test was performed only one time (Carra et al., 2003; Keramidas et al., 2011; Perrey et al., 2002).

Throughout the test, the pulmonary ventilation and gas exchanged were recorded by means of the portable metabolic measurement system (Cosmed K^4b_2, Rome, Italy; for more details see above).

The locomotor muscle oxygenation was measured second-by-second in the vastus lateralis muscle during the constant-load exercise using a non-invasive near-infrared spectroscopy wireless device (NIRS) (Portamon, Artinis, Medical System, Zetten, The Netherlands). The spectroscopic measurement of muscle oxygenation was based on quantifying variations in optical characteristics at wavelengths at 760 nm and 850 nm. The optode was secured with medical adhesive and covered with a black bandage to minimize light contamination. The sensor was applied on vastus lateralis muscle about 15 cm above the knee (after the muscle been localized via a voluntary knee flexion at 90°) and was held tightly in position by elastic straps. The optode was placed over the belly of the muscle, in order to minimize the possible effects of muscle perfusion heterogeneity. Skinfolds were measured at the location of the probe using a Harpenden caliper (Baty International, West Sussex, United kingdom), to ensure that skin fold was lower than