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Effects of gradual change of Exercise Intensity on Muscle Oxygenation, measured by Near-infrared Spectroscopy

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Resumo

Introdução

A intensidade do exercício em ciclistas, assim como a variação da cadência são factores muito importantes na oxigenação muscular dos mesmos. O objectivo do estudo foi avaliar a relação do aumento gradual da intensidade do exercício de pedalagem na oxigenação muscular em ciclistas bem como a fase recuperação após exaustão, comparando um grupo de profissionais e amadores, utilizando a Espectroscopia de Infravermelho próximo (NIRS).

Métodos

Dois grupos de atletas caucasianos do sexo masculino (Grupo A: três atletas profissionais; Grupo B: três atletas amadores) pedalaram até à exaustão, realizando um protocolo incremental, usando o Ergómetro de laboratório Lode Excalibur Sport e os próprios pedais. A cadência permaneceu constante e a potência foi aumentando ao longo do exercício. A oxigenação muscular foi monitorizada continuamente pela Espectroscopia de Infravermelho próximo (NIRS) no músculo Vasto Lateral (VL), e os parâmetros hemodinâmicos (Ventilação [VE], *Uptake* O_2 [VO_2], *Output* de CO_2 [VCO_2] e Frequência Cardíaca [HR]) foram monitorizados continuamente por um aparelho automático de análise e electrocardiograma.

Resultados

Durante o exercício, quando a intensidade aumenta, o músculo diminui a sua saturação de O_2 de uma forma linear, em atletas profissionais e amadores, assim como a Frequência Cardíaca e o VO_2/kg. Quanto à Ventilação, há um aumento quadrático em relação à intensidade, em ambos os grupos. Durante a recuperação, a saturação de O_2 aumenta de uma forma linear.

Conclusões

Durante o teste, a saturação de O_2 muscular descreve uma descida linear, em ambos os grupos.. A velocidade de recuperação da oxigenação muscular após a exaustão e significativamente superior nos ciclistas profissionais, quando comparada com os ciclistas amadores. Por fim, isto leva-nos a concluir que uma maior variação relativa da extracção muscular de O_2 durante o exercício em atletas profissionais, sugere uma produção aumentada de energia aeróbia, e consequentemente maior aptidão aeróbia. Estes são, então, factores muito importantes na saturação muscular de O_2.

Palavras-chave

Oxigenação muscular, NIRS, ciclismo, Saturação O_2.

Abstract

Background

Exercise intensity in cycling, as well cadence variation, is one of the most important factors in cyclists muscle oxygenation. The aim of the study was to assess the relationship between pedaling exercise intensity and muscle oxygenation in cyclists as well as the recovery phase after exhaustion, measured by Near-Infrared Spectroscopy (NIRS), comparing a group of professional cyclists and a group of amateur cyclists.

Methods

Two groups of male caucasian athletes (Group A: three professional cyclists; Group B: three amateur cyclists) cycled until exhaustion, performing an incremental protocol, using the Lode Excalibur Sport Ergometer laboratory bicycle and their own pedals. The pedaling cadence remained constant and the working power changed throughout the exercise. Muscle oxygenation was monitored continuously by near-infrared spectroscopy on the *Vastus Lateralis*, and Hemodynamic parameters (Ventilation [VE], O_2 uptake [VO_2], CO_2 Output [VCO_2] e Heart Rate [HR]) were monitored continuously along the test by an automatic analyzer and Electrocardiogram.

Results

During incremental exercise, muscle O_2 saturation describes a linear decrease, in both groups. HR and VO_2/kg increase in a linear way during exercise, but VE increases in a quadratic way in professional and amateur cyclists. During muscle saturation recovery, the linear increase of O_2 saturation is significantly different between the two groups.

Conclusions

During exercise, muscle O_2 saturation has a linear decrease, in both groups. The rate of muscle O_2 saturation recovery after exhaustion is significantly higher in professional cyclists, when compared to amateur cyclists. This last finding and the larger relative change of muscle O_2 extraction in the working muscle throughout the test in professional cyclists, suggest that higher aerobic energy production, and consequently higher aerobic fitness. These are very important factors in muscle O_2 saturation.

Keywords

Muscle oxygenation, NIRS, cycling, O_2 saturation.

Introduction

The impacts of the changes in pedaling cadence on performance, cardiopulmonary and metabolic responses have attracted the attention of researchers and it is known that time until exhaustion decreases with the increase of the pedaling cadence [1-5], especially in untrained subjects, but not in triathletes. The key link between pedaling cadence and performance seems to be the aerobic fitness of the subject [6]. A decrease in muscle efficiency at high cadences has been described as the main reason for those observations [2, 4, 5, 7, 8]. Concerning the pulmonary oxygen uptake, contradictory results were obtained: while some studies showed no relationship between pedal cadence and pulmonary oxygen uptake [3, 9-11] others claimed the occurrence of higher pulmonary oxygen uptake at higher pedal cadence for the same work rate [1, 2, 4, 8, 12, 13]. Accordingly, the reason why professional cyclists spontaneously adopt higher cadences (over 90 rpm) during endurance cycling, flat stages and time trials is not fully explained by energy consumption. It is also reported that the most economical cadence increases with increasing workload in elite cyclists [10, 14], which is supported by a lower peak force and shorter duration for muscle contraction, which may cause a reduction in intramuscular pressure, alleviating blood flow restriction and preventing muscle fatigue [15, 16]. Literature has accepted these reasons to justify the higher cadences adopted spontaneously by professional cyclists during endurance cycling, flat stages and time trials [17]. Also, a greater glycogen depletion in type II fibers at 50 rpm, compared to 100 rpm, at high workloads has been described [18]. This indicates a greater activation of the quadriceps muscle at 50 rpm in opposition to 100 rpm, explaining the possible benefit of choosing higher cadences at high workloads. The finding that minimum EMG amplitude occurs at a progressively higher cadence as power output supports this theory [19].

The large monoarticular muscles working over the hip and knee joints are considered the main power producing muscles (the gluteus and the vasti muscles) [20]. The *Vastus Lateralis* (VL), among the vasti muscles, is one of the main contributors to pedaling work force in pedaling exercise, so it is commonly used for NIRS studies during pedaling exercise [17, 21].

Cycling research has been focused on studying the effects of changing pedaling cadence on performance, pulmonary oxygen uptake or muscle oxygenation, while keeping exercise power constant. To our knowledge, no study had observed the relationship between muscle oxygenation and the change of working power, during an incremental exercise until exhaustion. We designed the present study to assess the effects of a gradual change of exercise intensity on muscle oxygenation, in professional and amateur cyclists, with the objective of obtaining new knowledge that could be implemented in a protocol using non-invaseive NIRS technology to individualize athletes' training methodologies.

Methods

Subjects

Two groups of subjects were studied: a group of three male professional cyclists with a 2016 activity of ≥ 20000 km (age 28,7 ± 6,4 years, weight 67,3 ± 4,5 kg, height 177 ± 3,6 cm, 20,7 ± 0,6 kg/m^2 BMI); and a group of three male amateur cyclists (age 34 ± 3,6 years, weight 71,7 ± 6,1 kg, height 181 ± 3,4 cm, 22 ± 2,6 kg/m^2 BMI) with a 2016 activity between 5000-10000 km and last month's activity ≥ 400 km. None of the subjects reported a history of injury during the previous 2 years. Before the test, all subjects received a detailed explanation of the experimental protocol, they were informed about the risks and signed the statement of consent. The study was approved by the Clínica Médica do Exercício do Porto (CMEP) Ethics Department.

Experimental protocol

Each subject from the first group performed an incremental cycle exercise test until exhaustion (RAMPA 45) to determine VO_2 max and the power output achieved at VO_2 max. The test began with 3 minutes resting, followed by 3 minutes of warming at 0 W. After that, the power was increased constantly with a rate of 45 W per minute until exhaustion. Pedal cadence was kept constant between 80-90 rpm and the test was stopped manually when the subject was not able to keep increasing the VO_2, despite strong verbal encouragement. After that, the test finished with 3 min of active recovery, cycling at 0 W. The second group performed the same incremental exercise test until exhaustion, but with a power increase rate of 35 W per minute (RAMPA 35). The Lode Excalibur Sport Ergometer (The Netherlands), which is renowned worldwide as the *gold-standard* in cycling ergometry, was used to this experiment, to measure the cycling power.

Measurements

Hemodynamic parameters

An automatic analyzer (Metalyzer 3B, Cortex, Germany) was used to assess the gas exchange variables during each test, and a facial mask with gas detector sensor connected to the analyzer was applied to each participant. It was calibrated according to manufacturer's recommendations with gases of known concentration (16% O_2 and 4% CO_2) before the tests. A 12-lead electrocardiogram was used to monitor continuously the heart rate (HR). Pulmonary oxygen uptake (VO_2), Carbon dioxide output (VCO_2), ventilation (VE) and HR values were averaged into 15s intervals. Data was automatically displayed in the software MetaSoft Studio 3.0 (Cortex, Germany). Anaerobic Threshold (AT) is the moment when VCO_2 changes the increasing rate, when the slope of VCO_2 increases, was manually determined.

Muscle oxygenation

Local muscle oxygenation was measured continuously with a continuous-wave NIRS system (Invos Cerebral/Somatic Oximeter, Medtronic, USA) in the VL during the test. The NIRS probe is composed of two light sources and one photodiode detector, which were spaced by 3 cm and 4 cm, to provide a light penetration depth of 2 cm [22], which allows to have an actual measure of oxygenation at the level of VL. The sensor was applied to the shaved skin, overlying the VL, 10 cm above the upper border of the patella, and parallel to the major axis of the thigh. It was fixed with tape to avoid movement during the test and covered with the cycling shorts, to avoid contamination of external light to the measurement photon pathway. Before each test, the device was calibrated according to the manufacturer's recommendations. The large monoarticular muscles working over the hip and knee joints are considered the main power producing muscles (the gluteus and the vasti muscles) [20]. The Vastus Lateralis, among the vasti muscles, is one of the main contributors to pedaling work force in pedaling exercise, so it is commonly used for NIRS studies during pedaling exercise [17, 21]. NIR light (700-1000 nm) penetrates superficial layers (skin, subcutaneous fat, skull, etc.) and is either absorbed by chromophores (oxy- and deoxyhemoglobin and myoglobin) or scattered within the tissue. NIRS is a noninvasive and relatively low-cost optical technique that is becoming a widely used instrument for measuring tissue O_2 saturation, changes in hemoglobin volume and, indirectly, brain/muscle blood flow and muscle O_2 consumption. This allows us to investigate the balance between O_2 delivery and extraction at the muscle level [23, 24].

The NIRS device provides the mean of the absolute values for oxygenation level in each 6 seconds of the test. Consequently, we decided to express and analyze the relative values against the higher value during the warming phase, for each participant, which we considered as 100%.

Statistics

The difference between two independent experimental groups was evaluated using the unpaired student t-test for normally distributed variables. The significance level was set for all statistical analyses at $p<0,05$. Data analysis was performed with the GraphPad Prism 7 software for Mac.

Results

Hemodynamic parameters

HR increased over time and power increasing in all volunteers. During the recovery time, HR decreased in both groups. As shown in Figure 1, inter-group comparison revealed that HR is significantly different during exercise until exhaustion (p<0,001). HR increases with power in a linear way (Group A: r^2=0,93; Group B: r^2=0,84).

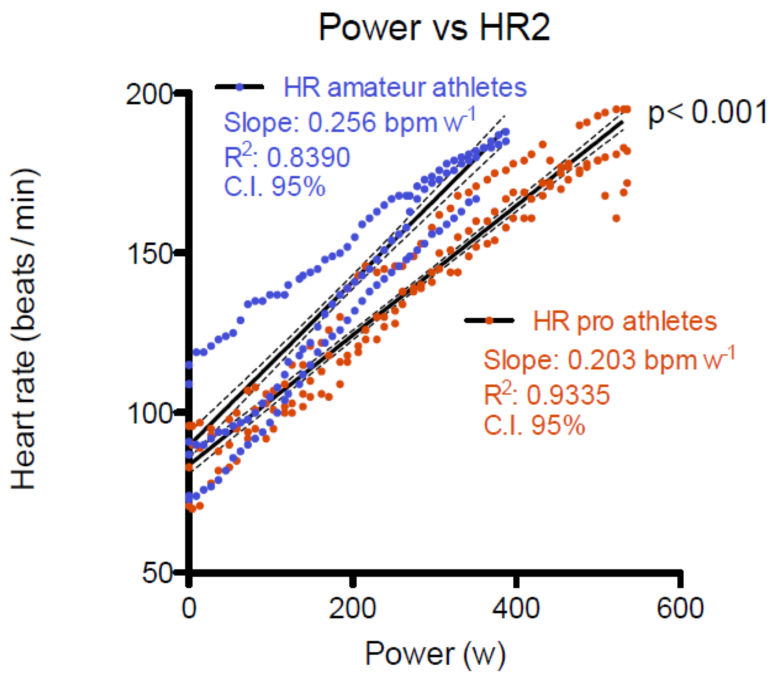


Figure 1 – Relationship between Heart rate in both groups (HR2) and Power (Comparison between the two groups)

On the other hand, VE showed an increase in a quadratic way in both groups (Group A: r2=0,92, p<0,0001; Group B: r2=0,97, p<0,0001). The slopes of each regression are significantly different (p<0,0001). (Figure 2)

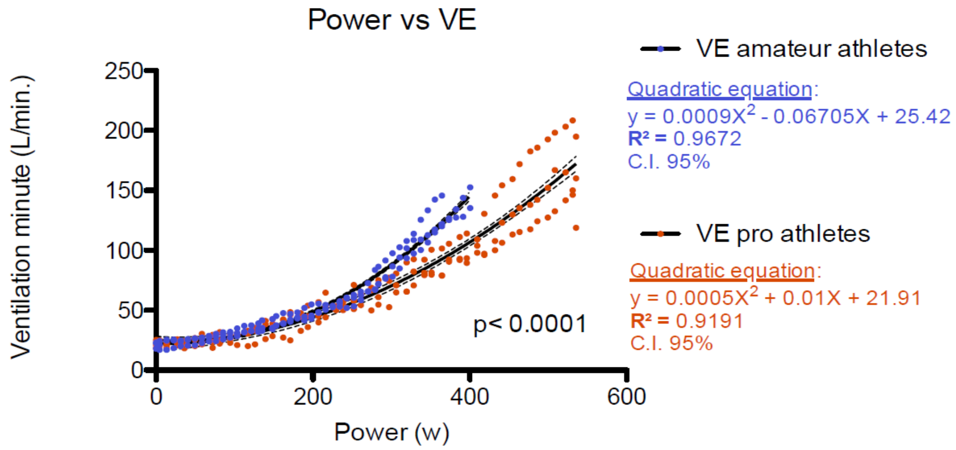


Figure 2- Relationship between VE and Power (Comparison between the two groups)

VO_2/kg was calculated and we found that it increases during exercise (Group A: r^2= 0,91; Group B: r^2=0,97). VO_2/kg along the exercise is significantly different between the two groups (p=0,0183). (Figure 3)

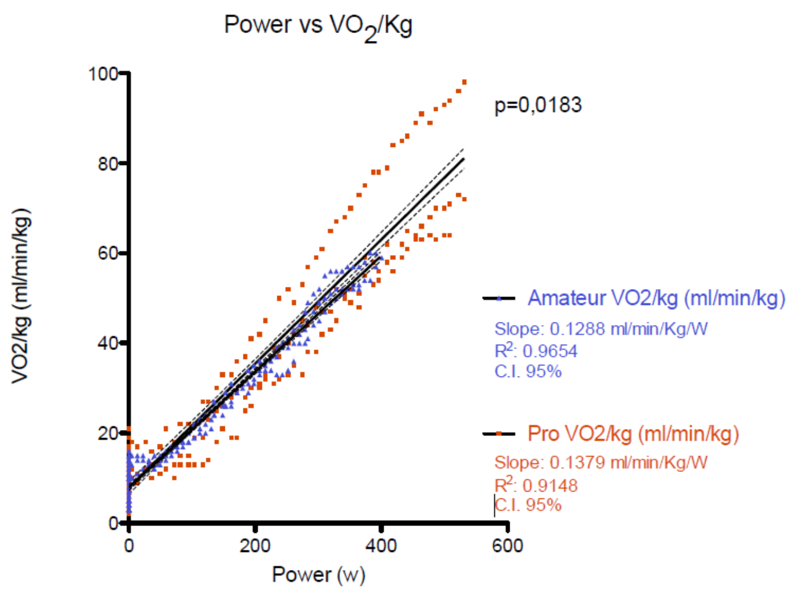


Figure 3 – Relationship between VO2/kg and Power (Comparison between the two groups)

Muscle oxygenation

	Pro cyclists	Amateur cyclists
Rest	73,0	88,2
Start pedaling	86,6	89,8
Start power	95,1	89,7
AT	50,8	76,0
Final Load	10,9	55,4

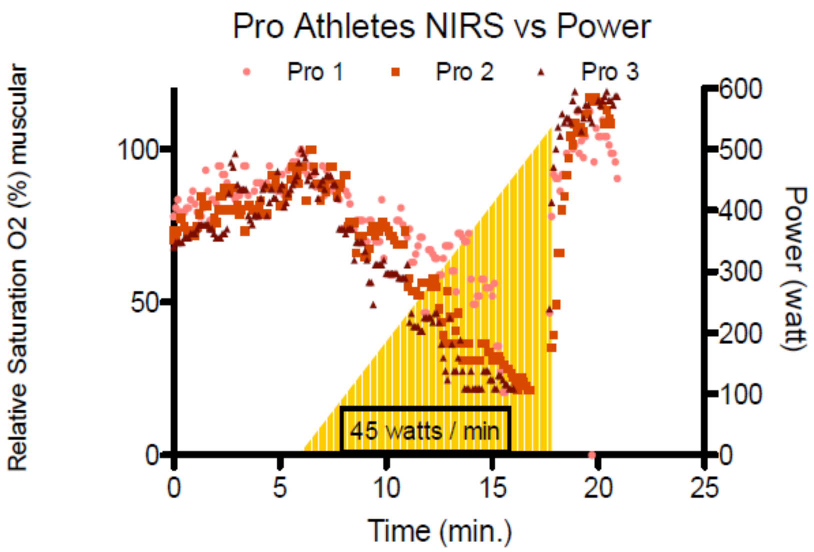
Table I – Relative Muscle O2 Saturation in distinct phases – Mean values (%).

As shown in Table I, professional cyclists have a greater relative deoxygenation during exercise, when both groups are compared. At the AT point, professionals reveal a lower muscle O_2 saturation, as well as in the final load.

All the participants leveled their final load intensity at 10 in The Borg Scale [25] which is a simple method of rating perceived exertion.

Muscle O_2 saturation decreased during the incremental exercise and increased abruptly during the recovery, in all the subjects from both groups. (Figure 4)

Values of O_2 saturation are relative to the highest O_2 saturation during warming phase.



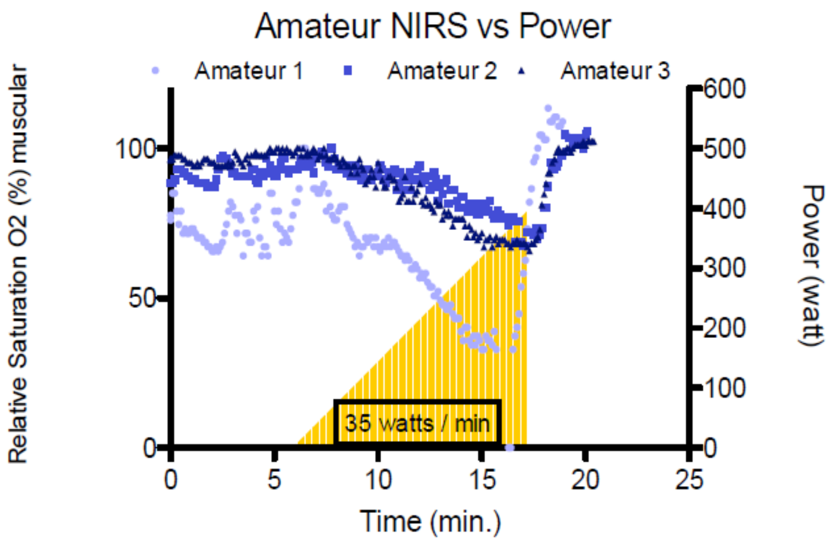


Figure 4 – Relative Muscle O_2 saturation over time.

As shown in Figure 5, all the regressions have a r^2 between 0,88 and 0,96. Intra-group comparison showed different slopes of desaturation but the mean slopes from each group were not significantly different ($p=0,21$) (Figure 6).

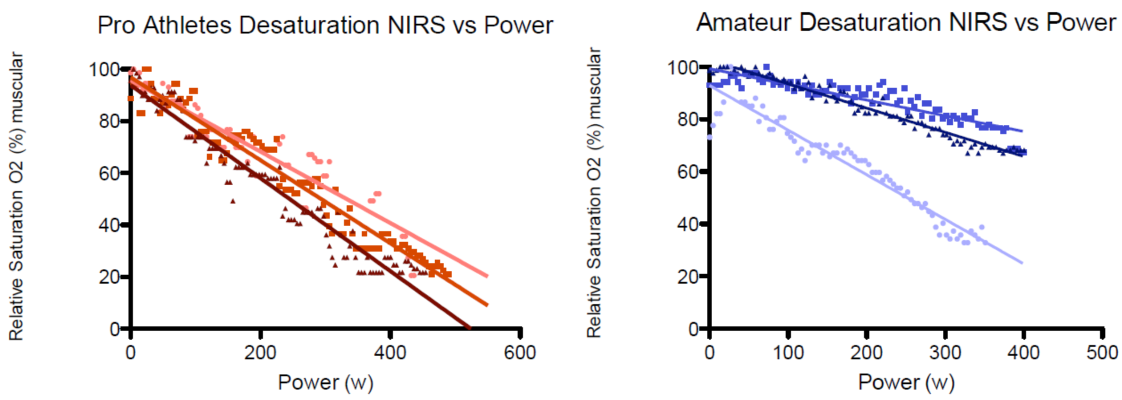


Figure 5 – Relationship between Relative Muscle O_2 Saturation during incremental exercise.

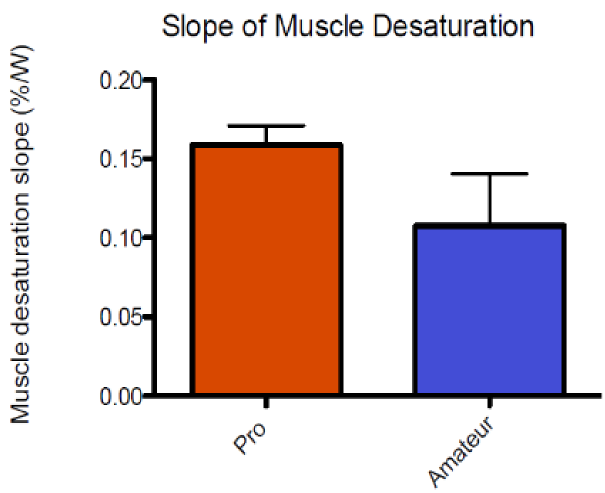


Figure 6 – Muscle Desaturation slopes in Pro and Amateur cyclists.

On the other hand, inter-group comparison showed that the muscle saturation recovery is significantly faster in professional athletes compared to amateur athletes (p=0,047) (Figure 7).

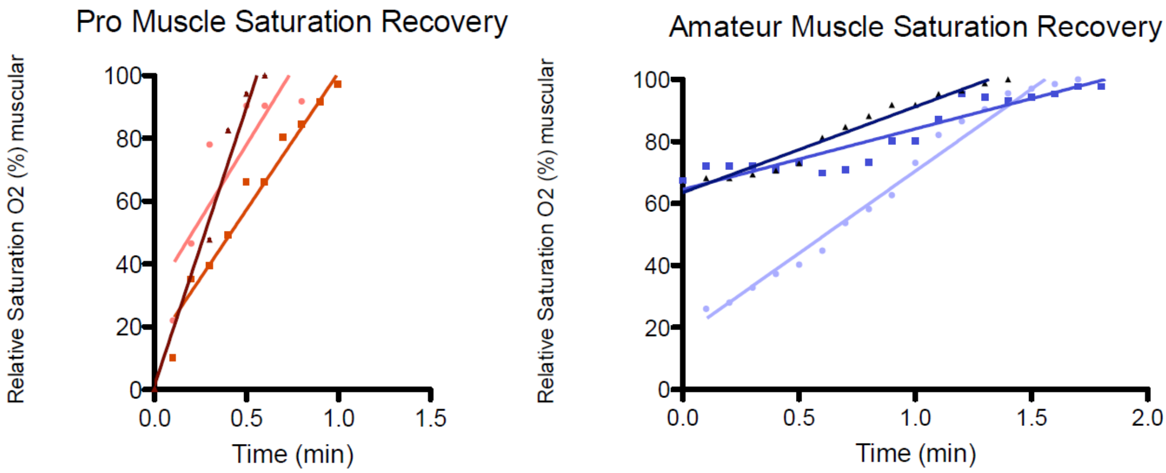


Figure 7 – Relative Muscle O2 Saturation Recovery.

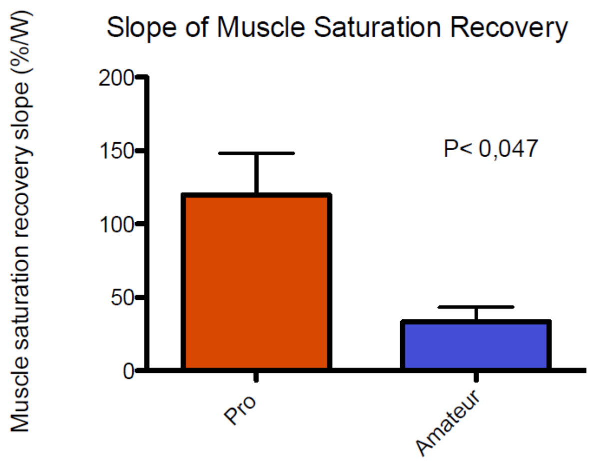


Figure 8 – Muscle Desaturation slopes in Pro and Amateur cyclists.

Discussion

To our knowledge, this is the first study that compares both gradual increment of working power and the effect of aerobic fitness (professional vs. amateur cyclists) on the response of muscle oxygenation during exercise until exhaustion and recovery phase. The main findings of this study were (1) during incremental exercise performed until exhaustion, muscle oxygenation shows a linear decrease in professional and amateur cyclists, and (2) during the recovery phase, the muscle O_2 saturation is significantly different between groups, more specifically, the muscle O_2 saturation recovery rate is significantly higher in professional cyclists, when compared to amateur cyclists. This finding supports the idea of an important contribution of aerobic fitness and muscle condition in performance [6].

We observed a higher acceleration of VO_2/kg in professional athletes, comparing to amateur athletes, during the incremental test. However, the HR has the opposite behavior, with higher increasing rate in amateurs. In addition, concerning the VE, amateurs also have a higher increasing rate, when compared to professionals, which suggests lower aerobic fitness.

We observed that professional cyclists have a larger relative change of muscle O2 extraction in the working muscle throughout the test, when compared with amateur cyclists (Table I).

Professional cyclists, who have higher cycling experience, do not experience an increase of anaerobic energy production during the decrease in the oxygen level during the test [26], demonstrated by NIRS values. In fact, what happens is the dissociation of O_2 from hemoglobin and myoglobin, regarding aerobic metabolism in mitochondria in the VL. It is already explained the effects of endurance training on the increasing of muscle oxidative capacity [27-29] by means of the increase in capillary density (enhanced muscle perfusion), in slow twitch fiber area, and enzyme activity [28, 30, 31]. We do not have any biochemical or histological analyses from our participants, however, the participants' aerobic power, cycling experience and competitive performance suggest that professional athletes have already acquired such developments, contributing to an increase of muscle oxidative capacity through their daily training routine.

Therefore, the capacity is higher in professional than in amateur cyclists. Additionally, the pedaling skill also influences the muscle physiology, because higher skill reduces stress on the leg extensor muscle while cycling, even in highly trained cyclists [32]. These observations can explain, in part, the higher rate in muscle O_2 saturation recovery in professional cyclists: during this phase, the muscle alleviates the pressure instantly and reduces the O_2 extraction and the developments mentioned above cause a rapidly recovering of the baseline muscle saturation.

NIRS technology has been used in sports medicine, namely in dynamic exercise. These findings may allow the study and the improvement of training methodologies and its efficiency.

Methodological considerations

The main limitation of the study is the lack of sensitivity of the NIRS system to muscle O_2 saturations below 15%, during heavy exercise. The system is not designed to measure such low saturations.

The other limitation is that the study results concern only a small part of the VL (4 cm), and can not be assumed to other muscles involved in cycling. However, from all the muscles involved, VL is the one that gives a better representation, making these results very interesting.

Prior the beginning of one of the tests, the gas analyzer did not calibrate completely. Data from that subject gave us values a little higher than expected.

Conclusions

In summary, during incremental exercise performed until exhaustion, muscle deoxygenation decreased in a linear way in both groups. Professional cyclists had a higher VO2 max, reached a higher hear rate and pedaled until a higher load, as expected. They did so at significantly lower muscle oxygenation levels. Amateur cyclists had much higher muscle oxygenation, but in spite of that they could not achieve high exercise loads. This suggest that the ability of achieving very low levels of muscle oxygenation is an indicator of aerobic fitness and not the opposite. Reaching very low muscle oxygenation levels with exercise does not imply lack of fitness. Professional cyclists can perform at anaerobic levels. Muscle oxygenation recovers faster in athletes. Still it is puzzling that at rest athletes have lower muscle oxygen values. Second, during the recovery phase, the muscle O2 saturation is significantly different between groups, more specifically, the muscle O2 saturation recovery rate is significantly lower in amateur cyclists, when compared to professional cyclists. This last finding and the larger relative change of muscle O2 extraction in the working muscle throughout the test in professional cyclists, suggest that higher aerobic energy production, and consequently higher aerobic fitness

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