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Original Article

Comparing muscle oxygen saturation patterns in swimmers of different competitive levels

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Abstract:
Monitoring training intensity through physiological parameters is crucial for understanding athletes' adaptive responses. Research has identified maximum muscle deoxygenation and the cumulative time with muscle oxygen saturation below 90% (SmO2 ≤ 10%) as key indicators of acute peripheral demand and effective muscle adaptations. This study examines variations in SmO2 among swimmers of different competitive levels using the Moxy® device during typical training sessions. The Moxy® device uses NIRS, an emerging technique that is increasingly valued for its ability to directly and non-invasively monitor tissue oxygenation and hemodynamic parameters during physical activity. The objective is to determine whether the intensity during a typical swim training session (code B1) can reduce SmO2 to 10% or lower and to assess differences in athletes' ability to maintain low muscle oxygen saturation for an extended period. The study sample consists of four male competitive swimmers with varying levels of competition, with SmO2 measurements taken from the deltoid, a key muscle in swimming. The results reveal that national-level swimmers spend significantly more time below the 10% SmO2 threshold compared to regional-level swimmers, indicating a higher peripheral muscle demand and a greater capacity to maintain training intensity. This study emphasizes the importance of SmO2 measurements for personalizing training and optimizing athletic performance, facilitating the creation of more effective training programs to enhance overall performance. Additionally, it highlights the significant potential of NIRS technology in sports science research and its application in refining training methodologies across various athletic disciplines.
Keywords: **Muscle deoxygenation; Peripheral adaptations; Near-infrared spectroscopy (NIRS); Swimming training; Anaerobic threshold**

Introduction

Monitoring training intensity through physiological parameters is crucial for understanding athletes' adaptive responses to training (Dalamitros et al., 2021). This assessment allows the identification of potential areas for improvement and limiting factors of physical performance (Perrey, 2022) and helps prevent the risk of injuries (Vallance et al., 2020). The study of systemic physiological changes induced by physical exercise, such as heart rate, oxygen consumption, and blood lactate concentration, is a key element in estimating exercise intensity and evaluating individual adaptation to training (Perrey, 2022). These measurements are widely used in sports, particularly in swimming (Smith, Norris & Hogg, 2002; Keskinen, Keskinen & Mero, 2007; Pyne, Lee & Swanwick, 2001). However, traditional methods such as lactate measurements are invasive and not always precise (Swart & Jennings, 2004). Additionally, one of the main challenges in monitoring heart rate in high-level athletes is the low sensitivity of heart rate response to workload (Klusiewicz et al., 2021).

Considering these limitations of traditional methods, it may be useful to explore other methodologies for monitoring muscle behavior and intensity. The two main methodologies for monitoring local muscle behavior during exercise are surface electromyography (EMG) for measuring muscle activity and Near-Infrared Spectroscopy (NIRS) for detecting muscle oxygenation (Ferrari, Muthalib & Quaresima, 2011). Both techniques are applied in both field and laboratory settings (Perrey & Ferrari, 2018; Yogev et al., 2023). NIRS is an emerging technique increasingly valued for its ability to directly and non-invasively monitor changes in tissue oxygenation and hemodynamic parameters during physical activity (Perrey & Ferrari, 2018; Hamaoka et al., 2007; Bhambhani, 2004). Recent studies indicate that skeletal muscle oxygen saturation (SmO2), which represents the balance between oxygen supply and consumption at the local muscle level (Hamaoka et al., 2007), can be used to describe and predict an individual's efficiency in performing endurance physical activities (Batterson et al., 2023). Measuring this variable can help coaches and athletes understand how the body responds to training and manages oxygen supply and utilization during prolonged exertion in real time (Klusiewicz et al., 2021; Farzam, Starkweather & Franceschini, 2018).

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Several authors (Kirby et al., 2021; Rodrigo-Carranza et al., 2021; Crum et al., 2017; Borges & Driller, 2016; Racinais, Buchheit & Girard, 2014; Grassi et al., 1999) have emphasized that NIRS measurements can be an effective method for determining training intensity zones, which are based on metabolic changes occurring in the active muscle along with heart rate. Additionally, it is possible to identify a specific level of oxygenation to which the muscles return after a certain type of physical exertion, thereby enabling the monitoring of recovery periods (Buchheit et al., 2011; Stöcker et al., 2016; Kime et al., 2003). Consequently, this technology can be useful in various sports research fields to customize an athlete's training. One sport where the data obtained can assist in creating a specific athletic practice for the individual is swimming. In swimming, where small variations in technique and physical condition can significantly impact performance, it is essential to explore how NIRS-derived measurements can improve our understanding of SmO2 during cyclic and characteristic movements (Jones, Parry & Cooper, 2018). Some researchers (Pratama & Yimlamai, 2020; Dalamitros et al., 2019; Jones, Parry & Cooper, 2018; Wu, Song & Xu, 2015) have recently applied this technology in swimming as a complementary method to improve understanding of recovery processes, training, and peripheral adaptations. However, despite its potential, the use of NIRS in this sport is still underexplored, leaving a gap in understanding how swimmers manage oxygen delivery and utilization during high-intensity efforts, highlighting the need for further research in this area.

Swimming workouts consist of intervals of varying intensity, which differentially stimulate aerobic and anaerobic metabolic processes. Additionally, in sports where arm muscles are dominant, such as swimming, which show a larger cross-sectional area of type II muscle fibers, muscle power dependency is greater than cardiorespiratory dependency. Therefore, it is necessary to identify training sessions that elicit a high peripheral demand to introduce sessions that target muscle oxidative adaptations (Paquette, Bieuzen & Billaut, 2019).

In the study by Paquette et al. (2019), it is suggested that maximum muscle deoxygenation and cumulative time at maximum muscle deoxygenation in canoe athletes, below 90% (SmO2 $\leq$ 10%), are good indicators of acute peripheral demand and key factors for effective muscle adaptations. Therefore, the objective of this study is to investigate variations in peripheral muscle oxygen saturation (SmO2) using the Moxy® device in swimmers during a typical training session to understand if anaerobic threshold intensity allows reaching an SmO2 of 10% or lower and to determine optimal peripheral adaptations. Additionally, the study aims to evaluate whether there are significant differences in the ability of athletes of different levels to maintain significant low muscle desaturation for an extended period.

Material and methods

Participants

The sample consists of 4 male competitive swimmers (average age 18.5 ± 2.9 years; height 177.54 ± 0.10 cm; body mass 70.5 ± 7.4 kg) from the Youth (n = 2), Junior (n = 1), and Senior (n = 1) categories, all with several years of experience in swimming and participation in regional and national competitions. Athletes 1 and 2 are classified as national-level athletes due to their participation for national competitions with high qualifying times. In contrast, athletes 3 and 4 are classified as regional-level athletes, as they have not achieved high qualifying times and predominantly participate in regional competitions. Additionally, they do not present any respiratory, cardiovascular, metabolic, musculoskeletal, or neoplastic diseases, nor any infectious or inflammatory processes at the time of measurement.

Procedures and Measures

Participants were asked to abstain from consuming drugs, antioxidants, and nutritional supplements 24 hours before the experimental session. All athletes were informed of the potential risks and provided written informed consent for participation in this study. Informed consent was obtained from parents or guardians for participants under 18 years of age. The study was conducted in accordance with the Declaration of Helsinki. The study was designed and coordinated by the research staff of the Laboratory of the Laboratory for Innovative Teaching and Sports Performance Analysis at the University of Salerno (Unisa).

SmO2 was measured using the MOXY® monitor, a continuous wave NIRS device (Fortiori Design LLC, Hutchinson, MN, USA). The device employs four wavelengths (680, 720, 760, and 800 nm) to assess absorbance through a modified version of the Beer-Lambert law. This calculation aims to determine the ratio between the concentrations of oxygenated hemoglobin and myoglobin relative to the total amount of hemoglobin and myoglobin (Feldmann, Schmitz & Erlacher, 2019; Crum et al., 2017). The ratio is then multiplied by 100 and expressed as a percentage (Fortiori Design LLC, 2015; Barstow, 2019). The obtained value, defined as muscle oxygenation (SmO2), is expressed as a percentage on a scale from 0 to 100% (Kirby et al., 2021; Feldmann, Schmitz & Erlacher, 2019) and is useful for understanding the oxidative metabolism of skeletal muscle in real-time during exercise (Grassi & Quaresima, 2016). The default sampling frequency is 0.5 Hz, allowing data acquisition at the four wavelengths used for 80 consecutive cycles. The average output is generated every 2 seconds (Feldmann, Schmitz & Erlacher, 2019; Batterson et al., 2023). The distance between the emitter and the two detectors is 12.5 and 25 mm, respectively, allowing a penetration depth of 12.5 mm (Feldmann, Schmitz & Erlacher, 2019; McManus, Collison & Chris, 2018). The muscle oxygen saturation measurement device has built-in memory to record training parameters and offers non-invasive measurements, wireless connectivity, small size, and waterproofing (Klusiewicz et al., 2021). Thanks to the built-in memory, it was possible to transfer data from the Moxy monitor to the "Moxy Monitor Setting" app version 1.5.5, from which they were then downloaded using the default filter to reduce signal noise.

Measurements were conducted at the indoor swimming pool of the University Sports Center (CUS) in Salerno, with a length of 25 meters that meets semi-Olympic standards. The operations were carried out at a constant water temperature of 28°C during the general period of the competitive season. Before the training sessions began, all Moxy devices were carefully positioned and checked to ensure proper functioning. Resting SmO2 and Thb measurements were recorded for each athlete. Before each training session, the deltoid area was prepared by shaving the skin and sanitizing it with alcohol before applying the device. The deltoid was selected as the muscle of study because it is part of the upper limb musculature, which plays a predominant role in propulsion during swimming (Morouço et al., 2015), and due to its significant involvement, both during the recovery phase and the propulsion phase in freestyle swimming (McLeod, 2011; Marugo, 2018). The dominant side was chosen as it provides more accurate information on overall oxygen utilization (Reinpõld & Rannama, 2023).

To measure the SmO2 of the deltoid, a Moxy device was placed along the line connecting the acromion and the epicondyle following the SENIAM project for electromyographic measurements (Hermens et al., 2000). The emitter and detectors were aligned in the direction of the muscle fibers and secured to the skin using the material suggested by the manufacturer, in addition to extra fixation with a waterproof and transparent bandage to ensure a secure hold. SmO2 data were consistently recorded during all training sessions.

The training protocol consists of a standardized warm-up detailed in Table 1 and a training session outlined in Table 2. The warm-up includes a total of 1800 meters of continuous swimming with specific exercises for arms and legs, followed by a passive rest of two minutes before the main part of the training and thus the examined protocol. The training session was performed using the freestyle stroke. Freestyle was chosen as it is the most commonly used swimming style in training due to its efficiency and suitability for long-duration activities (Bartolomeu, Costa & Barbosa, 2018; Gonjo et al., 2018). Other styles, particularly breaststroke and butterfly, are more demanding both technically and energetically and cannot always be sustained over long distances at moderate speeds (Di Prampero, 2015; Zamparo, Cortesi & Gatta, 2020; Barbosa et al., 2006).
The intensity zone of the examined training (B1) was determined based on the communication codes used in Italian swimming, defined by the Italian Swimming Federation (FIN), which identify various work zones from low to high intensities (Rossetto, 2022; Bottalico, 2022). These zones are defined based on the stimulation of different metabolic energy systems (Puce et al., 2018). The pace to be maintained during the training sessions was calculated using the differential test. Water starts with a push from the edge were used to eliminate the influence of diving.

Table 1. Warm-up

Set	Total Volume
1x400m	400m
8x50m (25REM/25GB)	400m
2x(4x75m) (25GB+25TECHNIQUE+25COMPLETE)	600m
2x(4x50m) PROGRESSION	400m

Table 2. Training

Code	Training
B1	24x100 a 1'40''

Analysis

For each trial and each athlete, the central portion equivalent to 150 data points was analyzed. The data were normalized based on the minimum and maximum values recorded during the trial itself. For the analyzed data portion, the mean and standard deviation were calculated. The number of data points below the 10% threshold was measured, subsequently converted into seconds, and used for comparison between athletes. To quantify the difference between national-level and regional-level athletes, the time spent below the 10% SmO2 threshold was used to calculate Cohen's d, a measure of effect size.

This method allows for understanding the magnitude of the difference between the two groups in a standardized way. All analyses were conducted in MATLAB (The MathWorks, Inc. 2024) using a code specifically written for this study.

Results

In Fig. 1, 2, 3, and 4, the SmO2 curves for each athlete are shown, along with the 10% threshold. The SmO2 data, including means and standard deviations, are presented in Table 3, along with the time spent below the 10% SmO2 threshold.

Figure 1. Muscle Oxygen Saturation (SmO2) Curve of Athlete 1 during the Training Session

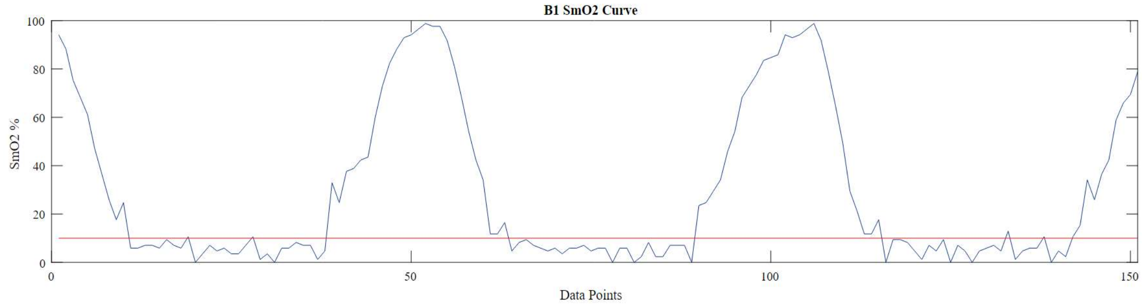

Figure 2. Muscle Oxygen Saturation (SmO2) Curve of Athlete 2 during the Training Session

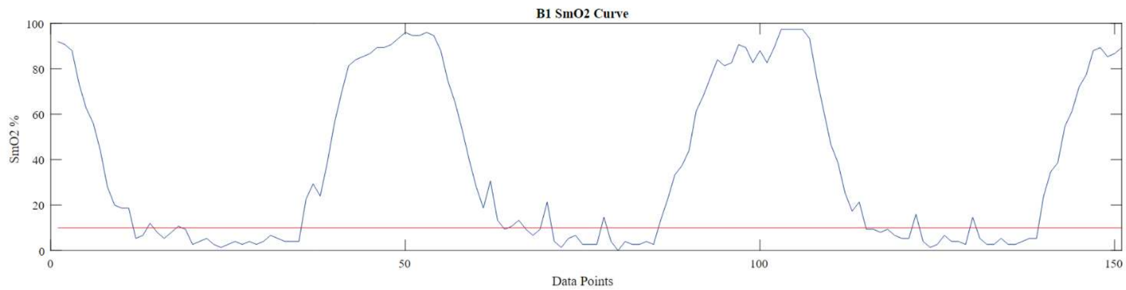

Figure 3. Muscle Oxygen Saturation (SmO2) Curve of Athlete 3 during the Training Session

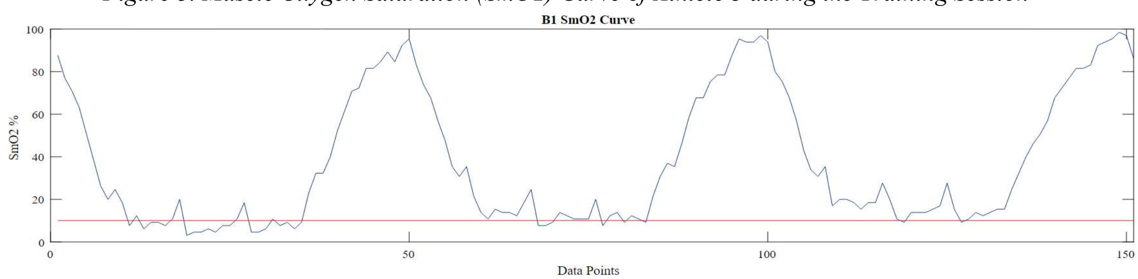

Figure 4. Muscle Oxygen Saturation (SmO2) Curve of Athlete 4 during the Training Session

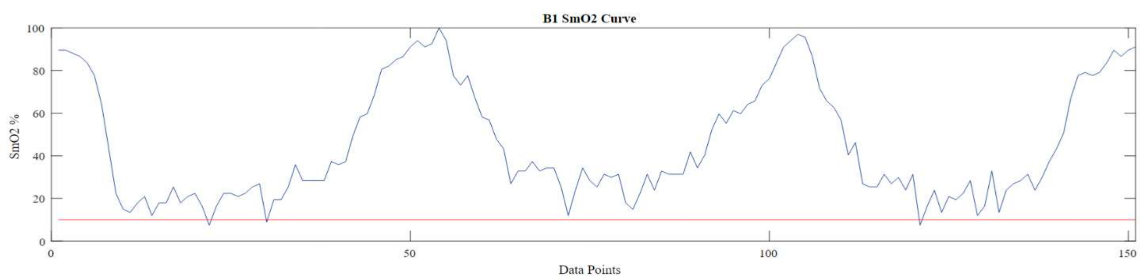

Table 3. Mean and Std. Dev. of SmO2 and Time Spent Below the 10% Threshold

Athlete	Mean (%)	Std. Dev. (%)	Time SmO2 ≤ 10% (s)
Athlete 1	29.48	32.62	152.00
Athlete 2	36.61	35.63	126.00
Athlete 3	37.72	30.79	54.00
Athlete 4	45.32	26.80	6.00

The Cohen's d effect size was found to be approximately 3.99 (Table 4). This value indicates a very large effect, suggesting a substantial difference between the two groups in the time spent below the 10% desaturation threshold.

Table 4. Time Spent Below the 10% Threshold with Mean, Std. Dev., and Cohen's d Effect Size

National-level athletes	Time SmO2 ≤ 10% (s)	Mean + Std. Dev. (s)	Cohen's d Effect Size
Athlete 1	152.00	139 ±18.39	3,99
Athlete 2	126.00		
Regional-level athletes			
Athlete 3	54.00	30 ±33.94	
Athlete 4	6.00		

Discussion

Muscular oxidative capacity, which refers to the muscles' ability to efficiently extract and utilize oxygen during physical exercise, improves when there are variations in muscle oxygenation during training (Daussin et al., 2008). Prolonged periods of training with low partial oxygen pressure at the muscle level stimulate mitochondrial biogenesis (Hoppeler et al., 2003). Consequently, training sessions that induce repeated and significant muscle deoxygenation could serve as an effective stimulus to promote positive muscular adaptations. Understanding the degree of muscle deoxygenation that occurs during training is crucial, as it affects the signals responsible for post-training metabolic modifications (Paquette, Bieuzen & Billaut, 2019).

The study explored variations in muscle oxygen saturation (SmO2) using the Moxy® device during a typical swimming training session. It was observed that a B1 code training (anaerobic threshold) in swimming induced significant muscle deoxygenation, as SmO2 dropped below 10%. This low SmO2 value could be attributed to both increased oxygen utilization by the muscle to sustain the exercise intensity and a lower Thb concentration, a parameter not analyzed in this context since, unlike SmO2, it is considered less reliable (Crum et al., 2017). As also highlighted by the study by Paquette et al. (2019), high intensities result in significant levels of deoxygenation, but such intensities often also induce substantial neuromuscular fatigue. Therefore, B1 training performed at a sub-maximal intensity in swimming could still elicit a significant peripheral demand without causing excessive neuromuscular fatigue. The results also indicate significant differences in the ability of national-level swimmers compared to regional-level swimmers in reaching and maintaining SmO2 below 10% during B1 intensity training. National-level swimmers, in fact, spent significantly more time below this threshold, suggesting a greater peripheral muscular demand during the training session and a better ability to sustain such intensity.

Conclusions

This study highlights the potential of muscle oxygen saturation (SmO2) measurements as a valuable tool for monitoring and enhancing athletic performance in swimmers. The results show that swim training conducted at anaerobic threshold intensity can reduce SmO2 below 10%, serving as a reliable indicator of acute peripheral demand and a key element for promoting effective muscle adaptations. Maintaining this muscle deoxygenation threshold could be used to distinguish national-level athletes from those at lower levels. Additionally, national-level athletes demonstrate a greater capacity for muscle desaturation, which could be leveraged to design more effective training programs aimed at improving overall performance.

The practical implications of this study are relevant and could have a considerable impact on how coaches manage and optimize training programs. The use of real-time SmO2 monitoring allows coaches to more precisely adjust the intensity and duration of training sessions, maximizing adaptive benefits while simultaneously reducing the risk of overtraining. This information can be used to develop personalized programs that more effectively meet the individual physiological needs of athletes.

From a theoretical perspective, the study enriches the existing literature by offering new insights into the use of NIRS in sports, particularly in swimming. The research lays the groundwork for further studies aimed at exploring how muscle oxygenation can be integrated with other physiological parameters for a more comprehensive assessment of athletes' capabilities.

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