

The use of muscle near-infrared spectroscopy (NIRS) to assess the aerobic training loads of world-class rowers

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ABSTRACT: The objectives of this study were (1) to characterize the changes in oxygenation derived from muscle near-infrared spectroscopy (NIRS) during aerobic constant-load exercise with intensities close to Maximal Lactate Steady-State (MLSS) and (2) to establish reference values in the world-class rowers, for such workload often included in rowing training programs. Eight senior world-class rowers performed an incremental progressive submaximal exercise test and a 30-minute test on a rowing ergometer. The power corresponding to intensive aerobic training ($84 \pm 1\%$ of the anaerobic threshold) was adopted as an exercise load in the 30-minute test. The NIRS device was fixed on the vastus lateralis muscle which was active during rowing to record muscle O_2 saturation (SmO_2) and total hemoglobin concentration (THb) at rest and during exercise. Statistically significant increments in blood lactate (LA) and heart rate (HR) were observed, with 1.18 ± 0.61 mmol/l and 10 ± 5 beats/min, respectively, in 30th minute compared to 10th minute in 30-minute test. SmO_2 decreased significantly by $2.9 \pm 1.4\%$, whereas THb did not change. The examinations may suggested the low diagnostic value of THb in constant-load exercise. In each subject, SmO_2 was gradually reduced during the intense aerobic exercise. During workload close to MLSS, the SmO_2 of the vastus lateralis ranged from 14.0 ± 3.13 to $11.1 \pm 2.81\%$ in 10 and 30 minutes respectively, with a reduction in muscle oxygenation (ΔSmO_2) exceeding 50%. The non-invasive nature of the NIRS measurement and the continuous monitoring of SmO_2 values are useful in the practice of monitoring training in terms of aerobic training loads.

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INTRODUCTION

For many years, the most common indicator used to evaluate the general physical capacity and sports performance of rowers has been maximal oxygen uptake (VO_{2max}) [1]. However, the methods of direct determination of VO_{2max} involve substantial costs of measuring equipment and participation of qualified staff to carry out exercise tests. Furthermore, they require high motivation of the participant to perform the maximum exercise.

Other indicators used to evaluate physical capacity and monitor training are blood lactate (LA) measurements and recording heart rate (HR). LA measurements require capillary blood to be collected, which, due to the need to ensure the comfort of competitors, leads to a limited frequency of collection. Recording heart rate (HR) during training and competitions provides the material for the analysis of the athlete's response to exercise. Although this method has been commonly used to monitor training load, it should be stressed that in addition to the unquestionable usefulness (especially in endurance sports), it also has some limitations. Training practice has shown relatively low usefulness of HR measurements in strength training or interval training, or, according to Born et al. [2], in training in

naturally hilly terrain (uphill and downhill sections). Furthermore, HR depends on many factors related to e.g. emotional state, degree of rest and hydration of the person, and environmental conditions (temperature, humidity, time of day, altitude, etc.). One of the main limitations of HR monitoring in elite athletes is the low sensitivity of heart rate (HR) response to exercise loading in fit individuals due to cardiac muscle development and adaptations. Moreover, analysis reveals that maximum heart rate can be altered by 3 to 7% with aerobic training/detraining [3].

In the last few years, portable measuring devices have been introduced into training practice, using near-infrared spectroscopy (NIRS) to evaluate myoglobin oxygen saturation in muscle cytoplasm and haemoglobin in blood vessels of muscle microcirculation (muscle oxygen saturation, SmO_2) [4]. Monitoring of oxygen saturation in muscles provides real-time information about both local muscle oxygen delivery and utilization during exercise or work. This is a local measurement, during which, as demonstrated by Paquette et al. [5], there are significant differences in muscle oxygen saturation in a given test exercise depending on the location of the NIRS device. The

first scientific studies using NIRS in athletes (trained rowers) were published in 1992 [6], but it was the implementation of portable wireless muscle oximeters to measure muscle oxygen saturation in 2006 that stimulated the rapid development of this measurement method. According to many authors, NIRS measurements represent a simple, safe, and fast way to evaluate exercise capacity during short-term maximum contractions [7] and to determine the so-called training intensity zones [8–10]. Furthermore, modern oximeters allow the measurements in the sport competition settings in athletes of various sports such as skaters [11], canoeists, and kayaking [5].

Devices for muscle oxygen saturation measurement have a built-in memory that allows for recording training parameters and offer non-invasive measurement, wireless connectivity (e.g. with HR recorders or smartphones), small size and waterproofness, high sampling rate and an affordable price that encourage coaches to implement them in their coaching practice. While the HR and oxygen uptake responses are characterized by a certain lag, the tissue oxygenation index (TOI) provides faster feedback [2]. Particularly interesting are the recent findings [5] which showed that monitoring of muscle oxygen saturation in canoeists and kayakers can be particularly important as a predictor of sports performance. There are few such studies, and therefore the need arises to assess the usefulness of muscle oxygen saturation measurements for monitoring training loads in other sports. It is worth adding that, according to the oximeter manufacturers, they can be used to evaluate the effects of exercise intensity and training duration on muscle oxygenation and recovery rates. In training practice, elite Polish rowers are often exposed to training loads with a power close to the maximal lactate steady state (MLSS), with their intensity verified with blood lactate measurements. Taking into account the non-invasive nature and practical usefulness of NIRS measurements, the present study attempted to verify such a training load using this method. To the best of our knowledge, few authors [12–14] have dealt with this kind of problem to date. Therefore, the objectives of this study were (1) to characterize the changes in oxygenation derived from muscle near-infrared spectroscopy (NIRS) during aerobic constant-load exercise with intensities close to maximal lactate steady-state (MLSS) and (2) to establish reference values in world-class rowers, for such workloads are often included in rowing training programmes.

MATERIALS AND METHODS

Subjects

Eight world-class rowers participated in the research. They were elite athletes from the Polish National Team (including 2 lightweight athletes) preparing to compete in the World Championship. All the rowers studied were medal winners of world and European championships or finalists of the European championships and the World Cup. The basic characteristics of the participants are presented in Table 1.

The research was carried out during the competition period (in July 2019) before the World Rowing Championships after obtaining

TABLE 1. Basic characteristics of the examined rowers (n = 8).

| Variable/Group | Mean ± SD |
|-----------------------------|-------------|
| Age (years) | 29.2 ± 4.7 |
| Body height (cm) | 195 ± 3.9 |
| Body weight (kg) | 89.5 ± 10.0 |
| BMI (kg/m ²) | 23.5 ± 2.8 |
| Training experience (years) | 15.1 ± 4.9 |

the consent of the Scientific Research Ethics Committee of the Institute of Sport – National Research Institute.

Exercise tests

The rowers performed two submaximal exercise tests: the progressive exercise test and the 30-minute test on a Concept 2 rowing ergometer (Morrisville, USA). The progressive test was performed first to determine the anaerobic threshold for a lactate concentration of 4 mmol/l (AT4). This test is routinely used by Polish rowers and consists of an incremental workload of 3 minutes, separated by a 30-second rest for blood sampling [1].

Within 2 to 5 days after the progressive test, the rowers performed 30-minute submaximal exercise (30-minute test) at constant power and a constant individual stroke rate. This exercise was divided into three 10-minute intervals, followed by a 1-minute rest for blood sampling. The test was preceded by a 5-minute warm-up with an intensity corresponding to a heart rate of 130 beats/min. The rest between the warm-up and the main exercise load was 2 minutes. The main exercise load was assumed to be 84 ± 1% of the previously determined anaerobic threshold (AT4). According to our research [15], the exercise load adopted using this method in rowers is slightly lower than the maximal lactate steady state (MLSS). MLSS was defined as in the study by Heck *et al.* [16] as the highest concentration of blood lactate that does not rise above 1.0 mmol/l during the last 20 minutes of constant-power exercise. The test is often used in the training practice of Polish rowers at different sports skill levels as a load corresponding to high-intensity aerobic training in a state of relative equilibrium between lactate production and utilization.

Blood samples were obtained from the earlobe at rest and immediately after each test effort to determine the lactate concentration (LA) using the Super GL 2 analyser (Dr Müller, Germany). In the progressive test, the number of blood samples depended on the rower's physical capacity, i.e. the number of exercise steps, and was different for each athlete. In the 30-minute test, 4 blood samples were taken (at rest and immediately after each 10-min time interval). During testing, the heart rate (HR) was also continuously recorded by means of a Polar S610i heart monitor by Polar Electro Oy (Finland).

Measurements of muscle oxygenation

During the 30-minute test, an NIRS device (Moxy monitors; Fortiori Design LLC, Hutchinson, MN, USA) was placed on the vastus

lateralis (VL) muscle that is active during rowing, see Figure 1. Moxy is a continuous wave. It uses a new type of algorithm that is based on Monte Carlo modelling. The system uses 4 wavelengths at 680, 720, 760, and 800 nm. It has 2 emitters to detector spacings at 12.5 and 25 mm.

The device was approximately 15 cm above the proximal border of the patella and was fixed to the right limb with dark 7.5 cm dynamic tape. Two indices were recorded both at rest and during exercise: muscle oxygen saturation (SmO_2) and total haemoglobin (THb). SmO_2 reflects the dynamic balance between oxygen (O_2) consumption and supply, while THb is an indicator of local blood volume (relative change in blood volume) [17]. The analysis of the results used mean NIRS measurements for 1.0 minute at rest and 10, 20, and 30 minutes of exercise. The differences in SmO_2 (Δ) between resting and exercise levels were also calculated.

Rating of perceived exertion

In the research, the Borg scale was used to assess the level of exercise intensity. The scale was made up of grades from 6 to 20 (6–20 interval) [18], which was previously used also in a study of rowers [19]. During the test, the Borg scale was placed in front of the athletes and the assessment was made at the end of each 10-minute section of exercise and at the end of the 30-minute test.

Statistical analysis

The statistical analysis was carried out using STATISTICA 12 (StatSoft, Poland). First, the data were tested for normality of distribution and homogeneity of variances using the Shapiro-Wilk test and Bartlett's test. The results confirmed that the data were normally distributed and that the variances were homogeneous. We performed a one-way ANOVA for the LA, HR, SmO_2 and THb scores. Mauchly's test was applied prior to the interpretation of the results of each analysis. If the results of the test were negative, the correctness of the calculations was also verified by means of multivariate analysis (Wilk's λ), which is not sensitive to violations of the sphericity assumption. In the final stage of the statistical analysis, we applied Tukey's test, which allowed for a detailed interpretation of significant differences between the mean values of the variables. We estimated effect size using partial eta squared (η_p^2), which was interpreted as follows: $0.01 < \eta_p^2 \leq 0.09$ – small effect size, $0.09 < \eta_p^2 \leq 0.25$ – medium effect size, and $\eta_p^2 > 0.25$ – large effect size [20].

The Borg rating for perceived exertion scale (RPE) was additionally used for subjective evaluation of the physical effort. The responses of the subjects were analysed by means of Friedman's ANOVA. In all the tests used the statistical significance was set at $p < 0.05$.

RESULTS

The resting value of SmO_2 was $65.5 \pm 1.9\%$, while that of THb was 13.054 ± 0.093 g/dl. During the 30-minute submaximal workload, statistically significant increments in LA concentration and HR were



FIG 1. Typically used location of the NIRS recorder on the vastus lateralis muscle.

observed, amounting to 1.18 ± 0.61 mmol/l and 10 ± 5 beats/min, respectively, in 30 min compared to 10 min. Furthermore, SmO_2 decreased significantly by $2.9 \pm 1.4\%$, while THb did not change; see Table 2. The drop of SmO_2 during 30 minutes of the test was observed in the first minute of each 10-minute interval. There was a 1-minute break between each period.

In all cases, as the duration of the exercise increased, SmO_2 was gradually decreasing; see Figure 2 and Figure 3. All identified statistically significant differences also turned out to be large, as the values of the partial eta squared ranged from 0.64 (SmO_2) to 0.83 (HR).

TABLE 2. Mean power, blood lactate concentration (LA), heart rate (HR), oxygenation of the vastus lateralis (SmO₂), total haemoglobin concentration (THb) values and rating of perceived exertion (RPE) recorded during the 30 min test in the examined rowers (n = 8).

| Variable/Time | 10 min (Mean ± SE) | 20 min (Mean ± SE) | 30 min (Mean ± SE) |
|------------------------------------|----------------------------|----------------------------|----------------------------|
| Mean power (W) | 320.4 ± 11.7 | 321.1 ± 11.9 | 321.5 ± 12.0 |
| LA (mmol/l) | 2.33 ± 0.30 ^{2,3} | 2.98 ± 0.40 ^{1,3} | 3.51 ± 0.49 ^{1,2} |
| HR (beats/min) | 158.8 ± 3.2 ^{2,3} | 164.4 ± 3.5 ^{1,3} | 169.0 ± 3.4 ^{1,2} |
| SmO ₂ (%) ^A | 14.0 ± 3.1 ³ | 12.6 ± 3.2 ³ | 11.1 ± 2.8 ^{1,2} |
| ΔSmO ₂ (%) ^B | 51.5 ± 2.7 ³ | 52.9 ± 3.1 ³ | 54.4 ± 2.6 ^{1,2} |
| THb (g/dl) ^C | 13.073 ± 0.084 | 13.068 ± 0.085 | 13.074 ± 0.082 |
| RPE (6–20) | 12.7 ± 0.5 | 13.6 ± 0.8 | 14.1 ± 1.0 |

The upper index in a given row indicates a measurement with a significantly different mean (p < 0.05). ΔSmO₂ – % of baseline. A – values “on line” from the recorder, B – reduction in oxygenation, C – non-significant differences (p < 0.51).

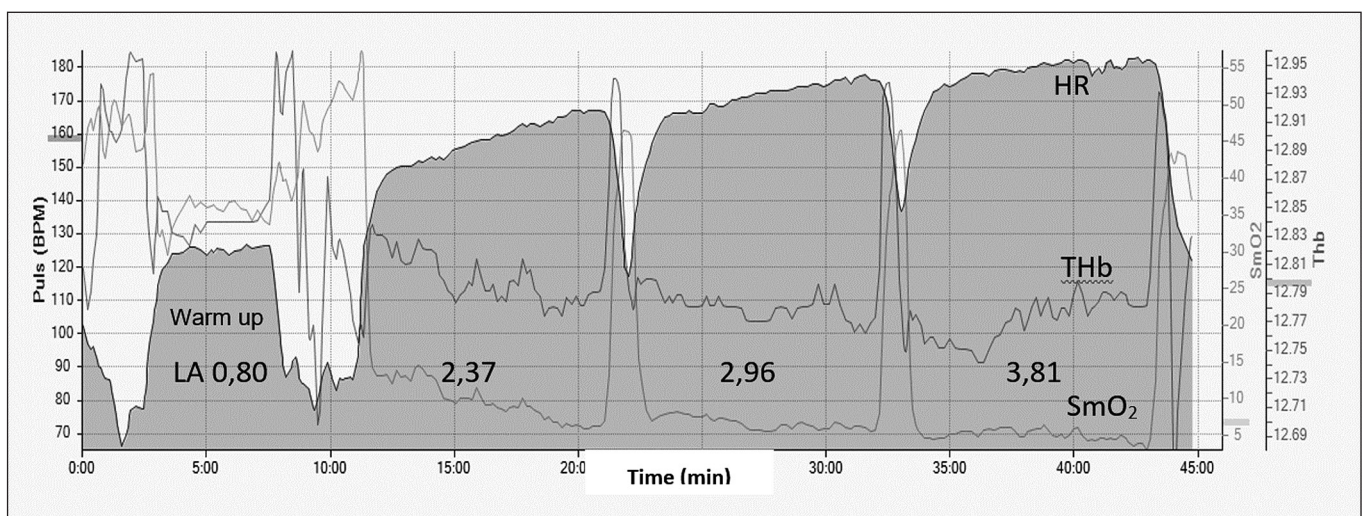


FIG. 2. Individual recording of vastus lateralis muscle oxygenation (SmO₂) with blood lactate (LA), total haemoglobin (THb) and heart rate (HR) in rowers during the 30-minute test on a rowing ergometer (SmO₂: lower record, THb: middle record and HR: upper record).

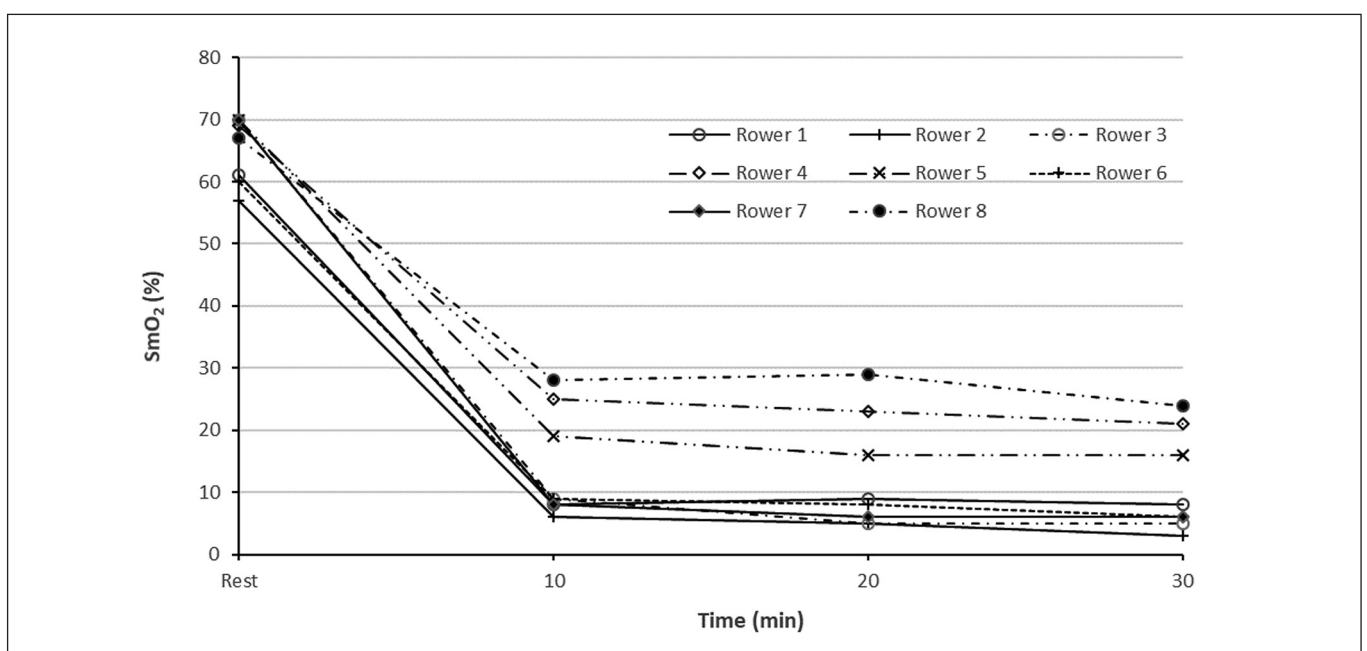


FIG. 3. Individual values of vastus lateralis muscle oxygenation (SmO₂) during the 30-minute test on a rowing ergometer in the examined rowers (n=8).

The highest muscle oxygenation (SmO_2) in rowers 8 and 4 presented in Figure 3 was accompanied by the lowest blood lactate concentrations in the examined group (1.65 and 3.09 mmol/l in 30 minutes of exercise, respectively), while in rower 5, the lactate concentration was 4.20 mmol/l. The results of Friedman's ANOVA did not show statistically significant differences ($p < 0.11$) in the rating of perceived exertion depending on the stage of the trial; see Table 2.

DISCUSSION

In the present study of Polish elite rowers, $84 \pm 1\%$ of AT4 power (321 ± 34 W) was determined as a submaximal load for 30-minute exercise. The metabolic response of LA of 2.94 ± 1.11 mmol/l was recorded (expressed as the mean value from measurements for 10, 20, and 30 minutes). The LA increase between 10 and 30 minutes was 1.18 ± 0.61 mmol/l and exceeded the criteria for the determination of MLSS [16]. In our previous study of rowers [15], mean LA concentration for MLSS was higher (3.66 ± 0.93 mmol/l) while in a study of German rowers [21], it was similar (3.0 ± 0.6 mmol/l). Despite a higher increase in LA than the adopted MLSS criterion, the exercise used can be found appropriate for high-intensity endurance training. High intensity of exercise was also evidenced by high HR values recorded in 30 min of exercise (169 ± 10 beats/min) and a significant cardio-respiratory drift (HR increase between 10 and 30 min was 10 ± 5 beats/min).

Based on the presented data, it seems interesting to verify the usefulness of SmO_2 and THb measurements using a Moxy device for the selection and evaluation of high-intensity aerobic exercise. According to the literature, this oximeter is a reliable device to measure SmO_2 at low and moderate levels of intensity. Unfortunately, at higher levels of intensity, there are greater differences in measurement results, probably due to tissue ischaemia or increased movement artefacts due to more frequent muscle contractions [9]. Other studies [22] have documented that both Moxy and PortaMon devices that are frequently used in scientific research provide physiologically reliable indicators of tissue oxygen saturation at rest and during exercise. In conclusion, the study confirmed good reliability of Moxy measurements, although it should be noted that this device is mainly dedicated to training monitoring.

Much attention in the literature has been devoted primarily to muscle oxygen saturation analysis during graded exercise tests, and it has been emphasized, among other things, that muscle oxygenation devices are a useful and reliable tool for determination of the lactate threshold loads for runners [8]. According to the quoted authors, these recording devices should be implemented by coaches and players as portable and non-invasive devices for monitoring changes in the load at the lactate threshold level in runners. Similarly, other studies have also indicated an acceptable level of compatibility between the indices measured using NIRS and the traditionally determined lactate thresholds for cyclists [10]. Also in a study of long-distance runners and triathletes, a high correlation between muscle

oxygenation breakpoint and the thresholds determined based on blood lactate concentration [14] was confirmed. It was also demonstrated that in cross-sectional studies of people with different aerobic fitness status, a higher level of VO_2max leads to the shift of muscle oxygen saturation breakpoint in the graded RAMP test towards the higher values of exercise intensity [23].

On the other hand, the submaximal constant-load intensity is often used in endurance training. From a practical point of view, it is especially important whether the muscle oxygen devices dedicated to coaches and athletes allow for the effective and precise choice of exercise load for heavy-intensity endurance training close to MLSS, which is often used by rowers. In an interesting scientific report, Bellotti et al. [12] tested the hypothesis that it is possible to accurately determine the MLSS status in healthy individuals based on deoxygenated haemoglobin, an indicator measured by NIRS. It was demonstrated that MLSS can be accurately estimated by measuring the level of deoxygenated haemoglobin. It was found that the threshold determined based on SmO_2 allowed for the correct determination of the running speed for 30-minute exercise at the level of maximal steady-state speed [14]. The main advantages of $\text{NIRS}_{\text{MLSS}}$ compared to techniques based on blood lactate concentration are non-invasiveness and time/cost efficiency.

In the summary of the literature data, Perrey and Ferrari [4] also confirmed that muscle oxygen saturation devices are a reliable and useful tool for determining training intensity, especially at the level of MLSS loads. Additionally, the tissue-saturation index (TSI) is characterized by faster feedback compared to HR and VO_2 , whereas SmO_2 measurements are not influenced by many factors such as temperature, hydration, emotional state, and others. Furthermore, the current assessment of muscle oxygen saturation using a preview on commonly used HR recorders offers opportunities for correcting the exercise load applied.

It should be noted that in the present study, the high intensity of aerobic training was characterized by a significant reduction in SmO_2 (on average $2.9 \pm 1.4\%$) between the 10th and 30th minute of exercise. As can be seen from Figure 3, the individual reduction in SmO_2 concerned all rowers, although it occurred at different percentage values of this index. In some rowers, the recorded levels of SmO_2 were below 10%. In others, they ranged from 25 to 30%. For comparison, in a study of canoeists racing at a distance of 200 and 500/1000 m on water, also with the use of the NIRS Moxy device located on the vastus lateralis muscle, a decrease in SmO_2 expressed as a difference from the resting value (ΔSmO_2) of 52 ± 17 and $51 \pm 18\%$ [5], respectively, was recorded. The data quoted were similar to our results (from $51.5 \pm 2.7\%$ for 10 min to $54.4 \pm 2.6\%$ for 30 min); Table 2. However, in the same study, kayakers, whose involvement of lower limb muscles during rowing is lower, the described index was $46 \pm 26\%$ (200 m) and $43 \pm 14\%$ (500/1000 m). Furthermore, in 30-minute submaximal exercise on the mechanical treadmill, relatively constant values of SmO_2 were observed for both the load corresponding to the maximal steady-state exercise

intensity and slightly above this state. However, the kinetics of changes in SmO_2 [14] were not studied in detail during this exercise.

These observations lead to the conclusion about the need to interpret SmO_2 measurements not only in absolute values but also in terms of the nature of changes in the discussed index over time. It is important whether there is a tendency to stabilize, or decrease in the oxygen saturation of the muscles in the subsequent minutes of exercise, because the significant decrease in SmO_2 was accompanied by a significant increase in LA, Table 2. Furthermore, the 30-minute exercise was accompanied by increasing rower's fatigue assessed on the Borg scale (although not significant), determined for 10 minutes as "Fairly light/Somewhat hard" (12.7 ± 0.5) and for 30 minutes as "Somewhat hard/Hard" (14.1 ± 1.0), Table 2. As mentioned earlier, THb can be used to monitor changes to blood volume throughout a test. In contrast SmO_2 , THb values did not change in the following minutes of steady-state exercise. This could mean that during the test, although cardiovascular drift was observed, there was no major change to the amount of blood being delivered, which could be due to increasing contractile strength of the muscle (compressing the vessels underneath the sensor). However, in order to deal with the increasing O_2 demands of the muscle (shown by decreasing SmO_2) the heart needs to beat faster to supply adequate oxygen. The data obtained in this respect may suggest the low diagnostic value of this index in constant-intensity exercise. Similarly, Crum *et al.* [9] found that THb is characterized by low variation during the graded intensity test and does not correlate significantly with oxygen uptake and heart rate, which means that it does not appear to be an important index of muscle oxygen saturation. However, it should be emphasized that other authors using NIRS measurements showed that blood flow in tissues changes during physical exercise [24]. According to Gail and Segal [25], it seems plausible that functional sympatholysis is strongly correlated with changes in THb during exercise.

Limitations of the study

To sum up the discussion, it is important to mention a factor that may have influenced the conclusions drawn from the study. The sample size was small. However, in the case of La, HR, SmO_2 and ΔSmO_2 , the power of the tests ranged from 0.98 to 1, and all the effects were large. As far as THb is concerned, sample size 12 would provide a test power of 0.95. We are therefore convinced that the

test results of 8 competitors, who were elite senior rowers who have succeeded in the most prestigious rowing regattas, have a cognitive value and can be useful as reference data.

CONCLUSION

The present study of world-class Polish rowers demonstrated that the high intensity of the 30-minute aerobic exercise was accompanied by a significant reduction in SmO_2 by $2.9 \pm 1.4\%$ with no THb changes, which may suggest a low diagnostic value of THb in constant-load intensity exercise. Furthermore, the analysis of the results indicates the necessity to interpret SmO_2 measurements not only in absolute terms but first of all to observe the direction of saturation changes. It is important whether there is a tendency to stabilize or decrease muscle oxygen saturation in successive minutes of exercise, because the significant decrease in SmO_2 was accompanied by a significant increase in LA. Therefore, further research is needed, with a greater number of participants and performing the same exercise several times to see if there are individual muscle oxygen saturation profiles during the exercise. During aerobic constant-load exercise with intensities close to MLSS, the SmO_2 of the vastus lateralis ranged from 14.0 ± 3.13 to $11.1 \pm 2.81\%$ in 10 and 30 minutes respectively, with a reduction in muscle oxygenation (ΔSmO_2) exceeding 50%. The non-invasive nature of the measurement and the continuous monitoring of SmO_2 values are useful in the practice of monitoring training in terms of aerobic training loads. Will NIRS muscle oxygen saturation devices fully meet the expectations of scientists and coaches? We believe that the development of measurement technologies will allow many more limitations of this method to be solved in the coming years, which will increase its practical usefulness.

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Conflict of interests

The authors declared no conflicts of interests regarding the publication of the manuscript.

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