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Intra-Reliability of a Wearable Near-Infrared Sensor for Monitoring the Intensity of Exercise

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Abstract: The Q-LAC analyzer, a portable device employing near-infrared spectroscopy (NIRS), was designed to measure muscle oxygen saturation (SmO_2) during physical exercise. This study aimed to assess the reliability of the Q-LAC analyzer in determining SmO_2 levels during incremental cycling exercise. Thirteen physically active males (age 28.1 ± 5.3 y; height 181.2 ± 5.7 cm; body mass 79.9 ± 11.1 kg; BMI 24.2 ± 2.4 kg/m^2) participated in this study. A submaximal incremental exercise test (SIET) on an electromagnetic cycle ergometer with a seven-day interval was performed twice. SmO_2 levels in the vastus lateralis (VL) muscle of the dominant leg were simultaneously recorded using the Q-LAC device during both tests. The study calculated the intraclass correlation coefficient (ICC), the coefficient of variation (CV), the standard error of measurement (SEM), the smallest worthwhile change (SWC), and mean detectable change (MDC). A within-within-subjects ANOVA revealed no statistically significant effects for session ($F_{1,12}$ = 0.97, p = 0.34, η^2 = 0.07) and the interaction between session and workload ($F_{4,48}$ = 0.19, p = 0.94, η^2 = 0.02). ICC values ranged from 0.72 to 0.91. Furthermore, the analysis of CV, SEM, and SWC indicated that SmO_2 measurements obtained with the Q-LAC device exhibit good reliability but marginal sensitivity. In conclusion, the portable Q-LAC analyzer provides consistent measurements of muscle oxygen saturation during low-to-moderate-intensity exercise on a cycle ergometer.

Keywords: muscle oxygen saturation; near-infrared spectroscopy; portable device; exercise intensity

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1. Introduction

The use of muscle near-infrared spectroscopy (NIRS) technology is gaining popularity in both laboratory and applied sports settings to monitor changes in muscle metabolism and muscle oxygen saturation (SmO_2) during and after exercise or training interventions [1]. This rise in popularity is partly due to the availability of commercially accessible portable wireless muscle oximeters. NIRS offers a non-invasive means of gathering information about oxygenation and hemodynamics in muscle tissue. It relies on the oxygen-dependent properties of near-infrared light. The NIRS signals represent a weighted average of the oxygen saturations of hemoglobin (Hb) in the vascular bed (including small arteries, arterioles, capillaries, venules, and small veins) and myoglobin (Mb) in muscle fibers [2].

As capillaries contribute to approximately 90% of the total blood volume in muscle [3], and assuming that all muscle regions receive adequately oxygenated arterial blood under normal conditions, changes in oxygenation detected by NIRS primarily reflect alterations in capillary (Hb-related) and intracellular (Mb-related) oxygen levels. Recent scientific reports suggest that this approach enables the discrimination of aerobic and anaerobic workload during incremental exercise tests [4] and provides insights into the physiological responses to exercise [5].

The incremental exercise test (IET) to volitional exhaustion is commonly used in laboratory conditions to assess aerobic performance and evaluate key cardiorespiratory fitness parameters, including oxygen consumption (VO_2), ventilation (VE), heart rate (HR), and oxygen pulse (VO_2/HR) [6]. Additionally, the IET provides valuable insights into metabolic thresholds (aerobic and anaerobic), substrate utilization, maximal work rate (Wmax), and maximal aerobic speed/power (MAS/MAP) [6]. These data enable the determination of individual exercise intensity and the optimization of training prescriptions. Previous research has indicated that a ramp test with a linear load, characterized by a lack of steady-state phases, is effective in determining the aforementioned variables [7]. Unfortunately, ergospirometry analysis has limitations, such as the inability to comprehend peripheral responses like SmO_2 in skeletal muscles [4]. In endurance training, which is based on low- and moderate-intensity exercises, power meters and heart rate monitors are used to monitor status [4]. However, environmental conditions (temperature, humidity, time of day, altitude, etc.), the degree of rest, hydration status, and emotional state may influence HR responses [8]. Hence, the monitoring of local muscle oxygenation by modern portable oximeters presents an intriguing perspective for athletes and the general population.

Prior to introducing a new device for monitoring SmO_2 in sports field conditions, it is imperative to scrutinize both absolute and relative reliability. Absolute test–retest reliability pertains to the consistency of repeated measures, while relative reliability encompasses the capacity to discern differences between subjects while considering measurement error [9]. Consequently, these analyses play a crucial role in establishing the ability to obtain valid measurements, enabling the monitoring of meaningful results and facilitating the interpretation of an athlete's progression across acute responses in single sessions and long-term adaptations [10]. Therefore, reliable and valid measurements with sufficient sensitivity are vital. Previous studies have evaluated the reliability of portable and wireless NIRS devices in assessing SmO_2 or the TSI (tissue saturation index) in healthy adults [11], male marathon runners [12], trained cyclists [13,14], patients with flow limitations of the iliac arteries, and healthy cyclists [15]. In those studies, intra-rater reliability was investigated using various statistical approaches, including the intraclass correlation coefficient (ICC) [11–15], the standard error of measurement (SEM) [11,14], the coefficient of variation (CV) [11,13–15], mean detectable change (MDC) [14], Bland–Altman plots [11,15], and limits of agreement [12,15]. The majority of them evaluated SmO_2/TSI during incremental exercise tests [12–15]. In previous studies, the reliability of SmO_2 results derived from portable NIRS devices has been studied for Humon Hex [11], Moxy Monitor [12–14], and Portamon [15], but not for Q-LAC. Moreover, available NIRS devices have different frequencies of collecting data, e.g., for Moxy it is 1 Hz [12–14]. In turn, the new portable device named Q-LAC is characterized by a higher frequency equal to 8 Hz, which is a somewhat lower than Portamon, with a 10 Hz frequency [15]. Therefore, it seems that devices with higher frequency of data collection will be favorable to regular testing of physiological responses during exercise.

Considering these arguments, the assessment of reliability using the ICC [15,16] and sensitivity (ensuring the standard error of measurement is below the smallest worthwhile change) [17] is crucial for examining new tools to validly interpret acute and long-term responses in performance. Hence, the primary objective of this study was to determine the intra-reliability of the portable Q-LAC NIRS device during exercise with an incremental workload. Our hypothesis posited that the Q-LAC measurements would exhibit strong reliability between trials.

2. Materials and Methods

2.1. Participants

Thirteen active males (mean age: 28.1 ± 5.3 years, height: 181.2 ± 5.7 cm, body mass: 79.9 ± 11.1 kg, body mass index (BMI): 24.2 ± 2.4, percentage of fat mass (%FAT): 13.4 ± 3.9%) with a self-reported weekly physical activity of 7.1 ± 2.5 h were enlisted for the study. The participants had a mean training experience of 10.7 ± 7.1 years and had no history of systemic issues, including metabolic, respiratory, and cardiovascular conditions, for the three months preceding the measurements. They were non-smokers and refrained from using other drugs or nutritional support. Each subject received written information about the experiment and provided written informed consent. The study received approval from the Senate Research Ethics Committee (project identification code: 20/2022) in adherence with the Declaration of Helsinki.

The sample size was established a priori using G*Power 3.1 software (v.3.1.9.2, Heinrich-Heine-Universität Düsseldorf, Düsseldorf, Germany) [18], the expected effect size was set at (Cohen's f) 0.80, the α level was set at 0.05, and the power (1 − β) was set at 0.85. The 12 participants in the group were necessarily recruited.

2.2. Study Design

The research was carried out at the Exercise Laboratory, certified under PN-EN ISO 9001:2001 [19], maintaining controlled environmental conditions (consistent humidity and temperature at 20 °C). Each participant visited the laboratory on two occasions, with a 7-day interval between sessions, and all testing procedures were administered by the same group of researchers. The study involved two submaximal incremental exercise tests, evaluating muscle oxygen saturation on the dominant thigh. Both sessions were scheduled at the same time of day. Participants were instructed to refrain from moderate and vigorous intensity physical activity, as well as alcohol and caffeine ingestion, within the 24 h preceding the experiment. Given participants' prior familiarity with laboratory procedures, equipment, and staff, a separate familiarization session was deemed unnecessary. The study was conducted in accordance with the Declaration of Helsinki and approved by the local Research Ethics Committee (20/2022).

2.3. Body Composition Analysis

Prior to exercise testing, both height and body mass were measured using a WPT 200 medical scale (Radwag, Radom, Poland). Body composition was assessed using the InBody® 230 (InBody Co., Ltd., Seoul, Republic of Korea), employing bioelectrical impedance with two different frequencies (20 kHz and 100 kHz) across five body regions (right and left arm, trunk, left and right leg) and an eight-point system of electrodes. The Lookin'Body 120 (InBody Co., Ltd., Seoul, Republic of Korea) software was utilized for data evaluation. Before analysis, variables such as age and height were input into the software, and the %FAT was subsequently determined.

2.4. Exercise Protocol

The submaximal incremental exercise test (SIET) was conducted on the Excalibur Sport cycle ergometer (Lode BV, Groningen, The Netherlands), following the protocol described by Michalik et al. [7]. The test commenced at 0 W, with the load increased by approximately 0.278 $W \cdot s^{-1}$ (equivalent to 50 $W \cdot 3\ min^{-1}$). The exercise test continued until reaching 250 W (15 min), with a cadence set to maintain 90 revolutions per minute.

2.5. Measurements of Muscle Oxygenation

During the SIET, local muscle oxygen saturation (SmO_2) was measured by a portable near-infrared spectroscopy device, Q-LAC (Oxymotion, Lublin, Poland), with a sampling frequency 8 Hz. It was attached firmly to the belly of the vastus lateralis (VL) muscle of the dominant leg. The device was approximately 15 cm above the proximal border of the patella (see Figure 1). This muscle was selected based on previous research and considering the role of this muscle in cycling exercise [4,20]. The system uses the light waves (600–900 nm) from light-emitting diodes into the tissue. It has two emitters to each detector spacing at 15 and 30 mm. The sensor was attached in the special supporting thigh sleeve with a pocket on the sensor, which allows direct absorption of light into the tissue. The data were recorded continuously by software version 1.2.5 (Oxymotion, Lublin, Poland), which calculated the muscle oxygen saturation from the following equation: $SmO_2 = 100 \times (O_2Hb)/(O_2Hb + HHb)$, where O_2Hb is oxyhemoglobin and HHb is deoxyhemoglobin. For further analysis, values were registered at intensities of 50, 100, 150, 200, and 250 W. The data show differences between resting and exercise values. This approach includes the assumption that the most important marker is an amplitude of change in local tissue saturation compared to the baseline level. It means that the absolute value of tissue saturation should be interpreted as the delta of value changes with the assumption that the initial value is constant. This method demonstrates muscle responses on exercise intensity by measurement changes of oxyhemoglobin, deoxyhemoglobin, total hemoglobin, and intensity zones referring to concentration of lactate.

Figure 1. Placement of the Q-LAC monitor.

2.6. Statistical Analysis

The IBM SPSS statistical software (v.23., SPSS Inc., Chicago, IL, USA) was used for data analysis. The results were presented as mean and confidence intervals (95% CI) where appropriate. The Shapiro–Wilk test was used to evaluate normal data distribution, while homogeneity of variance was analyzed by Levene's test. A repeated-measure ANOVA (within-within-subjects ANOVA) was used, with the session (Test 1/Test 2) and workload (50/100/150/200/250 W) as within factors. A Bonferroni post hoc test was performed when a significant F ratio value was obtained. For significant differences to estimate the meaningfulness, the effect size was calculated as eta-square (η^2) with small, medium, and large effect sizes classified as 0.01, 0.06, and 0.14, respectively [21]. The Bland–Altman plot analysis was carried out to assess agreement between sessions. Limits of agreement (LoAs), computed as $\pm$1.96 SD, illustrate the extent of variability between the measurements under consideration. An ordinary least square regression analysis of the differences was carried out to examining homoscedasticity. If the slope of the regression and the Pearson's correlation coefficient (r) differ significantly from zero at the *p*-value level, proportional bias is present [22]. Additionally, relative reliability in each stage was quantified using the intraclass correlation coefficient (ICC) of the 2-way random effects model with single-measure $ICC_{2,1}$. Reliability was classified as of Landis and Koch criteria: 0.00–0.20 slight, 0.21–0.40 fair, 0.41–0.60 moderate, 0.61–0.80 substantial, and 0.81–1.00 almost perfect reliability [15,23].

Absolute reliability was estimated using the standard error of measurement (SEM) and was calculated as follows: SEM = $SD_{diff}/\sqrt{2}$, where SD_{diff} is the SD of the differences between the tests. To examine the sensitivity of SmO_2, the smallest worthwhile change (SWC) was calculated as between-subject SD multiplied by 0.2 (smallest effect in [24,25]). Additionally, the SEM was compared with the SWC using the threshold previously proposed by Liow and Hopkins [17,26]. This approach examines the ability of the test to detect a change considered as good for an SEM < SWC, satisfactory for an SWC = SEM, and marginal for an SEM > SWC. The minimal detectable change (MDC) was calculated according to Hopkins [27] from the standard error of measurement (SEM) at a CI 95%: MDC = SEM $\times$ 1.96 $\times$ $\sqrt{2}$. The within-subject absolute reliability or reproducibility of the Q-LAC measurements was determined by a coefficient of variation (CV), which was calculated from the following equation: 100 $\times$ SEM/mean [28,29]. Individual values were implemented to assess the mean CV for each SIET stage. Reliability was classified as follows: CV < 10% indicated excellent, 10% $\leq$ CV < 20% represented good, 20% $\leq$ CV < 30% signified fair, and CV $\geq$ 30% denoted poor reliability [15]. For all analyses, a level of $p < 0.05$ was considered statistically significant.

3. Results

Figure 2 shows the mean $\pm$ 95% CI of SmO_2 during exercise at intensities of 50–250 W in both tests. The within-within-subjects ANOVA revealed no statistically significant effects for session ($F_{1,12} = 0.97$, $p = 0.34$, $\eta^2 = 0.07$) or the interaction between session and workload ($F_{4,48} = 0.19$, $p = 0.94$, $\eta^2 = 0.02$) (Figure 2). We do not show results for factor workload, because it exceeds our testing hypothesis.

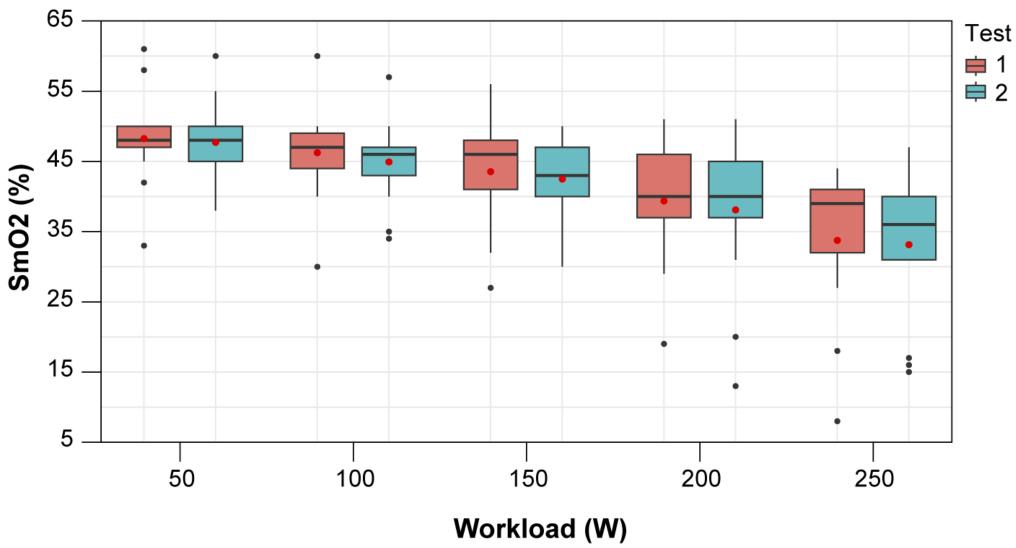

Figure 2. Distribution of muscle oxygen saturation percentage levels (SmO_2) by workload and test. The boxplots show the distribution of SmO_2 (y-axis) measured at different workloads (x-axis) of 50, 100, 150, 200, and 250 W for two different tests. Each workload is represented twice, corresponding to Test 1 and Test 2, respectively. The horizontal lines within each box represent the medians, while the red points and error bars indicate the means and their corresponding 95% confidence intervals. The individual points outside the boxes represent data points that are either outliers or leverage points.

The results of relative and absolute reliability indices for each workload are displayed in Table 1. For the ICC, SmO_2 showed substantial (50 W and 100 W) and almost perfect (150 W, 200 W, and 250 W) levels of reliability. Moreover, the CV demonstrated excellent reliability during all tested intensities (<10%). The comparison of the SEM and the SWC values induces marginal sensitivity to detect a change for each workload.

Table 1. Muscle oxygen saturation (SmO_2) values and reliability indicators across different workloads. Mean ± SD values [with 95% CI] are presented for SmO_2 (%) in Test 1 (T1) and Test 2 (T2) at workloads from 50 to 250 W. Reliability indicators include intraclass correlation coefficient (ICC), coefficient of variation (CV), standard error of measurement (SEM), smallest worthwhile change (SWC), and minimal detectable change (MDC) [all with 95% CI].

Workload (W)	**50**	**100**	**150**	**200**	**250**
SmO_2 (%) T1	48.2 ± 6.8 [44.1, 52.3]	46.2 ± 6.8 [42.1, 50.4]	43.5 ± 7.5 [39.0, 48.1]	39.4 ± 9.0 [33.9, 44.8]	33.8 ± 10.6 [27.4, 40.2]
SmO_2 (%) T2	47.7 ± 5.9 [44.1, 51.3]	44.9 ± 6.2 [41.2, 48.7]	42.5 ± 6.6 [38.5, 46.4]	38.1 ± 10.9 [31.5, 44.7]	33.2 ± 10.6 [26.8, 39.5]
ICC	0.721 [0.30, 0.91]	0.765 [0.41, 0.92]	0.898 [0.71, 0.97]	0.878 [0.66, 0.96]	0.906 [0.72, 0.97]
CV (%)	7.2 [5.1, 11.2]	6.9 [5.0, 11.4]	5.1 [3.7, 8.5]	9.1 [6.5, 15.0]	9.9 [7.1, 16.5]
SEM (%)	3.4 [2.5, 5.7]	3.1 [2.3, 5.2]	2.2 [1.6, 3.6]	3.5 [2.5, 5.8]	3.3 [2.4, 5.5]
SWC (%)	1.3 [0.9, 2.1]	1.3 [0.9, 2.2]	1.4 [1.0, 2.3]	2.0 [1.4, 3.3]	2.1 [1.5, 3.5]
MDC (%)	9.5 [6.8, 15.7]	8.8 [6.3, 14.4]	6.1 [4.4, 10.1]	9.7 [7.0, 16.1]	9.2 [6.6, 15.3]

The Bland–Altman analysis revealed a small bias for SmO_2 at intensities of 50 W (0.54%), 100 W (1.31%), 150 W (1.08%), 200 W (1.31%), and 250 W (0.61%) (Figure 3). Limits of agreement were approximately ±5% for all workloads, with the exception of 150 W, which demonstrated slightly higher variability (±6.1%). The majority of data points fell within the LoA, suggesting a strong concordance between the two tests. This pattern indicates that the differences observed between the first and second test measurements are minimal and fall within an acceptable tolerance range. The regression analysis of these differences produced equations characterized by low slopes (ranging from 0.002 to 0.21), accompanied by Pearson's correlation coefficients approaching null values (ranging from 0.04 to 0.31), all with p-values exceeding 0.05. Consequently, these results suggest an absence of a systematic bias in the measurement differences as the magnitude of the SmO_2 varies.

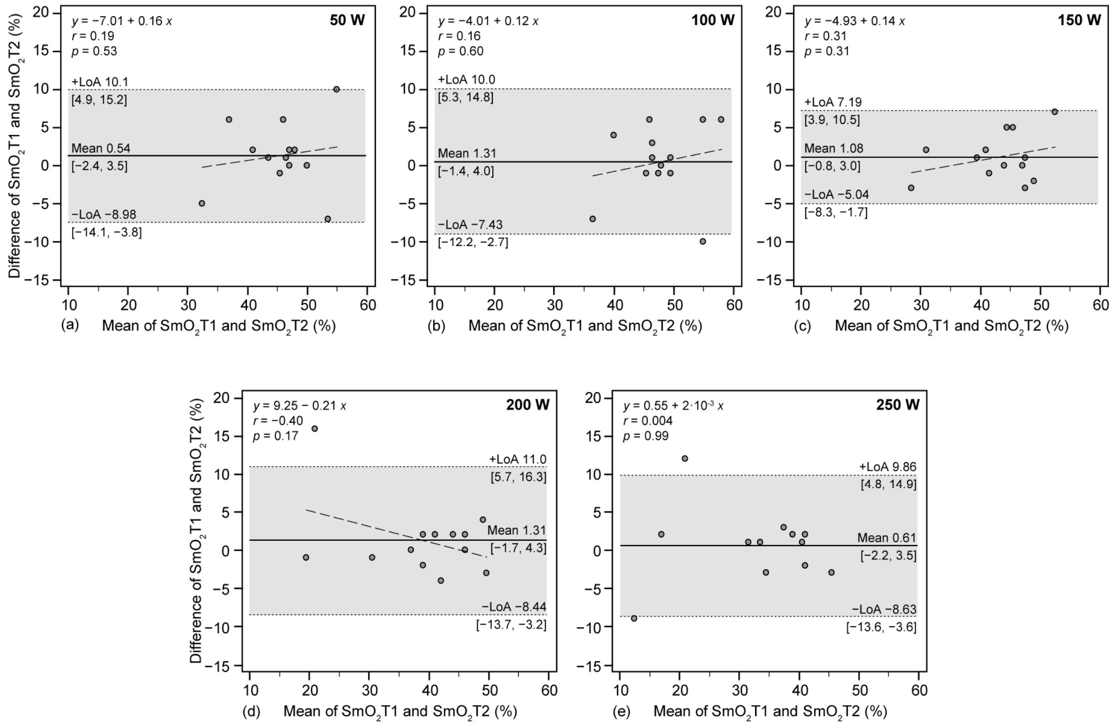

Figure 3. Agreement of SmO_2 values obtained in Test 1 (T1) and Test 2 (T2) for five workloads: 50 W (**a**), 100 W (**b**), 150 W (**c**), 200 W (**d**), and 250 W (**e**). The central solid line in each subgraph indicates the systematic bias, shown as the mean difference between T1 and T2. The dotted lines above and below this mean depict the random error via limits of agreement (LoAs), quantified as mean $\pm$ 1.96 SD. The 95% confidence intervals for these measurements are explicitly detailed [lower limit, upper limit]. Additionally, a dashed line in each subgraph represents the linear regression of the differences against their mean, depicting any proportional bias. The regression equation, along with Pearson's correlation coefficient (r) and the associated *p*-value, are shown in the upper right corner of each subgraph.

4. Discussion

The findings of this study indicate that the Q-LAC device is a reliable instrument for measuring the oxygen saturation of venous hemoglobin during low-to-moderate-intensity cycling exercise. Consistent with our hypothesis, the relative reliability (the ability to assess differences between subjects while taking the measurement error into account) was substantial to almost perfect, and absolute reliability (the similarity of repeated measures) was excellent in SmO_2. This study is the first to provide reliability data on oxygenation for the Q-LAC portable device.

Numerous prior studies investigating the intra-rater reliability of NIRS during exercise have demonstrated that reliability varies based on exercise modality and intensity, muscle group, NIRS device, and the training status of participants [11–15,30–32]. Therefore, it is imperative to establish reliability for specific NIRS-derived variables during exercise protocols intended to assess the effect of any intervention. Consistent with available studies, the Q-LAC sensor exhibited a high level of relative reliability in measuring SmO_2 in the VL muscle of the subjects, with an ICC range of 0.72 to 0.91. These findings align with earlier research that demonstrated strong test–retest reliability (0.81–0.90) for SmO_2 across various exercise intensities during a multi-stage cycling test, conducted on the right VL using another wearable NIRS sensor [14]. Furthermore, Crum et al. [13] reported good to excellent reliability (ICC: 0.77–0.99). Additionally, previous reports by Contreras-Briceño et al. [12] indicated excellent reliability for the NIRS sensor device at low intensity (rest and first ventilatory threshold (VT1)) and at high intensity (second ventilatory threshold (VT2) and max): 0.95, 0.97, 0.95, and 0.95, respectively. The abovementioned studies evaluated the

Moxy Monitor sensor [12–14]. In contrast, van Hooff et al. [15] investigated the relative reliability of the Portamon device during a continuous IET, showing an ICC range of 0.06–0.76 for the TSI in patients with flow limitations of the iliac arteries (FLIA) and 0.16–0.70 in healthy cyclists. It is noteworthy that some studies also included women [13–15], which may influence higher adipose tissue thickness (ATT) at the quadricep muscle measurement site, potentially limiting the quality of NIRS signals collected in female subjects. This study exclusively examined males; future analyses should encompass physically active females and individuals of varying ages for a comprehensive assessment.

Research on the reliability, minimum detectable change, and sensitivity of testing items in NIRS data used in combination is scarce. Unlike previous examinations into the absolute reliability of wearable NIRS devices during low-to-moderate-intensity exercise, our results demonstrate a notably higher level of absolute agreement (5.1–9.9%) [13,14]. In these studies, an increase in the coefficient of variation (CV) was observed with an escalation in workload. For instance, Crum et al. [13] reported CV values of 4, 5, 12, and 20% for 100, 150, 200, and 250 W, respectively. Furthermore, Yogev et al. [14] found even higher CV values for intensities of 1.0 W/kg, 2.5 W/kg, and 4.0 W/kg, at 11.0, 22.9, and 43.8%, respectively. On the other hand, Van Hooff et al. [15] compared a healthy group of cyclists and patients with FLIA; however, they revealed comparable values of the CV, 6–10% and 5–11%, respectively, for cyclists and patients measured at baseline, post-exercise recovery, and maximal task tolerance. It is important to note that we demonstrate lower values of the SEM (2.2–3.4 vs. 5–7) and MDC (6.1–9.7 vs. 12–18) for SmO_2 than previously published [14]. Both parameters are important and useful for sport practitioners, because when considering daily variation, absolute reliability is quantified by the SEM, while the MDC is used for interpreting the results of a longitudinal training intervention. Changes within a range of $\pm$ SEM may be meaningful for an individual person but should not be considered to represent a significant difference [15], whereas regular training programs can be considered to have a significant effect on SmO_2 if the values measured at a given absolute workload change by more than the MDC [15]. In our research, in the Bland–Altman plots, the limits of agreement were slightly lower than those reported by van Hooff et al. [15] for both examined groups. According to our best knowledge, this is the first study to report the sensitivity for SmO_2 analysis for a wearable NIRS sensor. The SWCs were below the SEM for all analyzed SIET intensities and indicated marginal sensitivity to detection changes. The cohort in the current study was physically active males but those not experienced at cycle training or training for a specific sport. Therefore, they may have demonstrated sufficiently large within-participant performance variation, which did lead to larger within-participant variability (SEM value), with resulting impacting on test sensitivity. Research with a larger sample size would have been interesting to analyze “high variability” and “low variability” cohorts [33]. In summary, the present results suggest that SmO_2 derived from the Q-LAC sensor is capable of assessing differences between subjects and may have the potential to monitor training responses, but the sensitivity of this device should be improved.

4.1. Future Research Perspective and Practical Applications

Further research is warranted to explore mathematical techniques for detection, including the capability to identify aerobic and anaerobic thresholds, the detection across multiple regions, and the impact of gender, performance level, and adipose tissue on threshold determination. For this sensor, comparing the reliability of SmO_2 with other common physiological measures such as oxygen uptake ($\dot{V}O_2$), heart rate (HR), blood lactate concentration ([La^-]), and rating of perceived exertion (RPE) will provide a useful contrast for each of these common markers during the same exercise protocol. Crum et al. [13] suggested the utility of training zones evaluated on muscle oxygenation rather than the traditionally used HR monitoring, given the various factors influencing HR responses [8,13]. Additionally, consecutive analyses should explore the relationships between other physiological variables such as VO_2. For instance, the inverse relationship between

SmO_2 and VO_2 expresses the increasing difference between the mean muscle capillary O_2 content and the rate of oxygen utilization by the working muscle [13]. Finally, future research areas could investigate the potential efficacy of the Q-LAC sensor for use during strength exercise, rest, and recovery strategies, such as muscle ischemia provoked by blood flow restriction or compression garments [31,32].

4.2. Strength and Limitations

The lower absolute reliability reported in the present study compared to research in previous studies is likely due to the recent improvements in NIRS technology and processing and filtering data specific for use in sports science. It should be noted that this is the first study that evaluated the Q-LAC sensor; thus, we could not directly compare results from other studies about the assessment of this device. Furthermore, Q-LAC is inexpensive in relation to other wearable NIRS devices. The Q-LAC device is small enough to be worn without encumbering most types of exercise and possesses data-capture capabilities; thus, it will have some utility in field-based conditions. Despite interesting findings and data shown by the current research, some limitations should be described. First, the SmO_2 response was only assessed in the dominant lower limb. Another limitation was the absence of measurements for adipose tissue at the locations where the portable NIRS devices were placed. It is worth noting that the existing literature suggests that increased adipose tissue and hypertrophy muscle can impede the penetration of light emitted by the source, consequently influencing the data recorded by NIRS-based devices [34]. The penetration of Q-LAC is maintained at approximately 3 cm and is higher compared to Moxy, at approximately 2 cm [13]. We did not detect significant artifacts in the SmO_2 measurements. This can be attributed to the absence of obesity-related characteristics among our study participants. It can be inferred that their physical characteristics align with those of individuals engaged in regular sports training, as indicated by the recorded BMI of 24.2 ± 2.4 and a body fat percentage of $13.4 \pm 3.9\%$. In future research, it would be pertinent to explore the thickness of adipose tissue using techniques such as caliper measurements (e.g., >7.5 mm ATT cut-off point [15]), ultrasonography, or alternative methods. This approach would enable a comprehensive evaluation of the muscles involved and provide more comprehensive data. Additionally, we did not examine SmO_2 during higher intensities, e.g., above the anaerobic threshold/critical power, which could be useful to determine local tissue hemoglobin oxygenation during time-trial performance [35].

5. Conclusions

The present study demonstrates that the Q-LAC device, employing near-infrared spectroscopy technology, offers a reliable and non-invasive method for assessing muscle oxygen saturation (SmO_2) during incremental cycling exercise. Our findings indicate that this device is a trustworthy instrument for measuring venous hemoglobin oxygen saturation at submaximal exercise intensities. The low standard errors associated with these measurements further support the reliability of this technology.

Near-infrared spectroscopy, as implemented in the Q-LAC device, proves to be a valuable tool for investigating exercise intensity and the dynamics of muscle oxygenation in peripheral regions. The non-invasive nature and relative affordability of this technology make it a practical option for researchers and practitioners in exercise physiology and sports science. This approach provides insights into both peripheral and central adaptations, which may be influenced by various factors such as training status, injury, nutritional state, or environmental conditions, all of which can impact cardiorespiratory performance.

In conclusion, the Q-LAC device shows promise as a complementary method to traditional measures of physiological responses to exercise. Its ability to assess SmO_2 changes during exercise offers an additional perspective on exercise-induced adaptations. Further research is warranted to explore the full potential of this technology across various exercise modalities and populations, as well as its integration with other physiological measures to enhance our understanding of exercise physiology.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the author (K.M.) on request.

Conflicts of Interest: The authors declare no conflicts of interest.

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