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Predictive Value of Forearm Muscle Oxygenation Parameters for Climbing-specific Finger Endurance and Competitive Climbing Performance

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Abstract

Purpose

Near-infrared spectroscopy (NIRS) is a valid and reliable method to assess forearm muscle oxygenation in sport climbing, focusing on evaluating single parameters. The study assessed the predictive value of various NIRS parameters in climbing-specific settings, during intermittent finger endurance testing and in a simulated climbing competition.

Methods

52 recreational climbers (28.5 ± 6.3 y) performed an intermittent finger endurance test and 10 competitive climbers (20.2 ± 6.3 y) participated in a simulated lead climbing competition. Continuous-wave NIRS were used to assess oxygenation and blood volume changes.

Results

NIRS parameters predicted 264 % of the variance in the intermittent test, with mean minima and maxima of O_2Hb and mean maxima of TSI% of the single repetitions being the predictors. No significant differences existed between the last valid and the first nonvalid on the combined dependent variable. For the simulated competition, a statistically significant difference between the 20s intervals on the combined dependent variables were found with posthoc testing showing significant univariate within-subjects effects for HHb, tHb & TSI, but not for O2Hb.

Conclusion

The results indicate that for the intermittent test, high re- and deoxygenation abilities, and for the climbing competition, the accumulation of HHb concentration levels have the highest predictability.

Introduction

The scientific foundation and monitoring of competitive sport climbing can still be described as deficient. Lead climbing is a sub-discipline in which a 15 m high climbing wall has to be climbed within 6 minutes. The route's difficulty gradually increases so that only one athlete reaches the top in optimal cases. During climbing, a high portion of the body weight is carried by the fingers [1]. Finger flexors are intermittently loaded to hold on to a grip, pull up on it, and be relieved when the climbers reach up for the next hold. An analysis of the load structure of lead competitions showed that, on average, the load period lasted 6.4 seconds and the rest period 1.8 seconds [2] From time to time, there are so-called rest positions along the route in which no locomotion takes place, and the athletes shake their arms for recovery purposes. Local

muscular endurance of the finger flexors, including the ability to recover quickly during rest periods, is therefore considered a relevant performance factor in lead climbing [3] with a whole series of studies backing this up as empirical evidence [4–13].

For performance diagnostics regarding muscular endurance, external criteria such as repetition numbers or force inputs, or invasive methods like lactate measurement were used until recently due to difficulties measuring load parameters in small muscle groups with non-invasive methods. With the development of near-infrared spectroscopy (NIRS), however, local muscular fatigue and recovery abilities can be measured non-invasively in the respective working muscles and it´s knowledge might be very beneficial for targeted climbing training.

There are few but informative studies regarding the use of NIRS for performance diagnostics in sport climbing: Venous occlusion technique, intermittent and continuous finger endurance tests, and a climbing-specific endurance test on a treadwall have all been used to assess oxygen kinetics of climbers. Regarding intermittent finger endurance tests, climbers showed a faster reoxygenation of oxy[heme] (O_2Hb) or tissue saturation index (TSI) during the rest phases of intermittent tests than non-climbers [9, 12] but Baláš et al. (2021) [14] couldn't detect significant ability group differences. During treadwall climbing, in the study of Fryer et al. (2018) [15], maximal desaturation of the tissue saturation index (TSI) significantly predicted climbing performance. Baláš et al. (2021) [14] found no differences between ability groups of O_2Hb, total[heme] (tHb), and deoxy[heme] (HHb) at peak, but at submaximal wall angles.

Previous studies using intermittent finger endurance tests focused on the evaluation of single parameters. Either O2Hb [9] or TSI [12, 14] changes were assessed during the relief phases of the intermittent contractions, and Baláš et al. (2021) [14] assessed maximal muscle desaturation (TSI) additionally.

To gain further insides into muscle metabolism, our study aimed to evaluate multiple parameters for O_2Hb, HHb, tHb and TSI during an intermittent finger endurance test simultaneously (sub-study one). Furthermore, an evaluation of the NIRS parameters on competition-typical climbing walls and their correlation with competitive performance in lead climbing is still pending. Since it is of outstanding relevance to know how muscular fatigue is expressed in competition, the aim of sub-study two was to perform NIRS measurements in a simulated climbing competition and to find out the significance of certain NIRS parameters about the fatigue state.

Methods

Two sub-studies were carried out to validate NIRS parameters for predicting climbing performance: In the first sub-study we used an intermittent endurance test on the fingerboard, and in the second sub-study we acquired NIRS data of athletes climbing a competition-like route on the climbing wall.

Participants

In the first sub-study, 52 (27 female, 25 male) intermediate to elite recreational climbers were recruited from local climbing gyms. Inclusion criteria were a minimum age of 16 years, regular climbing training, and the ability to self-report their climbing ability level. In the second sub-study, 10 intermediate to advanced level climbers (5 female, 5 male) of a statewide squad participated. Subject characteristics, assessed and reported according to recommendations by Draper et al. (2015) [16] are presented in table 1.

Table 1: Subject characteristics

	Sub-study 1	Sub-study 2
	M ± SD	M ± SD
Age [years]	28.5 ± 6.3	20.2 ± 6.3
Lead: self-reported ability[1] [IRCRA scale]	14.9 ± 2.7	18.9 ± 1.8
Climbing experience [years]	5.6 ± 5.2	6.4 ± 3.7

Legend: [1] 3 hardest ascents in the past 3 months

All participants joined in voluntarily and gave written informed consent. The Ethics Committee of the local University approved the research (approval number 20/104, 03 April 21).

Procedure

In the first sub-study, muscular endurance of the finger flexors was assessed via an intermittent finger endurance test, which represents a valid measurement for climbing performance [14,17] .

Participants first performed a standardized warm-up which, according to the protocol used by López-Rivera (2014) [7] , consisted of a general warm-up with various mobilization exercises for the trunk, arms, wrists, and fingers. Afterward, a specific warm-up on the fingerboard (3 series of intermittent pulling (7 s pulling, 2 s rest) with increasing load followed by 2 familiarization trials for the maximum strength test) was performed. The maximum force (MVC) of the finger flexors was assessed in the next step by a maximum strength test. Therefore, the participants loaded the testing rung (23 mm deep, 12 mm radius) maximally with each hand separately within a time frame of 5 s while standing on an Entralpi© force plate for measurement purposes. The maximum out of 3 attempts separated by a rest of 10 s between hands and 3 min between series was measured with the Entralpi© app.

After a pause of 10 min, the intermittent finger endurance test was performed with each hand separately in a randomized order. The participants had to complete as many intervals as possible. One interval consisted of a 7-second load period with a target force of 60% of the previously determined MVC, followed by a 2-second relief period. To monitor and control the actual force applied during the test, an

Entralpi© force plate with simultaneous visual feedback of the pulled weight via the Entralpi© app was used. Participants were instructed to maintain their force at the target force level. The experimenter aborted the test if the applied force dropped significantly below the target zone for an extended period longer than 2 s in 2 consecutive trials. Data were recorded, and the number of valid repetitions was determined retrospectively based on a maximal permissible tolerance of 10% of the target force.

In the second sub-study, NIRS data were collected during a training competition. After an individual warm-up, the athletes attempted a route in the upper range of their climbing ability until a fall occurred. Like in competitions, the climbing time was limited to six minutes. The route contained two rest positions where the athletes could shake their arms for recovery. The athletes made 3 attempts in the same route with a complete recovery period of at least 15 minutes afterward. None of the athletes was able to successfully ascend the route or exceeded the climbing time limitation.

NIRS

In both sub-studies, after completing the warm-up period, NIRS probes were attached to the participants. Therefore, the m. flexor digitorum profundus was palpated using the technique described by Schweizer and Hudek (2011) [18] and the probe was attached to the skin above the middle of the muscle belly using lightproof tape. After the NIRS probes were attached, the baseline values were recorded for 5 minutes while the participants were sitting in an armchair with their forearms lying in the standard anatomical position on the armrests. Participants were instructed to avoid any unnecessary movements during this period.

Continuous-wave Artinis portalite NIRS devices and Oxysoft software (version 3.0.95) (Artinis Medical Systems, Netherlands) were used in both sub-studies to assess oxygenation and blood volume changes. The settings were made according to the manufacturer's instruction and are specified as follows: 3-channel measurement, wavelengths: 760 nm & 850 nm, source-detector distance: 35 mm, distance between transmitters: 5 mm, constants to determine the scattering coefficients: k 1.1 nm, h $4.6*10^{-4}$ nm, differential pathlength factor[1]: 4, sample rate: 10 Hz.

Data processing included applying a generic smoothing filter (Moving Gaussian with a filter width of 0.2 s) to reduce high-frequency noise, visual inspection to exclude unusable data, and manual corrections of single movement artifacts (spikes).

Absolute concentrations of O_2Hb and HHb, tHb, and TSI were calculated using the spatially resolved spectroscopy method. For sub-study one, the following parameters were calculated for O_2Hb, HHb, tHb, and TSI. A schematic representation of the parameters is shown in figure 1.

- For the baseline period
    - *Baseline values* as the average of the last 60 seconds of the baseline values recording period
- For the testing period

- The total *minima and maxima* and the *mean minima* and *maxima* of all valid repetitions (local and total minima and maxima), whereby every single repetition was entered as a data pair consisting of minimum and maximum. Those were assessed as absolute values and in relation to baseline values (parameter values minus baseline values).
- *Delta contraction* as the percentual difference between the beginning and the end of the 7 s load period, and analogously *delta relaxation* as the difference between the beginning and the end of the 2 s relief period for all valid repetitions.
- Furthermore, *minima*, *maxima,* and *delta contraction*, and *relaxation* were assessed for the *last valid repetition* and the *first* nonvalid repetition.

[1] as suggested by van Beekvelt et al. (2001) [19] for forearm measurements

Results

In sub-study 1, the athletes pulled on average 74 ± 15% of body weight in the MVC test on the fingerboard (women: 70 ± 14%, men: 82 ± 14%). In the intermittent endurance test, they achieved an average of 10 ± 7 repetitions (women 9 ± 7, men 11 ± 8) within the valid range.

The multiple linear regression model showed that the NIRS parameters significantly predicted the number of valid repetitions in the intermittent finger endurance test, $F(3, 127) = 15.16$, $p < .001$, adj. $R^2 = .264$. Variables that added statistical significance to the prediction during the testing period were the mean maxima for O_2Hb, the mean maxima in relation to baseline values for TSI, and the mean minima for O_2Hb. Regression coefficients and standard errors can be found in Table 2.

Table 2
NIRS parameters that predict intermittent finger endurance performance

Number of valid repetitions	**B**	**95% CI for B**		**SE B**	**ß**	**R^2**	**Δ R^2**
		LL	UL				
Model						.26	.25
Constant	6.11**	2.09	10.12	2.03			
Mean maxima O2Hb	.38***	0.22	0.54	0.08	.61		
Mean maxima TSI in relation to baseline values	.17***	0.07	0.27	0.05	.27		
Mean minima O2Hb	− .28**	-0.46	-0.11	0.09	− .40		

Note: Model = "Included" method in SPSS Statistics 26; *B* = unstandardized regression coefficient; CI = Confidence interval; *LL* = lower limit; *UL* = upper limit; *SE B* = standard error of the coefficient; *ß* = standardized coefficient; R^2 = coefficient of determination; Δ R^2 = adjusted R^2. *p < .05. **p < .01. ***p < .001.

Regarding the comparison between the last valid repetition and the first nonvalid repetition, no statistically significant difference between the last valid and the first nonvalid repetition existed on the combined dependent variables, $F(9, 42) = 1.522$, $p = .172$; Wilks' Λ = .754, partial $\eta^2 = .246$.

In sub-study 2, there was a statistically significant difference between the 20s intervals on the combined dependent variables, $F(11, 31) = 44.138$, $p < .001$; Wilks' Λ = .060, partial $\eta^2 = .940$. Descriptive statistics of the NIRS parameters at the analyzed time points are presented in Table 3.

Table 3
Descriptive statistics of the NIRS parameters at the analyzed time points during a simulated lead climbing competition

Parameter	Baseline (M ± SD)	First interval (M ± SD)	Second-last interval (M ± SD)	Last interval (M ± SD)
O2Hb	54.18 ± 17.95	41.30 ± 21.52	38.30 ± 23.75	38.68 ± 23.80
HHb	24.78 ± 8.13	28.39 ± 8.15	39.97 ± 6.71	41.85 ± 6.55
tHb	78.96 ± 25.27	69.67 ± 28.81	78.26 ± 26.70	80.53 ± 24.35
TSI	68.33 ± 3.84	57.54 ± 6.35	46.36 ± 9.97	45.69 ± 9.87
Note: M = mean; SD = standard deviation				

Post-hoc testing with rANOVAs for each dependent variable showed significant univariate within-subjects effects for each parameter (O2Hb: F(3, 123) = 38.412, p < .001, partial $\eta^2 = .484$; HHb: F(3, 123) = 97.468, p < .001, partial $\eta^2 = .704$; tHb: F(3, 123) = 14.478, p < .001, partial $\eta^2 = .261$; TSI: F(3, 123) = 122.995, p < .001, partial $\eta^2 = .750$).

When comparing the NIRS parameters during the climbing ascents only, the significant difference between the 20s intervals on the combined dependent variables was found as well, $F(8, 34) = 28.142$, $p < .001$; Wilks' Λ = .131, partial $\eta^2 = .869$. Post-hoc testing with rANOVAs for each dependent variable, however, showed significant univariate within-subjects effects for HHb, tHb, and TSI only (HHb: F(2, 82) = 74.318, p < .001, partial $\eta^2 = .644$; tHb: F(2, 82) = 25.352, p < .001, partial $\eta^2 = .382$; TSI: F(2, 82) = 55.155, p < .001, partial $\eta^2 = .574$), but not for O2Hb (F(2, 82) = 2.846, p < .001, partial $\eta^2 = .065$). In Fig. 2, NIRS parameters during the climbing ascent are shown.

Single intervals were compared by paired t-tests. No significant differences between any of the analyzed intervals were found for O_2Hb. TSI and tHb were significantly different between the last and the first interval but Figure 2: NIRS parameters during the climbing ascent

not between the last and the second-last interval. For HHb, all comparisons showed significant differences.

Conclusion

Prolonged durations of high-intensity exercises such as climbing, lead to an accumulation of metabolic compounds associated with different energy pathways to buffer decreases in muscular adenosine triphosphate (ATP) concentrations. Many of them have dilatative functions and therefore enhance blood flow kinetics. Even though many compounds accumulate, evidence suggests that the primary drivers causing muscular fatigue are inorganic phosphates (P_i) and hydrogen protons (H^+) [20]. The latter one decreases pH levels, and those circumstances cause a configuration shift of hemoglobin due to changes in protein folding, classified as taut form. This results in releasing oxygen in favor of the attachment of H^+, decreasing hemoglobin's affinity for oxygen, weakening its binding capacity, and increasing the likelihood of dissociation, which causes a rightward shift of the hemoglobin dissociation curve [21, 22]. Oxygen-dependent light absorption differences in the near-infrared light spectrum make it possible to measure changes between the two forms of hemoglobin. NIRS, therefore, represents a valid method for measuring oxidative muscle metabolism [23] and the simultaneous analysis of oxy[heme] (O_2Hb) and deoxy[heme] (HHb), total[heme] (tHb), and tissue saturation index (TSI) gives interesting insights into muscle oxygenation in climbing-specific settings.

In sub-study 1, NIRS parameters that determined the number of valid repetitions in the intermittent finger endurance test were the mean maxima for O_2Hb, the mean maxima in relation to baseline values for TSI, and the mean minima for O_2Hb. Accordingly, climbers with better test performances showed higher O_2Hb concentrations at the beginning of each load period (maxima) and lower O_2Hb concentrations at the end of each load period (minima), representing a wider span between maxima and minima. In the context of the existing literature, higher O_2Hb concentration changes between climbers and non-climbers were reported by MacLeod et al. (2007) [9] during the relief phase of intermittent finger endurance tests, which is in accordance with our study, whereas Baláš et al. (2021) [14] found no differences for various ability groups. When looking at continuous tests, climbers/ elite level climbers deoxygenated the flexor digitorum profundus significantly more [6, 9] and faster [6] than non-climbers/ lower level climbers, which is in line with our findings, but again, in contrast, Baláš et al. (2021) [14] found no ability group differences. The differences between studies remain unclear and require further investigations since it seems unlikely they relate to the participant's characteristics.

The physiological and anatomical adaptations behind the findings above might be macro-and microvascular adaptations and shorter muscle fiber relaxation times [9]. The evidence is partly conflicting regarding macrovascular adaptations: Thompson et al. (2015) [24] assessed brachial arterial structure, blood flow, and function. They found greater resting, peak, and maximal brachial artery diameters and a higher peak reactive hyperaemic blood flow but no differences in flow-mediated dilation between climbers and controls during rest or after ischaemic conditions. Fryer et al. (2015) [6] found no ability group

differences for brachial artery blood velocity and blood flow during a continuous finger endurance test. Fergurson and Brown (1997) [25] reported a significantly higher vascular conductance of climbers than non-climbers using continuous and intermittent finger endurance tests. On the microvascular level, Thompson et al. (2015) [24] reported a higher capillary filtration capacity in climbers than in controls, which has been suggested to be the main factor for differences in oxygen kinetics measured via NIRS and being a training-induced adaptation [12, 26].

Even though climbers with better test performances had a wider span between minima and maxima O_2Hb concentration levels, the direct measurements of concentration changes during single repetitions (delta contraction and delta relaxation) were no significant predictors of intermittent finger endurance test performance. This might be because the calculation of deltas requires an accurate minimum and maximum, which means they are more sensitive to motion-induced measurement artifacts than single minima and maxima.

Regarding the comparison between the last valid repetition and the first nonvalid repetition, the nonsignificant difference on the combined dependent variable indicates, that either muscular fatigue is a continuous process, at least in the case where the load is kept constant for the entire duration of the exercise, or that physiological breakpoints do not match with the declined force output responsible for the differentiation between valid and nonvalid repetitions

Regarding sub-study 2, evaluating oxygen kinetics during competitive lead climbing has not yet been done. Therefore, this study breaks new scientific and technological ground and reveals interesting insights into the oxygen kinetics in climbing.

In detail, O_2Hb showed no significant univariate within-subjects effects. This is surprising given that most studies on the oxygen response in incremental ramp exercises showed decreases in O_2Hb concentrations during the test period [27]. As explained, the physiological mechanism behind this would be the rightward shift of the hemoglobin dissociation curve[21, 22, 27]. We couldn't observe such a decrease because of the intermittent structure of load and relief phases of the forearm flexor muscles in lead climbing. In highly trained lead climbers, the short relief phases could be enough for sufficient reoxygenation of the forearm muscles. Studies during intermittent finger endurance tests on the fingerboard showed that climbers have higher relief phase reoxygenation than non-climbers, which explained 41.1% of the force-time integral [9, 12]. On the contrary, Baláš et al. (2021) [14] found no significant differences in relief phase reoxygenation between advanced and recreational climbers.

Regarding HHb changes, we observed an accumulation in the concentration levels during the competitive climbing test, similar to findings during incremental exercises (for a review, see Boone et al. (2016) [27]). This indicates a cumulative load on the participant's forearm flexor muscles due to increasing difficulties of the climbing route. When comparing the HHb curve shape with the one described by Boone et al. (2016)[27] (a sigmoid shape with a sluggish increase at the onset of incremental ramp exercise at very low work intensities), we observed a steep slope right from the beginning, which indicates that already the

first moves required efforts of moderate intensities. Breakpoints in HHb response could be visually detected by identifying inflection points in 46% of the climbing attempts. HHb breakpoints are associated with integrated electromyography, ventilatory and muscle lactate thresholds, and critical power [27, 28]. However, in contrast to the study of Baláš et al. (2021) [14], the breakpoints could not precisely be calculated due to the influence of shaking, chalking, and clipping phases chosen by the athletes in a competition-like climbing route. In follow-up studies, rest phases could be eliminated to analyze the occurrence of breakpoints in HHb responses during wall climbing.

For the tHb response, significant univariate within-subjects effects had been found. T-tests further revealed a significant increase between the last 20 s interval and the first one, the comparison between the last and the second-last interval, however showed higher tHb concentration levels in the last interval, but didn't reach significance. It still seems unlikely that tHb, as observed in other studies by Boone et al. (2016) [27], levels off towards the end of incremental ramp exercises since we didn't observe any significant changes in the O_2Hb concentration, and its attenuation of the decrease rate has been associated with a reduction in tHb. Instead, the data indicate a steady increase of tHb, given that tHb is calculated as the sum of O_2Hb and HHb, with O_2Hb remaining constant and HHb constantly increasing.

Lastly, TSI showed a decreasing trend during the climbing attempts. Similarly to tHb, significant differences were found between the last 20 s interval and the first but not between the last and the second-last intervals, even though the decreasing trend continued. Yet again, the rising HHb concentration is the main underlying driver for the observed changes in TSI.

Limitations

The study contains several limitations: First, limitations regarding the sample size in both sub-studies. In sub-study one, recreational to elite level climbers participated; however, despite the large range of ability groups, at a closer look, most of the participants were classified as recreational to advanced level climbers, with only one participant being categorized as an elite climber. The underrepresentation of elite to higher elite-level climbers, therefore, limits the generalizability of the study´s findings. The same is true for sub-study 2, where the sample consisted of a small and, in terms of climbing abilities, very homogenous group of climbers, with the sample size being considered too small for the calculation of regression analyses. Secondly, in sub-study one, two adjacent repetitions out of a whole series of repetitions were compared, with the criteria for distinguishing valid and nonvalid repetitions, even though being well thought of [17], do represent external criteria that are not based on physiological break points. Moreover, the calculation of NIRS parameters of the first nonvalid interval required participants to perform at least two more repetitions after not being able to exert the required target force anymore. This implies, that data sets of participants who couldn´t perform at least two more repetitions and therefore may have different fatigue kinetics, were systematically excluded. However, since we aimed to distinguish between valid and nonvalid repetitions, this is a study-inherent problem. Thirdly, in sub-study two, breakpoints in HHb response, which reveal interesting insights into muscle oxygen kinetics, could not be determined due to the influence of shaking, chalking, and clipping phases.

Abbreviations

ATP	Adenosine triphosphate
HHb	deoxy[heme]
H^+	hydrogen protons
MVC	Maximal voluntary contraction
NIRS	Near-infrared spectroscopy
O_2Hb	oxy[heme]
P_i	inorganic phosphates
tHb	total[heme]
TSI	**tissue saturation index**
T1/2	**time-to half recovery**

Declarations

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Author contributions

All authors conceived of and designed the analysis, collected the data, discussed the results, and contributed to the final manuscript. Marvin Winkler performed the data and statistical analysis and took lead in writing and editing the manuscript. By providing critical feedback and revising the initial manuscript, Claudia Augste helped shaped the final manuscript. Claudia Augste and Stefan Künzell supervised the project.

Compliance with ethical standards

This study was part of the research project “Evaluation of training interventions to improve local muscular endurance in sport climbing using near-infrared spectroscopy (NIRS)” which was founded by the German Federal Institute of Sport Science (BISp ZMVI4-070705/20-21).

The authors have no competing interests to declare that are relevant to the content of this article.

The study conforms with the Declaration of Helsinki, and the Ethics Committee of the local University approved the research (approval number 20/104, 03 April 21).

All participants joined in voluntarily and gave written informed consent.

Data availability statement

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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Figures

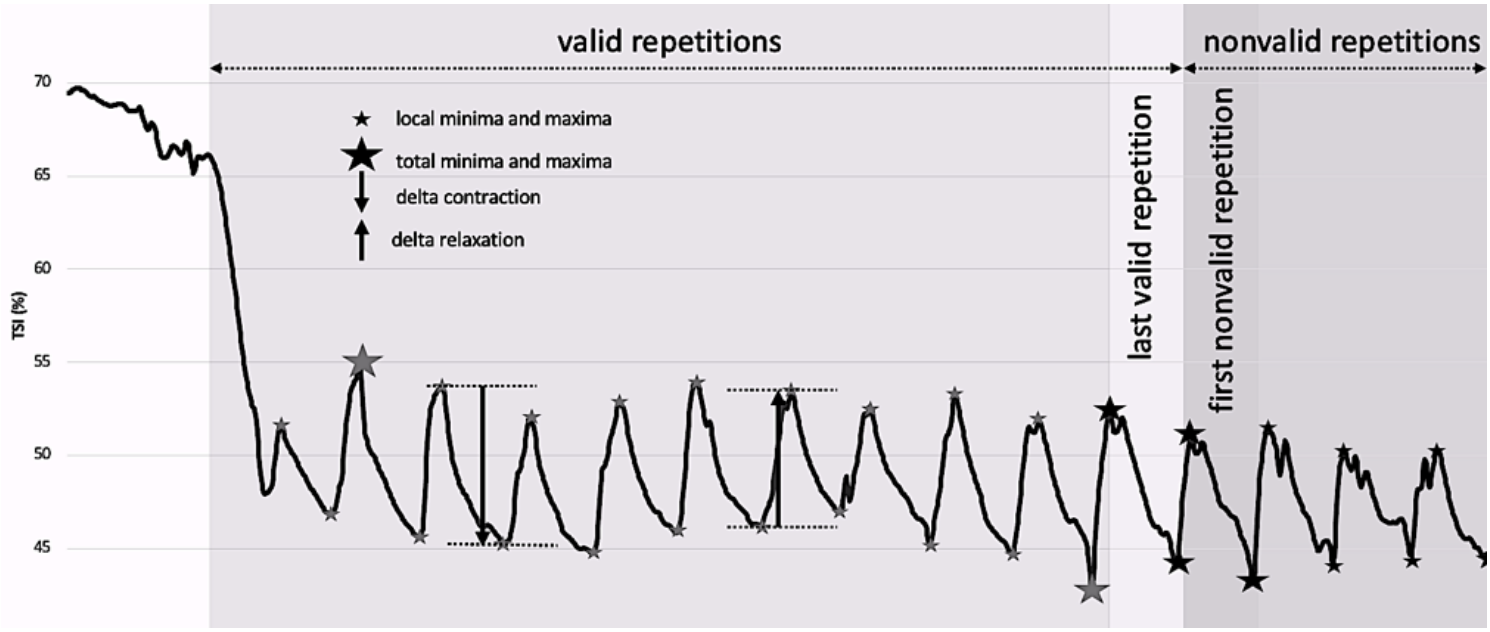


Figure 1

Schematic representation of the NIRS parameters assessed for the intermittent finger endurance test

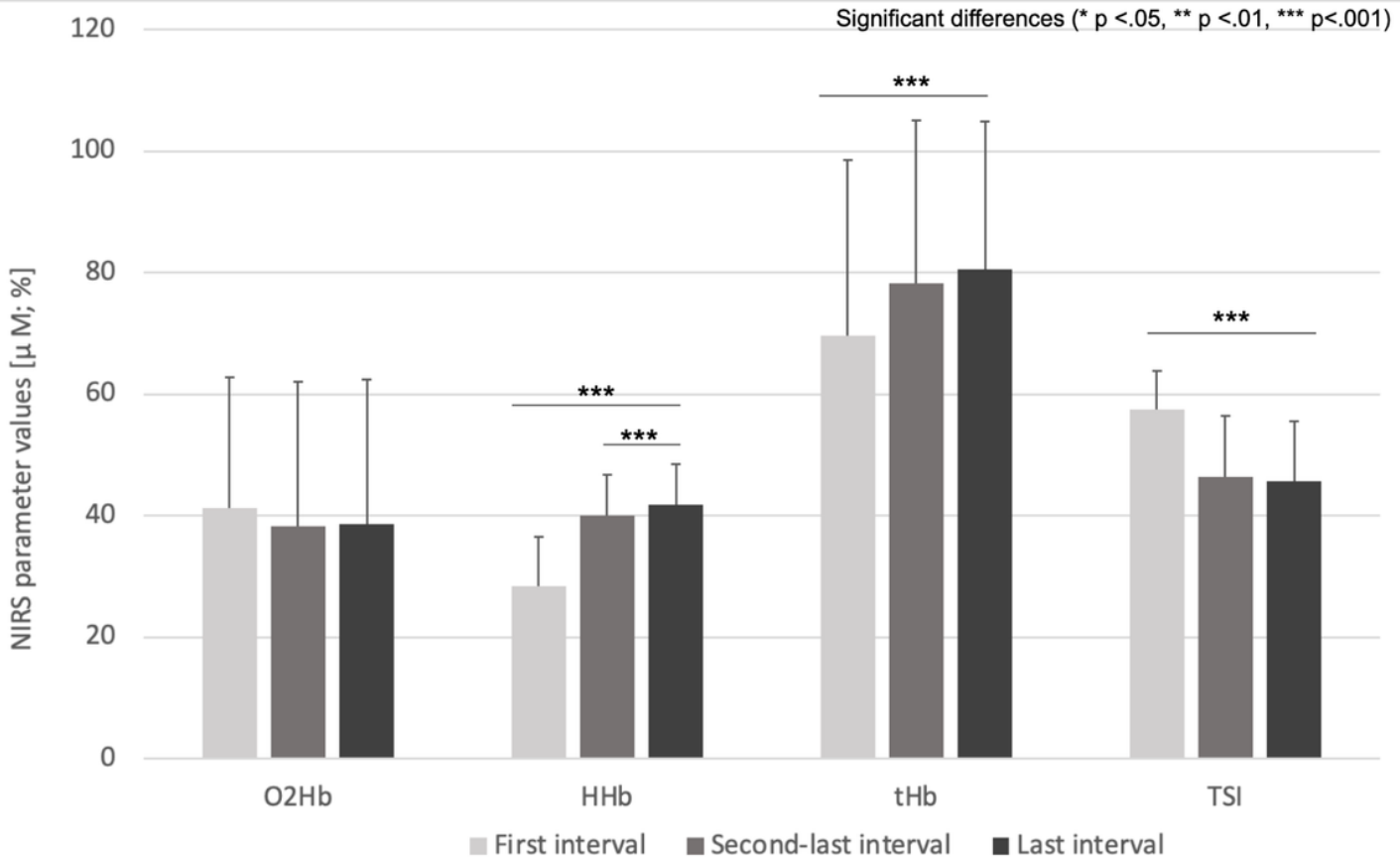


Figure 2

NIRS parameters during the climbing ascent