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Angaben zur Veröffentlichung / Publication details:

Winkler, Marvin, Stefan Künzell, and Claudia Augste. 2024. "Predictive value of forearm muscle oxygenation parameters for climbing-specific finger endurance and competitive climbing performance." *Sport Sciences for Health* 20: 109–17.
https://doi.org/10.1007/s11332-023-01072-w.

Sport Sciences for Health (2024) 20:109–117
https://doi.org/10.1007/s11332-023-01072-w

RESEARCH

Predictive value of forearm muscle oxygenation parameters for climbing-specific finger endurance and competitive climbing performance

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Received: 30 November 2022 / Accepted: 4 May 2023 / Published online: 19 July 2023

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 26.4% 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 repetition on the combined dependent variable. For the simulated competition, a statistically significant difference between the 20 s intervals on the combined dependent variables was 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.

Keywords Near-infrared spectroscopy · Intermittent finger endurance · Lead climbing · Oxidative muscle metabolism

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

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Introduction

Lead climbing is a sub-discipline in which a 15 m high climbing wall has to be climbed within 6 min. 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 s and the rest period 1.8 s [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], which is supported by a whole series of empirical studies [4–13].

Until recently, performance diagnostics of muscular endurance used external criteria such as repetition numbers or force inputs or invasive methods such as lactate measurement because it was difficult to measure 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 its 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 the 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. [14] couldn't detect significant ability group differences. During treadwall climbing, in the study of Fryer et al. [15], maximal desaturation of the TSI significantly predicted climbing performance. Baláš et al. [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. [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 the second sub-study was to perform NIRS measurements in a simulated climbing competition and to find out the significance of certain NIRS parameters for 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.

Table 1 Subject characteristics

	Sub-study 1 M ± SD	Sub-study 2 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

[1]3 hardest ascents in the past 3 months

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. [16] are presented in Table 1.

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 [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) with each hand separately and in a progressive way and aimed to reach their MVC within a time frame of 5 s. 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© force plate and app.

After a pause of 10 min, the intermittent finger endurance test was performed with each hand separately in a

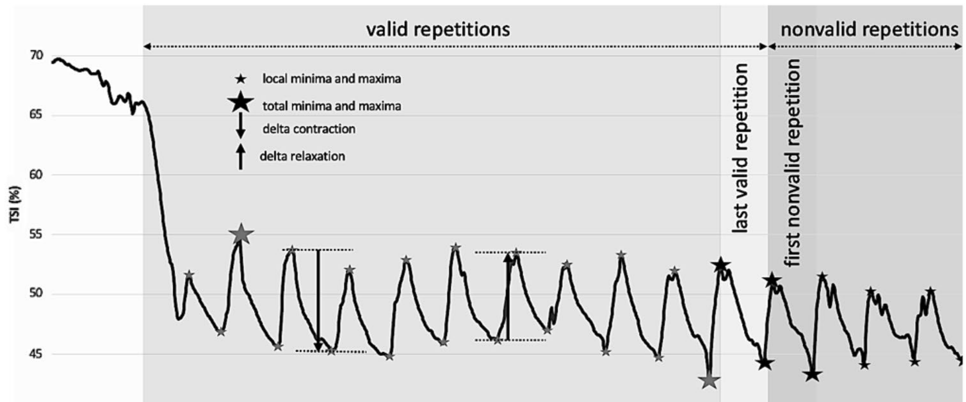

Fig. 1 Schematic representation of the NIRS parameters assessed for the intermittent finger endurance test

randomized order. The participants had to complete as many intervals as possible. One interval consisted of a 7 s load period with a target force of 60% of the previously determined MVC, followed by a 2 s 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 time deviation of 1 s and a force tolerance of 9% for the females and 6% for the males [17].

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 6 minutes. The route contained 2 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 min afterward. None of the athletes were 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 [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 min 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 (CW) 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. Since climbers have a low body fat percentage in general [9, 12, 19, 20] and on the forearms specifically [21–23], the effects of skinfold or adipose tissue thickness on CW NIRS [24] were considered to be neglectable.

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 Fig. 1.

- For the baseline period
  - *Baseline values* as the average of the last 60 s 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

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

Table 2 NIRS parameters that predict intermittent finger endurance performance

Number of valid repetitions	*B*	95% CI for B		SE B	*ß*	R^2	ΔR^2
		LL	UL				
Model						0.26	0.25
Constant	6.11**	2.09	10.12	2.03			
Mean maxima O_2Hb	0.38***	0.22	0.54	0.08	0.61		
Mean maxima TSI in relation to baseline values	0.17***	0.07	0.27	0.05	0.27		
Mean minima O_2Hb	−0.28**	−0.46	−0.11	0.09	−0.40		

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, ΔR^2 adjusted R^2

*$p < 0.05$

**$p < 0.01$

***$p < 0.001$

minimum and maximum. Those were assessed as absolute values and in relation to baseline values (parameter values minus baseline values).

p *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.

q Furthermore, *minima*, *maxima,* and *delta contraction*, and *relaxation* were assessed for the *last valid repetition* and the *first* nonvalid repetition.

Recovery parameters were not assessed since the aim was to find out which NIRS parameters changed between the last valid and the first nonvalid repetitions, and therefore, represent indicators of muscular fatigue. With the available measurement system, this differentiation could be done retrospectively only.

For sub-study two, filtered data were averaged over 20 s periods with the first interval beginning at the same time as the climbing attempt as done by Baláš et al. [14] due to the irregularity of finger flexor contractions and to further reduce motion artifacts in a competition-like setting. These data were used to analyze which NIRS parameters (O2Hb, HHb, tHb & TSI) changed during competitive lead climbing.

Statistical analysis

Before further statistical analyses, data were checked for outliers. If the reason for deviation couldn't be identified and the values couldn't be corrected, the ones categorized as extreme values using SPSS Boxplots were excluded from the data set. This was the case for, on average, 0.6 ± 3.0% of the values per participant.

Multiple linear regression analysis was used to assess which NIRS parameters predict the number of valid repetitions in the intermittent finger endurance test. Furthermore, one-way repeated MANOVA was used to calculate differences between the last valid repetition and the first nonvalid repetition.

For sub-study 2, one-way repeated MANOVA was applied to assess differences in NIRS values between selected 20 s intervals: baseline values, the first, the second-last, and the last interval of the climbing test. We didn't calculate regression analysis due to the small sample size.

Analyses were performed using SPSS software (IBM SPSS, Version 28.1), and the level of significance was set at $\alpha < 0.05$; a Bonferroni correction was applied for multiple comparisons.

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, $F(3, 127) = 15.16$, $p < 0.001$, adj. $R^2 = 0.264$. 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.

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, $F(9, 42) = 1.522$, $p = 0.172$; Wilks' $\Lambda = 0.754$, partial $\eta^2 = 0.246$.

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)
O_2Hb	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

M mean, *SD* standard deviation

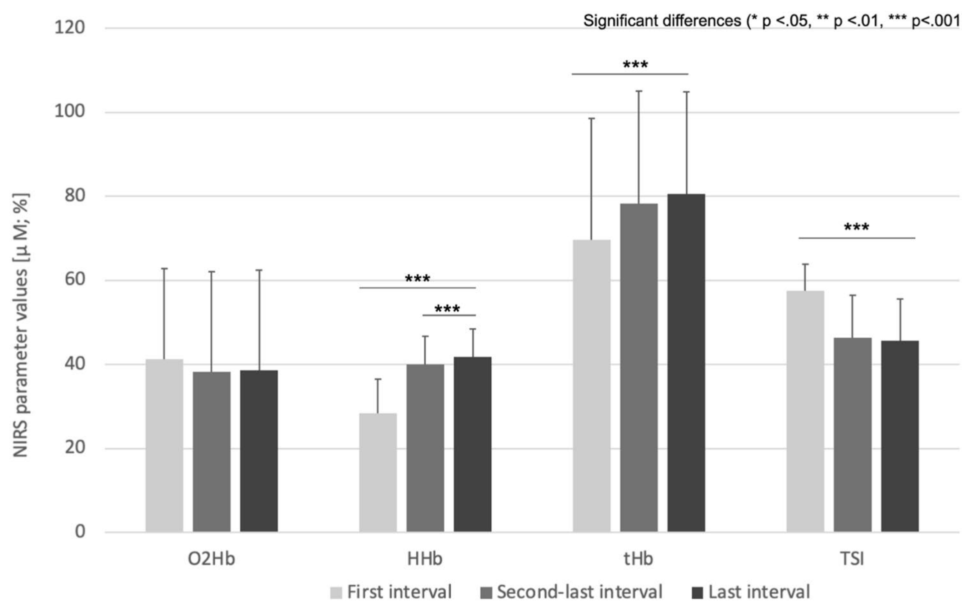

Fig. 2 NIRS parameters during the climbing ascent

In sub-study 2, there was a statistically significant difference between the 20 s intervals on the combined dependent variables, $F(11, 31) = 44.138$, $p < 0.001$; Wilks' $\Lambda = 0.060$, partial $\eta^2 = 0.940$. Descriptive statistics of the NIRS parameters at the analyzed time points are presented in Table 3.

Post-hoc testing with rANOVAs for each dependent variable showed significant univariate within-subjects effects for each parameter (O_2Hb: $F(3, 123) = 38.412$, $p < 0.001$, partial $\eta^2 = 0.484$; HHb: $F(3, 123) = 97.468$, $p < 0.001$, partial $\eta^2 = 0.704$; tHb: $F(3, 123) = 14.478$, $p < 0.001$, partial $\eta^2 = 0.261$; TSI: $F(3, 123) = 122.995$, $p < 0.001$, partial $\eta^2 = 0.750$).

When comparing the NIRS parameters during the climbing ascents only, the significant difference between the 20 s intervals on the combined dependent variables was found as well, $F(8, 34) = 28.142$, $p < 0.001$; Wilks' $\Lambda = 0.131$, partial $\eta^2 = 0.869$. Post-hoc testing with rANOVAs for each dependent variable, however, showed significant univariate within-subjects effects for HHb, tHb, and TSI only (HHb: $F(2, 82) = 74.318$, $p < 0.001$, partial $\eta^2 = 0.644$; tHb: $F(2, 82) = 25.352$, $p < 0.001$, partial $\eta^2 = 0.382$; TSI: $F(2, 82) = 55.155$, $p < 0.001$, partial $\eta^2 = 0.574$), but not for O_2Hb ($F(2, 82) = 2.846$, $p < 0.001$, partial $\eta^2 = 0.065$). 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 not between the last and the second-last interval. For HHb, all comparisons showed significant differences.

Discussion

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^+) [25]. 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 [26, 27]. 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 [28] 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 this context, it must be mentioned that due to a similar light absorption spectrum, NIRS cannot distinguish between hemoglobin and myoglobin and therefore represents a measurement that includes both [22].

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. [9] during the relief phase of intermittent finger endurance tests, which is in accordance with our study, whereas Baláš et al. [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. [14] found no ability group differences. The differences between studies remain unclear and require further investigation 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. [29] 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. [6] found no ability group differences for brachial artery blood velocity and blood flow during a continuous finger endurance test. Fergurson and Brown [30] 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. [29] 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, 31].

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 [32]. As explained, the physiological mechanism behind this would be the rightward shift of the hemoglobin dissociation curve [26, 27, 32]. 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. [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. [32]). This indicates a cumulative load on the participant's forearm flexor muscles due to the increasing difficulties of the climbing route. When comparing the HHb curve shape with the one described by Boone et al. [32] (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 [32, 33]. However, in contrast to the study of Balášš et al. [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. [32], 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.

Conclusion

The current study indicates that different NIRS signals and parameters should be used to assess climbers forearm flexor muscles fatigue and recovery kinetics depending on the measurement protocol. For intermittent tests, high re- and deoxygenation abilities are decisive, which can be assessed through changes in O_2Hb and TSI between load and relief phases. In contrast, incremental ramp exercises, such as competition climbing, result in an accumulation of HHb concentrations, which represents the best parameter to differentiate different intervals in the test course.

Limitations

The study contains several limitations: first, absolute and relative to baseline CW NIRS values were used, which weren´t calibrated to the participants individual levels which may impact the analysis. Second, 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. Thirdly, 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. Lastly, 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.

Acknowledgements We would like to thank everybody who contributed to this study: The study assistants for data acquisition and processing, the German Alpine Club for providing the athletes, the KletterBar Offenbach for letting us use their premises and installments, and especially the participants. Thank you. 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).

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.

Funding Open Access funding enabled and organized by Projekt DEAL.

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

Declarations

Conflict of interest 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.

Ethical approval 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).

Informed consent All participants joined in voluntarily and gave written informed consent.

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