



Acute Effect of High-Intensity Climbing on Performance and Muscle Oxygenation in Elite Climbers

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Received: 25 June 2021 / Accepted: 15 September 2021 / Published online: 11 November 2021
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Abstract

High-intensity training (HIT) is known to have deteriorating effects on performance which manifest in various physiological changes such as lowered force production and oxidative capacity. However, the effect of HIT in climbing on finger flexor performance has not been investigated yet. Twenty-one climbers partook in an intervention study with three assessment time points: pre-HIT, post-HIT, and 24-h post-HIT. The HIT involved four five-minute exhaustive climbing tasks. Eight climbers were assigned to a control group. Assessments consisted of three finger flexor tests: maximum voluntary contraction (MVC), sustained contraction (SCT), and intermittent contraction tests (ICT). During the SCT muscle oxygenation (SmO₂) metrics were collected via NIRS sensors on the forearm. The HIT had significant deteriorating effects on all force production metrics (MVC – 18%, SCT – 55%, ICT – 59%). Post-24 h showed significant recovery, which was less pronounced for the endurance tests (MVC – 3%, SCT – 16%, ICT – 22%). SmO₂ metrics provided similar results for the SCT with medium to large effect sizes. Minimally attainable SmO₂ and resting SmO₂ both showed moderate negative correlations with pre-HIT force production respectively; $r = -0.41$, $P = 0.102$; $r = -0.361$, $P = 0.154$. A strong association was found between a loss of force production and change in minimally attainable SmO₂ ($r = -0.734$, $P = 0.016$). This study presents novel findings on the deteriorating effects of HIT on finger flexor performance and their oxidative capacity. Specifically, the divergent results between strength and endurance tests should be of interest to coaches and athletes when assessing athlete readiness.

Keywords NIRS · HIT · Tissue oxygenation · MVC · Isometric · Finger flexors

Introduction

Sport climbing is characterized by a highly localized muscular demand for high-intensity work with short intermittent recovery periods [29]. Therefore, a better understanding of the effect of climbing-specific high-intensity training (HIT) on physiology and performance is relevant for coaches and athletes to plan training and prepare for competitions.

Numerous studies have looked at classical performance diagnostic metrics to assess the physiological determinants of climbing performance [12, 15, 28]. It was found that

commonly used fitness tests such as treadmill endurance testing, handgrip dynamometry, jump, sit and reach or flexibility tests are not sensitive enough to assess performance changes in climbers [12, 38]. It was also stated that intensity indicators such as systemic oxygen consumption (VO₂), blood lactate level, or heart rate during climbing are not suitable to assess acute physiological response at a local level [36].

Localized physiological responses have recently been investigated through a near-infrared spectroscopy (NIRS) approach [20]. NIRS provides insight into blood volume and oxygenation metrics, including changes in deoxyhemoglobin and deoxymyoglobin (deoxy[heme]) and oxyhemoglobin and oxymyoglobin (oxy[heme]), and total hemoglobin and total myoglobin (total[heme]) under the sensor. From this information, NIRS can estimate muscle oxygen saturation in-vivo (SmO₂) [13] and appears to be a highly suitable tool to investigate the local forearm oxygenation of sport climbers. For instance, Fryer and colleagues [17] demonstrated that the faster half-time of tissue oxygen resaturation, as a

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surrogate for better oxidative capacity, was associated with higher climbing ability. Furthermore, a larger range and faster rate of oxygen desaturation were shown to occur in elite-level climbers compared to intermediate climbers [16]. SmO₂ recovery dynamics have been used to identify climbing performance, as shown by Philippe and colleagues [33], where climbers displayed faster re-oxygenation of the finger flexor muscles when compared to non-climbers.

While acute changes in forearm flexor SmO₂ are linked to climbing performance, none of the aforementioned studies have looked at the acute effect of training on SmO₂. Eccentric contractions have been found to slow SmO₂ dynamics and reduce deoxy[heme] response [2, 8]. Specific tasks like trail running also show alterations in SmO₂ dynamics with a flattening of the response, which the authors of the investigation identified as an impairment of the muscles' oxidative capacity [19].

Finger flexor strength and endurance measurements have been shown to be a valid and reliable tool to assess sport climbing performance [30]; however, the acute effect of training on force decline has not been documented. While performance decrease following high-intensity training is well documented as a consistent and observable effect in a variety of exercises [6, 9, 32], the direct mechanism for this acute loss of performance is still unclear [21]. The extent to which performance is depressed depends on factors such as the athlete's training status and intensity and volume of the training [39]. Under experimental conditions, performance has been shown to remain depressed, even for periods of hours or even days following intensive exercise [7]. Finger

hang tests alone explained over 70% of the redpoint (RP) performance in a study by Balas and colleagues [5] and therefore can be considered a relevant performance indicator to evaluate improvement in climbing performance, specifically RP grade. In order to provide practical insight to monitor the effect of forearm flexors HIT in climbers and track their recovery, we hypothesized that training-induced changes in localized muscular performance would persist for up to 24 h and be reflected in SmO₂ dynamics.

Methods

Study Design

The experimental and control group (with and without HIT, respectively) completed a series of repeated strength and endurance assessments. The first assessment was completed 10 min before the HIT (pre-HIT), the second 10 min after the HIT (post-HIT), and the final assessment took place 24 h after the HIT (post24-HIT) (Fig. 1). The goal of the assessment time course was to evaluate the immediate effect of HIT on climbing strength and endurance and compare this to a practical recovery time-frame effect. During each assessment, a series of established climbing-specific finger strength and endurance tests were conducted, and measurements of applied force and SmO₂ were recorded. Finger strength and endurance were assessed via maximal voluntary contraction (MVC), exhaustive sustained contraction (SCT), and intermittent

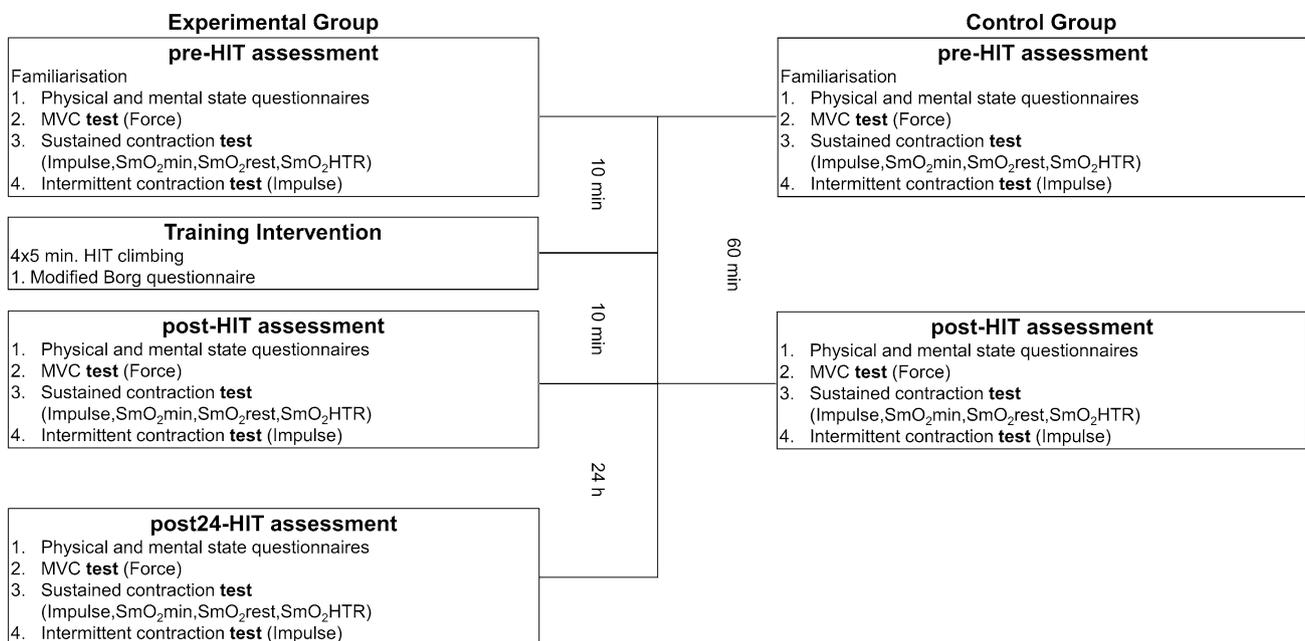


Fig. 1 Repeated measures design; test [test results]

contraction (ICT) tests. A series of questionnaires accompanied the assessments and HIT to further assess climbing ability and physical and mental condition during exercise. During the HIT, participants were asked to provide feedback on the level of physical stress elicited to ensure the effectiveness of the HIT. The study took place at a local sport climbing gym (O'Bloc, Bern CH).

Participants

Twenty-one participants, 12 males (mean \pm SD: age 30.3 ± 6.6 y; height 172.3 ± 5.5 cm; weight 66.8 ± 5.6 kg.) and 9 females (age 21.8 ± 5.6 y; height 162.3 ± 4.0 cm; weight 53.5 ± 6.7 kg) volunteered for the study. All participants climb regularly, were in good health, non-smokers, and unmedicated. Their self-reported, best in the previous three months, climbing ability was 23.5 ± 3.5 (range 19–29, Advanced to Higher Elite categories) on the International Rock Climbing Association Scale (IRCRA). Eight participants were assigned to the control group. The experimental and control group was selected based on participant availability, in accordance with training and competition timetables. The remaining thirteen participants were designated to the experimental group. The control group only took part in the pre-HIT and post-HIT assessments to assess the effect of the intervention. Differences in climbing ability and anthropometric measures between control and experimental group were considered negligible; climbing level experimental vs. control [23.3 ± 3.5 vs. 23.7 ± 3.5 , $t(15) = 0.232$, $P = 0.819$], and height and weight [166.8 ± 6.3 cm vs. 166.3 ± 8.4 cm, 61.9 ± 8.5 kg vs. 55.4 ± 9.8 kg, $t(15) = 0.141$, $P = 0.890$]. One subject in the experimental group could not complete the study (personal reasons), and technical difficulties resulted in two further participants (one control and one experimental) being removed from the NIRS analysis. One subject was removed as an outlier based on the results of a mental and physical readiness questionnaire; the participant's response represented an over-exerted state prior to the experiment. This resulted in the analysis of ten experimental participants and seven control. The participants were informed of the study design and the physical tasks ahead of time and written informed consent was obtained in advance. All participants were asked to refrain from smoking, alcohol, and caffeine consumption for at least 6 h prior to and throughout the experiment. Apart from these restrictions, participants were asked to maintain their individual diet routine. The study was carried out in accordance with the 1964 Declaration of Helsinki. The protocol was approved by the ethics committee of the local Faculty of Human Sciences, University of Bern.

Physical and Mental State

In order to assess the current physical and mental state of each subject and to determine the effectiveness of HIT, participants completed two valid and reliable questionnaires by Kellmann and Kölling [24]. The two questionnaires assess, 1. elicited stress and 2. recovery, both on a scale from 1 to 6; with 1 being a minimum state of stress and 6 being a maximum state of stress; and 1 being a minimum state of recovery, and 6 being a maximum state of recovery; respectively. A modified Borg questionnaire was used to evaluate the rate of perceived exertion during HIT on a scale from 1 to 10 [40]. Additionally, climbing ability was assessed using a self-reported questionnaire, which has been shown to be a valid and accurate reflection of climbing ability using the Ewbank grade classification for lead on-sight ascents [11]. The self-reported questionnaire for climbing ability asked about redpoint climbing ability, specifically the best climb in the previous three months. Redpoint is defined as completing a given climbing route in one attempt.

Warm-up

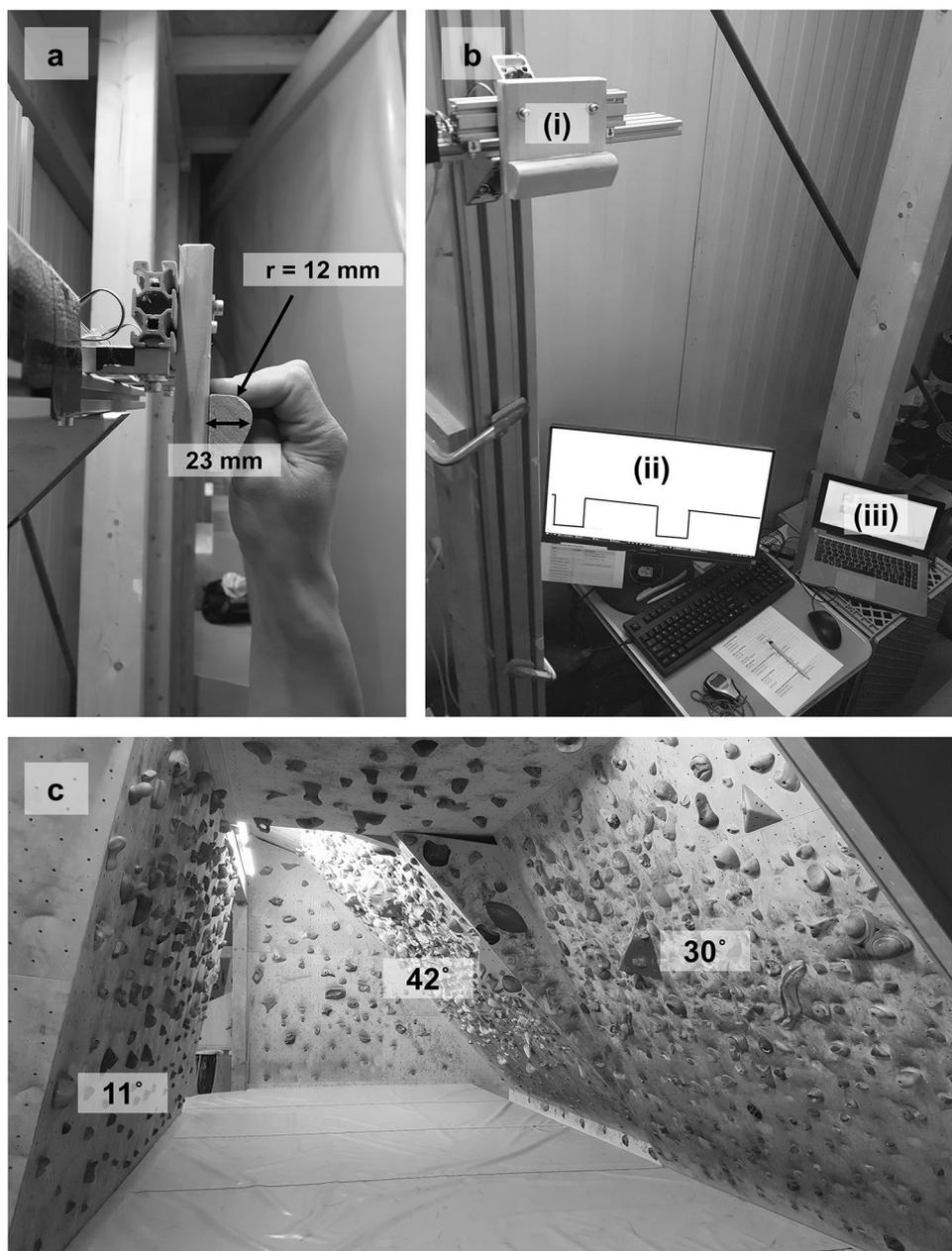
A standardized warm-up was conducted by all participants prior to the pre-HIT assessment. The warm-up started with five sets of rope skipping for 45 s with 15 s rest in between. This was followed by 5 min of self-paced climbing on a boulder wall. Finally, to warm-up for the specific tasks and to familiarize the participants with the assessment setup, six 7 s long, intermittent, isometric contractions, with 3 s rest each, were conducted at 30% body weight on the force measurement system.

Finger Flexor Strength and Endurance

The assessment of finger flexor strength and endurance followed an established, climbing-specific protocol, which has been found to strongly predict climbing performance and provide sufficient reliability [30]. All assessments were conducted using the self-reported dominant hand. Participants were instructed to use the half-crimp finger position without the thumb (Fig. 2). Participants were asked to position themselves vertically under the force measurement system (Fig. 2). The body and arm position had to remain in a vertical position under the measuring system. All participants were equipped with a 10 kg weight vest to allow force applications above bodyweight. Loud verbal encouragement was provided to ensure maximum effort.

A custom-made, climbing-specific force measurement system of the Sensory-Motor Systems Lab, ETH Zurich, was used (Fig. 2). The system consisted of a 23 mm deep wooden rung with a 12 mm radius as the handhold (specification previously applied by Baláš et al. [4]) The

Fig. 2 Study setup and equipment. **a** Rung and hold used for the tests; **b** Testing setup with (i) rung and force sensors, (ii) visual feedback display, and (iii) data collection PC and failure feedback; **c** The climbing wall with the three differently angled sections



rung was attached to two force sensors (CZL635, Phidget Inc., Canada, measurement range 0–50 kg each). The sensor signal was amplified, sampled at 122 Hz with an analog–digital converter, and send via USB (all provided by 1046_0, Phidget Inc., Canada) to a PC running Windows 10 (Microsoft Inc., USA). The total measured force was then recorded and displayed on a computer monitor using custom-made real-time visualization software (Python 3.6 with PyQt5). The system was calibrated using a 10 kg weight prior to the study and has high accuracy (root mean square error including hysteresis <math>< 0.08\text{ kg}</math>) and linearity (coefficient of determination $R^2 > 0.999$).

For the MVC test, participants were asked to pull with a continuous build-up of force within 2 s, avoiding jerking motions to the maximum force possible and maintain that force for 3 s [30]. The MVC test was repeated for a second time after a 2 min rest.

The SCT was conducted 10 min after the end of the second MVC test. As with the MVC test, participants were asked to apply force on the wooden rung in a controlled, non-jerking fashion. Participants were asked to apply 60% of their MVC to the wooden rung for as long as possible using the same half crimp grip. The measurement system provided the subject with visual feedback about the current

force being applied to arrive at and maintain 60% of MVC, which was defined as the target zone. The visual feedback was displayed on a PC monitor placed in front of the participants, with a live display of applied and desired force output (Fig. 2). If the force remained at less than 90% of the desired force for longer than 1 s, the test supervisor was informed, who then decided whether or not to stop the SCT.

After 10 min of passive rest, the ICT was conducted. The ICT is an interval test consisting of a continuous series of 7 s isometric contractions at 60% of MVC followed by a 3 s rest, thereby mimicking the typical demands of a series of difficult climbing moves. During the 3 s rest, the participants' hand remained on the wooden rung, but no pressure was applied. The visual feedback system was the same as for the SCT, and failure was defined by the same criteria as for the SCT.

Near-Infrared Spectroscopy Setup

NIRS sensors were placed over the finger flexor digitorum profundus (FDP), which was determined by palpation on the anterior side of the forearm, one-third between the medial epicondyle of the humerus and the styloid process of the ulna. The FDP is part of the forearm flexor group, which has the primary function of finger flexion and is of central importance in sport climbing and the conducted performance assessment [10, 18]. The sensors were fixed in place using medical adhesive tape (Hypafix; BSN Medical, DE) and covered with the compatible commercially available light shield to eliminate possible ambient light intrusion. A commercially available continuous-wave NIRS device was used (Moxy Monitor; Fortiori Designs LLC, MN, USA) to measure SmO_2 . The device uses four waves lengths (680, 720, 760 and 800 nm) to assess absorbency via modified Beer-Lambert resulting in a relative concentration of SmO_2 as percent in the following equation: $\text{oxy}[\text{heme}]/(\text{oxy}[\text{heme}] + (\text{deoxy}[\text{heme}])) = \text{SmO}_2$ [13]. The device detectors are spaced at 12.5 mm and 25 mm from the emitter. The sampling rate was set at 2 Hz, which samples the four wavelengths over 20 cycles for an averaged output every 0.5 s and gathered using the SWINCO NIRS software (Swinco AG, CH). With the emitter-detector spacing of 25 mm, a penetration depth of 12.5 mm can be expected. The adipose tissue thickness of the participants at the measurement site was negligible. NIRS data was only evaluated for the SCT.

Climbing Specific High-Intensity Training

The HIT was designed to elicit a high degree of local muscular fatigue. The HIT consisted of four series of 5 min climbing and 5 min rest. The climbing took place on a boulder wall consisting of three overhanging sections with different inclination (42°, 30°, and 11°) and equipped with a large

variety of commercially available climbing holds (Fig. 2). The climbing route was defined on-the-fly by an expert trainer who indicated to the subject which holds to use next. The expert trainer chose the route to ensure that the individual participants were able to continue climbing, but a high degree of intensity was maintained. If a participant fell from the wall, the participant immediately returned to the wall and continued climbing. Participants started on the 42° section of the wall and a climbing route was chosen such that the participant could climb in this section for the first 5 min interval. However, if due to fatigue, this became too difficult, the participant moved to the 30° section, and so forth.

Statistical Analysis

MVC was determined as the maximum force sample, reached through a consistent rate of force development, and was normalized by body weight. Abnormal spikes resulting from jerking motions were considered invalid. The higher value of the two MVC tests was recorded. NIRS data was not evaluated for the MVC tests.

For the SCT and ICT, impulse normalized by body weight was calculated from the time of contraction in the target zone and applied force. Impulse per body weight was used as the correct physical metric of the area under the curve (AUC) rather than endurance time in seconds. This should not confuse the reader; simply stated the larger the impulse the longer the endurance time as the force was controlled for and kept constant. NIRS data analysis was based on the principles proposed by Fryer et al. [17] and the protocols suggested by Ryan et al. [34]. The resting SmO_2 value ($\text{SmO}_{2\text{rest}}$) was determined from a standing position with the shoulder flexed overhead. Once the NIRS signal stabilized the 20 data points (10 s) prior to the start of the SCT test were averaged to determine $\text{SmO}_{2\text{rest}}$. The minimally attainable SmO_2 value ($\text{SmO}_{2\text{min}}$) was determined as the average of the minimally attained SmO_2 plateau at the end of each SCT over 20 data points (10 s). The SmO_2 half-time recovery ($\text{SmO}_{2\text{HTR}}$) was calculated as the time in seconds it took for SmO_2 to recover after the end of the test with the assistance of a curvilinear interpolation. NIRS data was not evaluated for the ICT because of the slow sampling rate of the NIRS device relative to the frequent alternation between activity and rest.

A repeated-measures ANOVA was used for the experimental group to assess differences between each of the three metrics (MVC, SCT, and ICT) of the three assessments (pre-HIT, post-HIT, and post24-HIT), respectively. For significant pairwise comparisons, Bonferroni correction was applied. The alpha level was set at $P < 0.05$. Partial eta squared (η_p^2) and Cohen's d were calculated as a measure of effect size for ANOVA and pairwise comparisons, respectively. Due to the small sample size, in order to not over

emphasize effect size, Cohen's d was interpreted according to Hopkins as cited by Knudson [26]. Values of 0.01, 0.05, and > 0.14 for η_p^2 and 0.2, 0.6, and > 1.2 for Cohen's d are considered small, medium, and large effects, respectively. Additionally, Pearson correlation analysis was conducted to assess the relationship between firstly, SmO_2 metrics, and force results, and then secondly the relationship between force results and questionnaire-derived climbing grades. Values of 0.1, 0.3 and > 0.5 for r are considered small, medium, and large effects, respectively.

Results

For every subject, all performance (impulse and MVC) metrics decreased after the HIT, with partial recovery after 24 h. All SmO_2 metrics increased after the HIT, with recovery after 24 h. In this way, the performance and SmO_2 metrics mirror each other. A series of correlations between change in performance and change in SmO_2 can be observed (Figs. 3 and 4).

Physical and Mental State

HIT scores for perceived exertion, for each of the four intervals, were 7.5 ± 1.8 , 8.2 ± 1.4 , and 8.8 ± 1.4 for the forearm flexors specifically and 8.6 ± 1.6 ; 5.5 ± 2.5 , 6.1 ± 2.1 , 6.8 ± 2.0 , and 6.9 ± 2.3 for the body as a whole. Pre-HIT scores for the state of recovery for forearm flexors and the body as a whole, respectively, were 4.7 ± 0.8 , and 4.2 ± 0.9 for the experimental group and 4.3 ± 0.7 , and 4.1 ± 0.4 for the control group. For the same timepoint, the scores for the state of stress for forearm flexors and the body as a whole, respectively, were 2.2 ± 0.8 , and 2.2 ± 0.4 for the experimental group and 2.4 ± 0.8 and 2.3 ± 0.5 for the control group.

MVC Test

Every subject in the experimental group had a reduction in MVC post-HIT and a near recovery post24-HIT; there was a significant effect of order (three time points, repeated-measures ANOVA, $P < 0.001$, $\eta_p^2 = 0.87$, Fig. 3). In post hoc analysis, their MVC decreased significantly by 18% between pre-HIT ($M = 8.59$, $SD = 1.04$) and post-HIT ($M = 7.02$, $SD = 0.55$), $P < 0.001$, $d = 3.23$; and non-significantly by 3% between pre-HIT and post24 HIT ($M = 8.35$, $SD = 0.85$), $P = 0.412$, $d = 0.49$. In the control group, the MVC decreased by 4% between the pre-HIT ($M = 8.65$, $SD = 1.23$) and post-HIT ($M = 8.31$, $SD = 1.50$), $P = 0.089$, $d = 0.77$.

Sustained Contraction Test

As with the MVC, every subject in the experimental group had a reduction in SCT impulse post-HIT and a

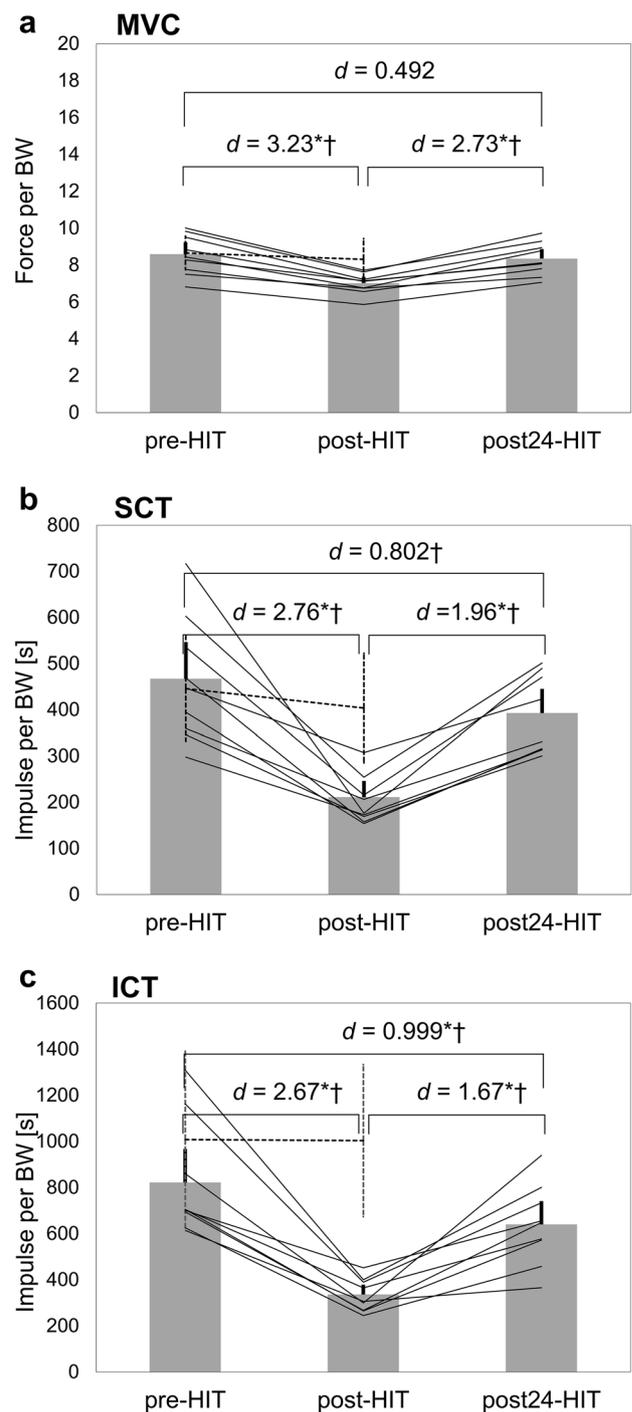


Fig. 3 Repeated measures ANOVA for the experimental group ($N_e = 10$). **a** Maximum voluntary contraction test (MVC), **b** Sustained contraction test (SCT), and **c** Intermittent contraction test (ICT); for all three testing time periods; pre-HIT 10 min before the HIT intervention, post-HIT 10 min after the HIT intervention, and post24-HIT 24 h after the HIT intervention. Gray bars represent experimental group means. Black vertical line 95% Confidence Interval (CI) accordingly. Horizontal black lines represent each subject's change in respective data for the experimental group. The horizontal dashed line represents the mean for the control group ($N_c = 7$). The dashed vertical line represents 95% CI. *Indicates significance at $P < 0.05$; †medium ($d \geq 0.6$) to large ($d \geq 1.2$) effect size

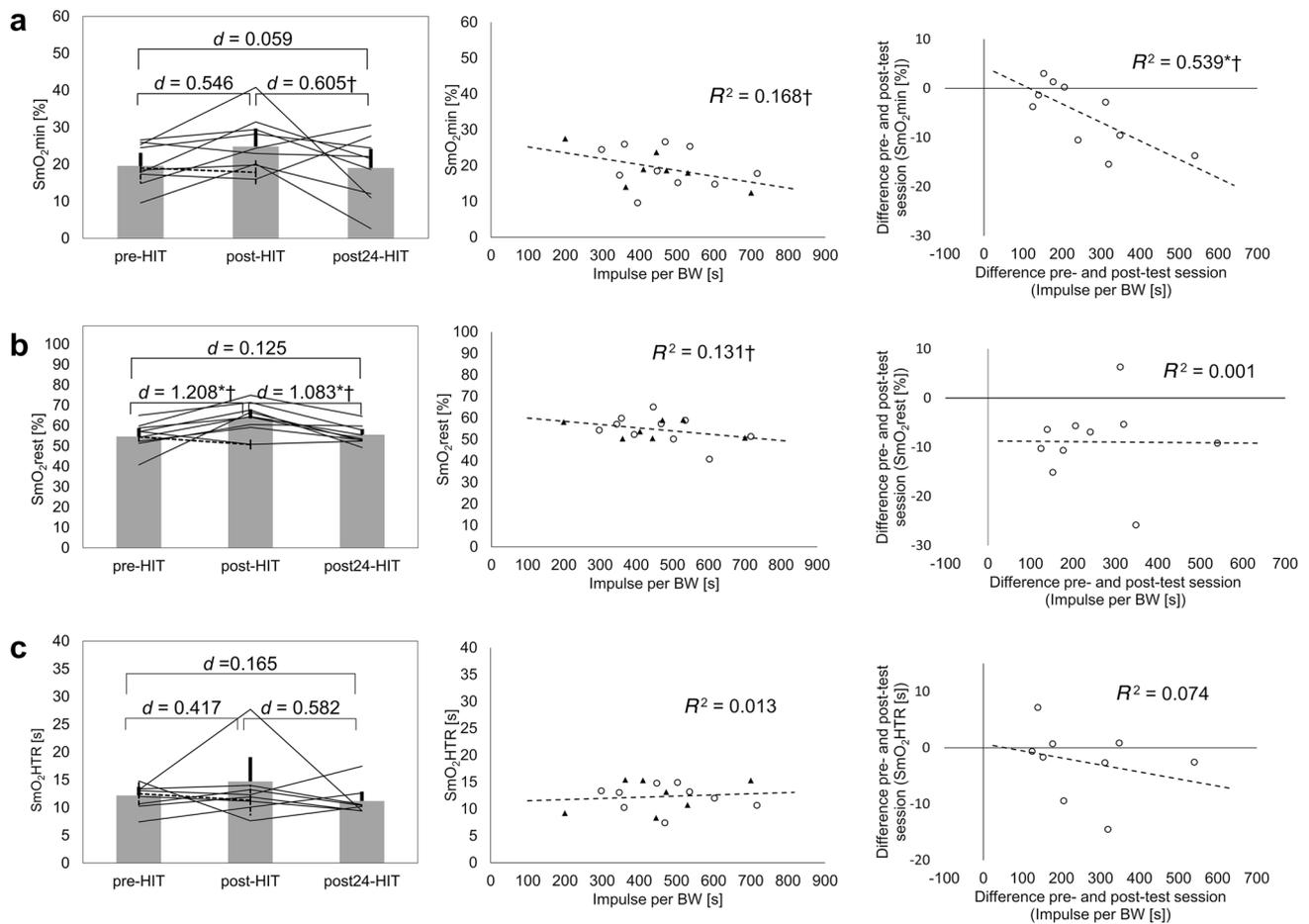


Fig. 4 Repeated measures ANOVA for the experimental group ($N_e = 10$). **a** Minimally attained muscle oxygenation (SmO_{2min}), **b** resting muscle oxygenation (SmO_{2rest}), and **c** half time recovery of SmO_2 (SmO_{2HTR}), all for the Sustained contraction test (SCT); for all three testing time periods; pre-HIT 10 min before the HIT intervention, post-HIT 10 min after the HIT intervention, and post24-HIT 24 h after the HIT intervention. Gray bars represent experimental group means. Black vertical line 95% CI accordingly. Horizontal black lines represent each subject change in respective data for the experimental group. The horizontal dashed line represents the mean

near recovery post24-HIT; there was a significant difference between the three assessment time periods (repeated measures ANOVA, $P < 0.001$, $\eta_p^2 = 0.82$, Fig. 3). In post hoc analysis, their SCT impulse decreased significantly by 55% between pre-HIT ($M = 467.08$, $SD = 127.80$) and post-HIT ($M = 211.00$, $SD = 56.92$), $P < 0.001$, $d = 2.76$; and non-significantly by 16% between pre-HIT and post-24 HIT ($M = 392.75$, $SD = 84.51$), $P = 0.062$, $d = 0.80$. In the control group, the SCT impulse decreased by 9% between the pre-HIT ($M = 445.55$, $SD = 153.45$) and post-HIT ($M = 403.79$, $SD = 159.95$), $P = 0.087$, $d = 0.77$. As with the MVC test, all participants, without exception, showed that impulse decreased in the post-HIT and recovered in

for the control group ($N_c = 7$). The dashed vertical line represents 95% CI. Pearson product-moment correlation for; pre-HIT SmO_{2min} and impulse; pre-HIT SmO_{2rest} and impulse; pre-HIT SmO_{2HTR} and impulse; the difference between pre-HIT and post-HIT SmO_{2min} and impulse; difference between pre-HIT and post-HIT SmO_{2rest} and impulse; the difference between pre-HIT and post-HIT SmO_{2HTR} and impulse. Circles (○) represent the experimental group, diamonds (▲) control group. *indicates significance at $P < 0.05$; †medium ($d \geq 0.6$; $r \geq 0.3$) to large ($d \geq 1.2$; $r \geq 0.5$) effect size

the post24-HIT. However, the extent of the recovery, when compared to baseline, was far less pronounced.

Intermittent Contraction Test

Again, every subject in the experimental group had a reduction in ICT impulse post-HIT and a recovery post24-HIT; there was a significant difference between the three assessment time periods (repeated measures ANOVA, $P < 0.001$, $\eta_p^2 = 0.80$, Fig. 3). In post hoc analysis, their ICT impulse decreased significantly by 59% between pre-HIT ($M = 821.67$, $SD = 234.65$) and post-HIT ($M = 336.25$, $SD = 69.09$), $P < 0.001$, $d = 2.67$; and significantly by 22%

between pre-HIT and pos24 HIT ($M=639.97$, $SD=163.84$), $P=0.016$, $d=1.00$. In the control group, the ICT impulse decreased by 1% between the pre-HIT ($M=1008.40$, $SD=516.09$) and post-HIT ($M=1003.20$, $SD=444.72$), $P=0.947$, $d=0.03$. Compared to MVC or the SCT, the ICT had the smallest post24-HIT recovery.

Climbing Ability

The SCT was the best indicator for redpoint grade as provided by the questionnaire (Table 1). ICT was also significantly related to redpoint grade (Table 1). MVC, while not significant ($P=0.86$), provided a medium effect size (Table 1). For the NIRS parameter, only SmO_2min provided a medium effect size but was not sufficiently large to yield a significant result (Table 1). SmO_2rest and SmO_2HTR both provide little explanation for the resulting redpoint grade (Table 1).

Near-Infrared Spectroscopy

SmO_2min

Eight of 10 participants showed an increase in SmO_2min post-HIT and a return to pre-HIT values in the post24-HIT; there was no significant effect, but a large effect size (three time points, repeated-measures ANOVA, $P=0.137$, $\eta_p^2=0.20$, Fig. 4). In post hoc analysis, SmO_2min increase showed a non-significant small effect size between pre-HIT ($M=19.56$, $SD=5.77$) and post-HIT ($M=24.81$, $SD=7.88$),

$P=0.303$, $d=0.55$; and no change between pre-HIT and post24 HIT ($M=19.00$, $SD=8.40$), $P=0.999$, $d=0.06$. In the control group, a small change in SmO_2min for the pre-HIT ($M=19.05$, $SD=5.23$) and post-HIT ($M=17.83$, $SD=4.10$) was documented, in the opposite direction of the experimental group, $P=0.415$, $d=0.33$. For SmO_2min Pearson correlation analysis between pre-HIT SmO_2min and impulse resulted in medium effect size, $r=-0.41$, $P=0.102$, but not significant (Fig. 4). The change in SmO_2min between pre-HIT and post-HIT when set in relation to the change in impulse for the same timeframe yielded significant results, $r=-0.73$, $P=0.016$ (Fig. 4).

SmO_2rest

Nine of ten participants showed an increase in SmO_2rest post-HIT and a return to pre-HIT values in the post24-HIT; there was a significant difference between the three assessment time periods (three time points, repeated-measures ANOVA, $P=0.002$, $\eta_p^2=0.50$, Fig. 4). In post hoc analysis, SmO_2rest increased significantly between pre-HIT ($M=54.68$, $SD=6.62$) and post-HIT ($M=63.58$, $SD=7.22$), $P=0.004$, $d=1.21$; and no change between pre-HIT and post24-HIT ($M=55.60$, $SD=4.44$), $P=0.999$, $d=0.13$. In the control group, a non-significant change in SmO_2rest for the pre-HIT ($M=54.48$, $SD=4.14$) and post-HIT ($M=50.72$, $SD=4.11$) was documented, in the opposite direction of the experimental group, $P=0.104$, $d=0.72$. For SmO_2rest Pearson correlation analysis between pre-HIT SmO_2rest and impulse yielded moderate results, $r=-0.36$, $P=0.154$ (Fig. 4). The change in SmO_2rest between pre-HIT and post-HIT when set in relation to the change in impulse for the same timeframe yielded no significant results, $r=-0.01$, $P=0.098$ (Fig. 4).

SmO_2HTR

Eight of 10 participants showed an increase in SmO_2HTR post-HIT and a return to pre-HIT values in the post24-HIT; there was no significant effect, but a large effect size (three time points, repeated-measures ANOVA, $P<0.229$, $\eta_p^2=0.17$, Fig. 4). In post hoc analysis, SmO_2HTR increase showed a non-significant small effect size between pre-HIT ($M=12.19$, $SD=2.40$) and post-HIT ($M=14.71$, $SD=6.73$), $P=0.686$, $d=0.42$; and no change between pre-HIT and pos24 HIT ($M=11.19$, $SD=2.56$), $P=0.999$, $d=0.17$. Change in the control group, while much smaller in the mean difference, yielded a greater effect size because of a much smaller variation (control pre-HIT: $M=12.51$, $SD=3.05$; control post-HIT: $M=11.34$, $SD=3.76$), $P=0.140$, $d=0.64$. However, in the case of the control group SmO_2HTR decreased. The Pearson correlation

Table 1 Pairwise Pearson product-moment correlation table

	Pearson's r	P	Lower 95% CI	Upper 95% CI
Redpoint Grade				
MVC	0.429†	0.86	-0.065	0.754
Impulse SCT	0.685*†	0.002	0.304	0.877
Impulse ICT	0.492*†	0.045	-0.015	0.787
SmO_2min	-0.428†	0.086	-0.754	0.066
SmO_2rest	-0.278	0.28	-0.669	0.234
SmO_2HTR	-0.010	0.972	-0.488	0.503
MVC				
Impulse SCT	0.418†	0.095	-0.079	0.748
Impulse ICT	0.285	0.267	-0.226	0.856
Impulse SCT				
Impulse ICT	0.638*†	0.006	0.226	0.856

MVC Maximum voluntary contraction, SCT Sustained contraction test, ICT Intermittent contraction test, SmO_2min minimally attained muscle oxygenation, SmO_2rest resting muscle oxygenation, SmO_2HTR half time recovery of SmO_2

*indicates significance at $P<0.05$

†indicates medium ($r \geq 0.3$) to large ($r \geq 0.5$) effect size

analysis between pre-HIT SmO_2HTR and impulse yielded a small relationship, $r=0.11$, $P=0.675$ (Fig. 4). The change in SmO_2HTR between pre-HIT and post-HIT, when set in relation to the change in impulse for the same timeframe provided, while not significant, a small effect size, $r=-0.27$, $P=0.479$ (Fig. 4).

Power

Because of the small sample size used in the study, and the loss of participants for the reasons explained earlier, a post hoc power analysis was conducted in order to determine achieved power; in order to put the results in proper perspective. Across impulse data, if considering the minimum effect size of $d=1.67$ and a sample of 10 participants, sufficient power can be assumed. However, when looking across the SmO_2 data effect sizes are smaller at minimum $d=0.42$ for the experimental sample of 10 participants. This results in a power being achieved of 0.34. This highlights a lack of power for the interpretation of at least some of the SmO_2 data. Due to the highly skilled nature of the participants, a small sample size was expected and is nonetheless considered warranted for the study.

Discussion

The main findings of the study were the significant change in both MVC and impulse during a climbing endurance task following HIT. The novel findings are the dissociation between recovery of MVC after a 24 h time period and both SCT and ICT in the same time period, with a significant portion of variance being observed explained through a change in SmO_2min .

The strength and endurance assessments identified an acute specific performance deterioration after HIT. When comparing the experimental group with the control group, this effect is clear, with the experimental group reducing performance in the MVC, SCT, and ICT by 18%, 55%, and 59%, respectively; while the control group saw performance reductions of just 4%, 9%, and 1%. The fact that both endurance tests show large reductions in performance, even after 24 h of rest, while the MVC test did not, further highlights the importance of performance and recovery tracking as different training modes can result in different performance effects. These results are consistent with findings in other sports that show a larger effect of HIT on endurance performance when compared to strength performance (e.g., De Souza et al. [37]). The same is true for simply changing the length of intervals, with longer intervals showing extended delay in peripheral fatigue when compared to shorter intervals [14]. While the exact mechanisms are unclear, this

effect has been attributed to low-frequency fatigue, caused by a decreased Ca^{2+} release from the sarcoplasmic reticulum [23]. This study is the first to show the effect of HIT on climbing finger strength and endurance.

In order to address the black box of physiological mechanisms behind the change in force seen as a result of the HIT intervention, NIRS was used to assess the SCT. Numerous studies have linked changes in NIRS derived SmO_2 signals to changes in oxidative capacity and high energy phosphate availability and recovery [27, 35]. While the SmO_2 data alone is not as conclusive as the force data, a clear trend, with adequate effect sizes, is visible. Both of the SmO_2 derived indicators of oxidative capacity show the same mean response with an increase in SmO_2min and SmO_2HTR after the HIT. These SmO_2 metrics have been tightly linked to performance [16, 17, 31] and changes in these metrics with changes in performance [22]. It must be stated, however, that these responses alone lack statistical strength; despite the numerous referenced findings, this study cannot definitively conclude that either of the aforementioned indicators of oxidative capacity, as they stand alone, reflect performance in the form of SCT. On the other hand, the change in SmO_2rest reported matches findings that intensive muscle contractions result in an acute increase in SmO_2rest [1, 2].

What we see is that the SmO_2 metrics alone do not strongly reflect performance. While SmO_2min had a medium effect size in this study, it is not to be viewed with high confidence due to high variability, something previously reported in climbing NIRS data [3]. This despite the fact that it has been shown that VO_2max and maximal oxygen desaturation are correlated [31]; this relationship between desaturation and performance appears to be less profound in climbing specific tasks, as in the current study. Alternatively, Fryer and colleagues [16] demonstrated differences in total SmO_2 desaturation in climbers of four different ability levels. Perhaps, a more heterogeneous subject pool with a greater range in climbing performance than in the current study would mark a greater relationship between SmO_2 metrics and climbing ability, as reported by Fryer et al. [16]. What appears to be of greater value is the relative change in individual SmO_2 metrics in relation to change in performance, specifically the increase in SmO_2min , which was highly significant in correlation to the loss in performance. This increased explanatory power to address change in performance is true for all three SmO_2 metrics; SmO_2min , SmO_2rest , and SmO_2HTR .

Study limitations in regard to the NIRS data collected need to be addressed. Only results of the SCT were evaluated. This was because of the low sampling rate of the device used, which would make the analysis of the ICT nonsensical. The fact that the ICT has been correlated to the actual climbing ability to a higher degree than a simple SCT [33], assessing this test with NIRS data could shed more light on

the effect of climbing training. It should be noted that in this study SCT showed a stronger correlation to climbing ability than ICT, even though both were significant. SmO₂HTR data was collected using a different method compared to Fryer and colleagues [17], who identified the relationship between oxidative capacity and climbing performance. Rather than using an arterial occlusion method, we choose to use an athlete and training-friendly option of an extended isometric contraction in the form of the SCT. While using an isometric contraction to assess SmO₂HTR recovery has been shown as effective in other studies [25], this should nonetheless be noted because, unlike Fryer and colleagues [17], we did not find a relationship between SmO₂HTR and redpoint grade. Using an isometric hold rather than an arterial occlusion would increase in-field usability as it could be assessed during a relevant climbing test, rather than a standalone test requiring a high-quality pressure cuff, but reliability and validity are questionable. The large increase in muscle oxygen consumption as a result of the isometric contraction, rather than just stopping oxygen supply through a cuff occlusion is likely the reason for the discrepancy seen.

Conclusions

This study presents novel findings on the deteriorating effects of HIT on finger flexor performance. Particularly endurance-related measures are affected to a greater extent than MVC. This effect is not only observable immediately after HIT, but SCT and ICT performance remain depressed even 24 h after the HIT. This performance loss is reflected by dynamics in SmO₂, and, specifically, SmO₂min appears suitable to assess performance loss and recovery. What appears to be highly relevant is the tracking of SmO₂ metrics, as the change in SmO₂ metrics resulting from training is more suited to assess a potential state of athlete readiness. In this way, a finger hang test alone in addition to SmO₂ dynamics could be used to assess recovery time frames following intensive training: which in many cases may be greater than 24 h.

Acknowledgements The research was supported by Idiag AG (CH). We would like to thank colleagues from our institutions for the know-how and insight which helped in the development of procedures and data collection and analysis. Specifically, we would like to thank Robert Simpson and Robin Staehli for software and hardware development.

Funding Open Access funding provided by Universität Bern.

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References

- Ahmadi S, Sinclair PJ, Davis GM. Muscle oxygenation after downhill walking-induced muscle damage. *Clin Physiol Funct Imaging*. 2007;28:071115151053003. <https://doi.org/10.1111/j.1475-097X.2007.00777.x>.
- Ahmadi S, Sinclair PJ, Foroughi N, Davis GM. Monitoring muscle oxygenation after eccentric exercise-induced muscle damage using near-infrared spectroscopy. *Appl Physiol Nutr Metab*. 2008;33(4):743–52. <https://doi.org/10.1139/h08-048>.
- Baláš J, Kodejška J, Krupková D, Hannsmann J, Fryer S. Reliability of near-infrared spectroscopy for measuring intermittent handgrip contractions in sport climbers. *J Strength Cond Res*. 2017;32(2):1.
- Baláš J, Michailov M, Giles D, Kodejška J, Panáčková M, Fryer S. Active recovery of the finger flexors enhances intermittent handgrip performance in rock climbers. *Eur J Sport Sci*. 2016;16(7):764–72. <https://doi.org/10.1080/17461391.2015.1119198>.
- Baláš J, Pecha O, Martin AJ, Cochrane D. Hand–arm strength and endurance as predictors of climbing performance. *Eur J Sport Sci*. 2012;12(1):16–25. <https://doi.org/10.1080/17461391.2010.546431>.
- Bentley DJ, Smith PA, Davie AJ, Zhou S. Muscle activation of the knee extensors following high intensity endurance exercise in cyclists. *Eur J Appl Physiol*. 2000;81(4):297–302.
- Bishop PA, Jones E, Woods AK. Recovery from training: A brief review. *J Strength Cond Res*. 2008;22(3):1015–24. <https://doi.org/10.1519/JSC.0b013e31816eb518>.
- Davies RC, Eston RG, Poole DC, Rowlands AV, DiMenna F, Wilkerson DP, Twist C, Jones AM. Effect of eccentric exercise-induced muscle damage on the dynamics of muscle oxygenation and pulmonary oxygen uptake. *J Appl Physiol* (1985). 2008;105(5):1413–21. <https://doi.org/10.1152/jappphysiol.90743.2008>.
- Della Corte J, Rangel L, de Souza Vale RG, Braga De Mello D, Marcos-Pardo PJ, Rosa G. Does high intensity interval training (HIIT) affect strength training performance? *Arch Med Deport*. 2019;36:8–12.
- Deyhle MR, Hsu HS, Fairfield TJ, Cadez-Schmidt TL, Gurney BA, Mermier CM. Relative importance of four muscle groups for indoor rock climbing performance. *J Strength Cond Res*. 2015;29(7):2006–14. <https://doi.org/10.1519/JSC.0000000000000823>.
- Draper N, Dickson T, Blackwell G, Fryer S, Priestley S, Winter D, Ellis G. Self-reported ability assessment in rock climbing. *J Sports Sci*. 2011;29(8):851–8.
- España-Romero V, Ortega Porcel FB, Artero EG, Jiménez-Pavón D, Gutiérrez Sainz Á, Castillo Garzón MJ, Ruiz JR. Climbing time to exhaustion is a determinant of climbing performance in high-level sport climbers. *Eur J Appl Physiol*. 2009;107(5):517–25. <https://doi.org/10.1007/s00421-009-1155-x>.
- Feldmann A, Schmitz R, Erlacher D. Near-infrared spectroscopy-derived muscle oxygen saturation on a 0% to 100% scale: reliability and validity of the Moxy Monitor. *J Biomed Opt*. 2019;24(11):1. <https://doi.org/10.1117/1.JBO.24.11.115001>.
- Froyd C, Beltrami FG, Millet GY, MacIntosh BR, Noakes TD. Greater short-time recovery of peripheral fatigue after

- short-compared with long-duration time trial. *Front Physiol.* 2020;11:399. <https://doi.org/10.3389/fphys.2020.00399>.
15. Fryer S, Giles D, Palomino IG, Puerta A de la O, Romero VE. Hemodynamic and cardiorespiratory predictors of sport rock climbing performance. *J Strength Cond Res.* 2018;32(12):3534–41. <https://doi.org/10.1519/JSC.0000000000001860>.
 16. Fryer S, Stoner L, Scarrott C, Lucero A, Witter T, Love R, Dickson T, Draper N. Forearm oxygenation and blood flow kinetics during a sustained contraction in multiple ability groups of rock climbers. *J Sports Sci.* 2015;33(5):518–26. <https://doi.org/10.1080/02640414.2014.949828>.
 17. Fryer S, Stoner L, Stone K, Giles D, Sveen J, Garrido I, España-Romero V. Forearm muscle oxidative capacity index predicts sport rock-climbing performance. *Eur J Appl Physiol.* 2016;116(8):1479–84. <https://doi.org/10.1007/s00421-016-3403-1>.
 18. Giles D, Romero VE, Garrido I, de la O Puerta A, Stone K, Fryer S. Differences in oxygenation kinetics between the dominant and nondominant flexor digitorum profundus in rock climbers. *Int J Sports Physiol Perform.* 2017;12(1):137–9. <https://doi.org/10.1123/ijsp.2015-0651>.
 19. Giovannelli N, Biasutti L, Salvadego D, Alemayehu HK, Grassi B, Lazzer S. Changes in skeletal muscle oxidative capacity after a trail-running race. *Int J Sports Physiol Perform.* 2020;15(2):278–84. <https://doi.org/10.1123/ijsp.2018-0882>.
 20. Grassi B, Quaresima V. Near-infrared spectroscopy and skeletal muscle oxidative function in vivo in health and disease: a review from an exercise physiology perspective. *J Biomed Opt.* 2016;21(9):091313. <https://doi.org/10.1117/1.JBO.21.9.091313>.
 21. Green HJ. Mechanisms of muscle fatigue in intense exercise. *J Sports Sci.* 1997;15(3):247–56. <https://doi.org/10.1080/026404197367254>.
 22. Jones B, Hamilton DK, Cooper CE. Muscle oxygen changes following sprint interval cycling training in elite field hockey players. *PLoS One.* 2015;10:e0120338. <https://doi.org/10.1371/journal.pone.0120338>.
 23. Keeton RB, Binder-Macleod SA. Low-frequency fatigue. *Phys Ther.* 2006;86(8):1146–50.
 24. Kellmann M, Kölling S. Recovery and stress in sport a manual for testing and assessment. Routledge: Taylor & Francis Group; 2019.
 25. Kime R, Hamaoka T, Sako T, Murakami M, Homma T, Katsumura T, Chance B. Delayed reoxygenation after maximal isometric handgrip exercise in high oxidative capacity muscle. *Eur J Appl Physiol.* 2003;89(1):34–41. <https://doi.org/10.1007/s00421-002-0757-3>.
 26. Knudson D. Significant and meaningful effects in sports biomechanics research. *Sport Biomech.* 2009;8(1):96–104. <https://doi.org/10.1080/14763140802629966>.
 27. McCully KK, Iotti S, Kendrick K, Wang Z, Posner JD, Leigh J, Chance B. Simultaneous in vivo measurements of HbO₂ saturation and PCr kinetics after exercise in normal humans. *J Appl Physiol* (1985). 1994;77(1):5–10. <https://doi.org/10.1152/jappl.1994.77.1.5>.
 28. Mermier CM. Physiological and anthropometric determinants of sport climbing performance. *Br J Sports Med.* 2000;34(5):359–65. <https://doi.org/10.1136/bjism.34.5.359>.
 29. Michailov ML. Workload characteristic, performance limiting factors and methods for strength and endurance training in rock climbing. *Med Sport.* 2014;18(3):12–5.
 30. Michailov ML, Baláš J, Tanev SK, Andonov HS, Kodejška J, Brown L. Reliability and validity of finger strength and endurance measurements in rock climbing. *Res Q Exerc Sport.* 2018;89(2):246–54. <https://doi.org/10.1080/02701367.2018.1441484>.
 31. Okushima D, Poole DC, Barstow TJ, Rossiter HB, Kondo N, Bowen TS, Amano T, Koga S. Greater V̇O₂peak is correlated with greater skeletal muscle deoxygenation amplitude and hemoglobin concentration within individual muscles during ramp-incremental cycle exercise. *Physiol Rep.* 2016;4(23):e13065. <https://doi.org/10.14814/phy2.13065>.
 32. Panissa VLG, Cal Abad CC, Julio UF, Andreato LV, Franchini E. High-intensity intermittent exercise and its effects on heart rate variability and subsequent strength performance. *Front Physiol.* 2016;7:81. <https://doi.org/10.3389/fphys.2016.00081>.
 33. Philippe M, Wegst D, Müller T, Raschner C, Burtscher M. Climbing-specific finger flexor performance and forearm muscle oxygenation in elite male and female sport climbers. *Eur J Appl Physiol.* 2012;112(8):2839–47. <https://doi.org/10.1007/s00421-011-2260-1>.
 34. Ryan TE, Erickson ML, Brizendine JT, Young H-J, McCully KK. Noninvasive evaluation of skeletal muscle mitochondrial capacity with near-infrared spectroscopy: correcting for blood volume changes. *J Appl Physiol* (1985). 2012;113(2):175–83. <https://doi.org/10.1152/japplphysiol.00319.2012>.
 35. Ryan TE, Southern WM, Reynolds MA, McCully KK. A cross-validation of near-infrared spectroscopy measurements of skeletal muscle oxidative capacity with phosphorus magnetic resonance spectroscopy. *J Appl Physiol* (1985). 2013;115(12):1757–66. <https://doi.org/10.1152/japplphysiol.00835.2013>.
 36. Sheel AW. Physiology of sport rock climbing. *Br J Sports Med.* 2004;38(3):355–9. <https://doi.org/10.1136/bjism.2003.008169>.
 37. De Souza EO, Tricoli V, Franchini E, Paulo AC, Regazzini M, Ugrinowitsch C. Acute effect of two aerobic exercise modes on maximum strength and strength endurance. *J Strength Cond Res.* 2007;21(4):1286–90. <https://doi.org/10.1519/R-20686.1>.
 38. Watts P, Jensen R, Gannon E, Kobeinia R, Maynard J, Sansom J. Forearm EMG during rock climbing differs from EMG during handgrip dynamometry. *Int J Exerc Sci.* 2008. Available from: <https://digitalcommons.wku.edu/ijes/vol1/iss1/2>. Accessed 14 Sept 2020.
 39. Westerblad H, Bruton JD, Katz A. Skeletal muscle: energy metabolism, fiber types, fatigue and adaptability. *Exp Cell Res.* 2010;316(18):3093–9. <https://doi.org/10.1016/j.yexcr.2010.05.019>.
 40. Whittaker RL, Sonne MW, Potvin JR. Ratings of perceived fatigue predict fatigue induced declines in muscle strength during tasks with different distributions of effort and recovery. *J Electromyogr Kinesiol.* 2019;47:88–95. <https://doi.org/10.1016/j.jelekin.2019.05.012>.