ORIGINAL ARTICLE

Measuring critical force in sport climbers: a validation study of the 4 min all-out test on finger flexors

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Abstract

Purpose The critical force (CF) concept, differentiating steady and non-steady state conditions, extends the critical power paradigm for sport climbing. This study aimed to validate CF for finger flexors derived from the 4 min all-out test as a boundary for the highest sustainable work intensity in sport climbers.

Methods Twelve participants underwent multiple laboratory visits. Initially, they performed the 4 min intermittent contraction all-out test for CF determination. Subsequent verification visits involved finger-flexor contractions at various intensities, including CF, CF −2 kg, CF −4 kg, and CF −6 kg, lasting for 720 s or until failure, while monitoring muscle-oxygen dynamics of forearm muscles.

Results CF, determined from the mean force of last three contractions, was measured at 20.1 ± 5.7 kg, while the end-force at 16.8 ± 5.2 kg. In the verification trials, the mean time to failure at CF was 440 ± 140 s, with only one participant completing the 720 s task. When the load was continuously lowered (−2 kg, −4 kg, and −6 kg), a greater number of participants (38%, 69%, and 92%, respectively) successfully completed the 720 s task. Changes of muscle-oxygen dynamics showed a high variability and could not clearly distinguish between exhaustive and non-exhaustive trials.

Conclusions CF, based on the mean force of the last three contractions, failed to reliably predict the highest sustainable work rate. In contrast, determining CF as the end-force of the last three contractions exhibited a stronger link to sustainable work. Caution is advised in interpreting forearm muscle-oxygen dynamics, lacking sensitivity for nuanced metabolic responses during climbing-related tasks.

Keywords NIRS · Critical power · Isometric contraction · Muscle oxygen · Intermittent exercise · Threshold

Abbreviations

ANOVA	Analysis of variance
CI	Confidence interval
CF	Critical force calculated as the mean force from the last three contractions
CF_{720}	Critical force calculated as the highest force that participants were able to tolerate for 720 s
CF_{min}	Critical force calculated as end-force from the last three contractions
CP	Critical power
CV	Coefficient of variation
ICC	Intraclass correlation coefficient
MVC	Maximal voluntary contraction
NIRS	Near-infra red spectroscopy
R	Pearson correlation coefficient
R^2	Coefficient of determination
RPE	Rate of perceived exertion
O_2	Oxygen
SD	Standard deviation
StO_2	Muscle oxygen saturation
W	Impulse from all contractions in the all-out test
W'	Impulse from all contractions in the all-out test over the critical force
RFD	Rate of force development

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Introduction

Sport climbing, a highly technical activity, places significant stress on the forearm flexors. Extensive research has emphasized the critical role of maximal finger-flexor strength and endurance as reliable predictors of climbing ability (Langer et al. 2023; Stien et al. 2022). Notably, research has shown that climbing-specific tests, including both whole-body climbing and isolated finger-flexor tests, demonstrate high predictability for sport climbing performance (Baláš et al. 2021). Various tests involving continuous and intermittent finger-flexor contractions at different intensities have been proposed (Fryer et al. 2015; Limonta et al. 2016; Michailov et al. 2018; Vigouroux and Quaine 2006). Despite efforts to explore the metabolic contributions of sustained and intermittent contractions (Maciejczyk et al. 2022), these tests face limitations in their transferability to prescribing training intensity, as they do not allow for the determination of intensities in metabolic steady and non-steady states.

Understanding maximal exercise intensity steady state is an important threshold concept in exercise performance. The concept of critical power (CP) directly addresses this exercise state defined as the highest exercise intensity that can be sustained for a significant duration of time or physiologically as the highest metabolic rate that can be maintained by supplied oxygen (O_2) consumption (Poole et al. 2016). Recent developments in climbing research have introduced the concept of critical force (CF) as a metabolic threshold between steady and non-steady state conditions, and an extension of the CP paradigm for sport climbing (Baláš et al. 2022; Giles et al. 2019, 2021). The application of multisession three tasks to failure and the 4 min all-out test has been employed to determine CF on a hangboard (Giles et al. 2019, 2021). In addition, exhaustive climbs at varying wall angles aimed to establish the critical angle as a parallel concept to CP (Baláš et al. 2022). Climbers performing the ascent 2° under critical angle sustained the task for 20 min with moderate perceived exertion, while those climbing 2° above critical angle failed approximately 16 min with higher perceived exertion. Notably, these validations have not been conducted for CF determined from hangboard tests, with only criterion validity against self-reported climbing ability reported. Given the integral role of hangboard training in climbing-specific strength training (Levernier and Laffaye 2019; Medernach et al. 2015), the prescription of appropriate intensity based on a simple diagnostic like the 4 min all-out test becomes crucial. Therefore, the determination of whether CF from the all-out test represents a boundary between localized steady and non-steady conditions is yet to be elucidated.

The 3 min all-out substitute for conventional CP determination was first introduced by Burnley et al. (2006)

providing valid estimate of the maximal steady state in cycling. Most participants managed to complete 30 min of exercise at 15 W below the end-test power. In contrast, exercising at 15 W above the end-test power, blood lactate and O_2 uptake rose inexorably until exhaustion, which occurred in approximately 13 ± 7 min. At a localized level, intermittent handgrip contractions at 15% and 30% under CF from the 5 min all-out test were sustained for 15 min, maintaining an apparent steady state of muscle-O_2 saturation (StO_2) (Hammer et al. 2020). Conversely, contractions at 15% and 30% above the CF led to time failure in 602 s and 342 s, respectively, accompanied by a progressive drop in StO_2 (Hammer et al. 2020). However, conflicting research suggests that the 3 min all-out test either fails to provide accurate estimates of CP (Kalva et al. 2017), with a general tendency to overestimates (Bartram et al. 2017; Karsten et al. 2014). The reason for this discrepancy, likely rooted in the impossibility of sustaining maximal effort for extended periods (Dotan 2022), remains unexplored. Recent discussions ponder whether the CP concept reflects the upper boundary of metabolic steady state (Jones et al. 2019) or if it represents a distinct entity, deviating from the original theory that CP is the highest work rate sustainable without fatigue for an extended duration (Dotan 2022).

The boundary between the heavy and severe exercise intensity domain is considered to represent the transition between sustainable and unsustainable exercise intensity. Various concepts like maximal lactate steady state, respiratory compensation point, deoxy [heme] and StO_2 localized threshold, and CP serve as markers for this transition. While these concepts share mechanistic principles, their alignment is often lacking. The proposed gray zone (Ozkaya et al. 2022) addresses the gap between commonly used maximal intensity thresholds with CP at the top end and maximal lactate steady state at the bottom end. While these thresholds all are correlated (Caen et al. 2022), they are not interchangeable. To address the boundary between sustainable and unsustainable exercise intensity in climbing-specific conditions, systemic variables (maximal lactate steady state, respiratory compensation point) have not proved valid (Baláš et al. 2021), and assessing localized muscle-O_2 supply and metabolic O_2 demands using NIRS (Hammer et al. 2020; Kirby et al. 2021) appears to be the only method to delineate forearm exercise intensity except for CF.

The use of the all-out test to determine CF of finger flexors in climbing is appealing due to its simplicity, however, this test differs from previous forearm all-out tests (Hammer et al. 2020; Kellawan and Tschakovsky 2014) by incorporating longer static contractions in the work:relief cycles and involving upper limb positions overhead, which may limit blood flow and O_2 delivery. Moreover, during repeated 7 s contractions, fatigue associated with partial vascular occlusion may lead to a continuous drop in applied force within

each contraction (Sadamoto et al. 1983), and the mean end-force might not represent the best estimate of CF.

Therefore, the study aimed to verify the concept of CF for finger flexors determined from the 4 min all-out test as a boundary for highest sustainable work intensity in sport climbers. In addition, the study seeks to explore, whether NIRS derived muscle oxygenation is useful in delineating this boundary. We hypothesized that CF, determined as the mean force from the last three contractions of the 4 min all-out test, overestimates the highest sustainable intensity in sport climbers. Furthermore, we expected that muscle-O_2 dynamics would clearly delineate sustainable and non-sustainable exercise intensities of finger flexors.

Methods

Participants

Twelve intermediate to elite sport climbers (10 males and 2 females, 27.2 ± 7.4 years) volunteered to participate in this study. All participants were healthy nonsmokers, not taking any medications, and were required to refrain from strenuous physical activity 24 h before testing and caffeine 12 h prior to testing to prevent any potential ergogenic effects (Guest et al. 2021; Saraiva et al. 2023). They were instructed to maintain consistent activity, diet, and caffeine habits throughout the study. Anthropometric and training characteristics are detailed in Table 1. The study was approved by institutional Ethics Committee in accordance with the Declaration of Helsinki. All participants were informed of the risks of the experiment and signed an informed consent.

Design

Participants visited the laboratory five to six times separated by 3–6 days. During their first visit, they completed questionnaires concerning their ability level, climbing preferences and experience and undertook anthropometric

Table 1 Training and performance characteristics of participants data are reported as means ± SD

Body mass (kg)	68.8 ± 10.8
Height (cm)	176.1 ± 7.7
F_{max} (kg)	53.8 ± 17.0
Climbing experience (years)	11.6 ± 6.8
Climbing ability – lead climbing (IRCRA scale)	19 ± 4
Climbing training (sessions/week)	2.8 ± 1.5
Climbing training (hours/week)	4.9 ± 3.3

F_{max} refers to finger-flexor maximal voluntary contraction of dominant hand. IRCRA scale indicates International Rock Climbing Research Association universal scale for sport climbing ascents

measurements (body mass, height). After a warm-up procedure similar to that described by Baláš et al. (2016): 5 min of stair walking, 5 min mobilizing exercises, 5 min traversing on the climbing wall and 5 min individual intermittent hanging on wooden rung), participants completed the test of finger-flexor maximal voluntary contraction (MVC) and 4 min finger-flexor all-out test to determine CF. Subsequent visits involved participants performing finger-flexor contractions at various intensities, including CF, CF −2 kg, CF −4 kg, and CF −6 kg, for 12 min or until failure. An additional visit was conducted with CF −8 kg for a participant unable to sustain CF −6 kg.

Finger-flexor tests

All finger-flexor tests were conducted using a climbing-specific handgrip dynamometer (1D–SAC, Spacelab, Sofia, Bulgaria). Participants utilized a half-crimp grip position on a 23 mm deep wooden hold with 10 mm radius, excluding the thumb. Tests were performed in a standing position, with the dominant hand and arms at approximately 180° shoulder flexion, elbow slightly flexed. Participants were instructed to progressively transfer their weight ("hang") on the wooden rung to develop as much force as possible or to attain the target force as quickly as possible. The detail-testing methodology is described elsewhere (Michailov et al. 2018).

Maximal finger-flexor strength

Maximal finger-flexor strength (in kg) was assessed through the MVC of the finger flexors, involving a 5 s hang on the wooden rung with the dominant hand. The highest peak value from the two trials was considered as maximal finger-flexor strength. The unit kg was used for all finger-strength measurements for easier interpretation of verification trials and comparisons with the original study on CF in climbing (Giles et al. 2021).

All-out test

The four-minute all-out test was conducted at a work:relief ratio of 7:3 s as proposed by Giles et al. (2021). During the work phase, participants were instructed to produce as much force as possible. During the relief phase, participants were allowed to shake their hand near the body to imitate real sport climbing conditions. In order to evaluate the CF, the mean force derived from the last 30 s of the test was defined (Kellawan and Tschakovsky 2014). Moreover, a decline in force is generally observed during the 7 s contractions. The mean force decrease from the last three contractions was labeled as $\Delta F_{max-min}$. In addition, the mean lowest force value from the last three contractions was referred as CF_{min} for further analysis. Impulse from all contractions (W) and

impulse over the CF (W') was calculated to approximate total muscle work and work related to energy store components (Bassan et al. 2019). Rate of force development (RFD) was calculated as the ratio between 50% peak force during a contraction and time to achieve it from the beginning of the contraction. The contraction times during the whole all-out test and last three contractions were computed to identify potential biases.

Verification of CF trials

To ensure the feasibility and tolerability of exercising at the CF intensity determined from the 4 min all-out test, a series of trials were conducted based on insights gained from previous piloting. Randomly assigned intensities, corresponding to CF or CF -2, -4, -6 kg, were applied during each of the four scheduled visits, all conducted at the same time of day. Participants were instructed to sustain intermittent finger-flexor 7:3 s contractions at the target intensity for 720 s or until failure. Following the completion of each trial, participants promptly provided their rate of perceived exertion (RPE) on a scale ranging from 6 to 20. The selection of a 720 s duration for the test was guided by previous piloting, considering that longer durations often resulted in mechanical discomfort from repetitive contractions. This factor was deemed significant, especially given that such discomfort is not commonly encountered during actual climbing due to frequent changes in grip positions. The highest force that participants were able to tolerate for 720 s was termed as CF_{720}.

Near infrared spectroscopy

Muscle-O_2 dynamics during all tests were assessed using a continuous wave near infrared spectroscopy (NIRS) device (Portamon, Artinis Medical System, BV, Netherlands). The device was placed over the belly of the flexor digitorum profundus of the dominant hand, following the protocol outlined by Fryer et al. (2018). To minimize optode movement during arm movement and limit ambient light penetration, the device was secured with bi-adhesive tape from the interior and black tape and a black sleeve from the exterior. StO_2 was used to determine muscle-O_2 dynamics during all tests. Specific metrics extracted from the all-out test included the rate of StO_2 decrease during the first contraction ($StO_{2\,rate}$), maximal muscle-O_2 desaturation ($StO_{2\,min}$), changes in StO_2 during relief periods from intermittent contractions during last 30 s (three) contractions ($\Delta StO_{2\,relief}$) and mean StO_2 from the last 30 s ($StO_{2\,end}$) using 10 Hz sampling frequency. Notably, $StO_{2\,rate}$ was computed as % StO_2 decrease per second between 0.5 and 6.5 s of the first contraction to avoid possible signal noise at the beginning and the end of the contraction (Fig. 1). Data from verification trials were processed using a 10 s moving average

(1 work-relief cycle), and parameters such as StO_2 from the whole test ($StO_{2\,mean}$) and last 30 s of the test ($StO_{2\,end}$) were analyzed. In addition, the StO_2-delayed slope (%/min) for the delayed phase after the initial drop in StO_2 was calculated following the approach proposed by Kirby et al. (2021). Muscle-O_2 balance, quantified through the StO_2-delayed slope, establishes a dynamic physiologic threshold distinguishing between sustainable and unsustainable exercise, aligning with the concept of a "critical metabolic rate" and predicts depletion and repletion of finite work capacity and time to exhaustion (Kirby et al. 2021). However, the proposed initial starting time 60 s could not be used universally due longer time of the StO_2 restoration in some participants and the starting point was determined visually as depicted at Fig. 2. In climbing-specific settings, StO_2-delayed slope was successfully used to predict the time to exhaustion during sustained finger-flexor contraction (Gilic et al. 2023).

Statistical analysis

Descriptive statistics (mean ± SD) were used to characterize anthropometric, training, and performance characteristics in all climbers. The Shapiro–Wilk test and visual data inspection using Q–Q plots were conducted to assess data distribution for all variables. In instances where normal distribution was violated, non-parametric approaches were employed for inferential statistics. Differences between mean- and end-time and RFD at the beginning and end of the all-out tests were assessed using Wilcoxon signed-ranked test and paired t tests, respectively. The effect of intensity on muscle-O_2 dynamics (StO_2-delayed slope, $StO_{2\,mean}$, $StO_{2\,end}$ during all-out and verification tests was assessed using repeated measure ANOVA with pairwise comparisons employing Bonferroni corrections. The assumption of sphericity was assessed using Mauchly's test. In cases where the assumption was found to be significant, Huynh–Feldt adjustments were applied. To compare consistency between CF, CF_{min} and CF_{720}, intraclass correlation coefficient (ICC) with 95% confidence interval (95%CI), repeated measures analysis of variance and limits of agreement with 95%CI were calculated. The association between climbing ability and selected variables was assessed using Pearson correlation coefficient. More specifically, the relationship between $StO_{2\,rate}$, CF and fatigue index was computed using linear regression. Cohen's d for pairwise comparisons and partial eta squared (μ_p^2) were used to assess effect size, statistical significance was set to $P < 0.05$.
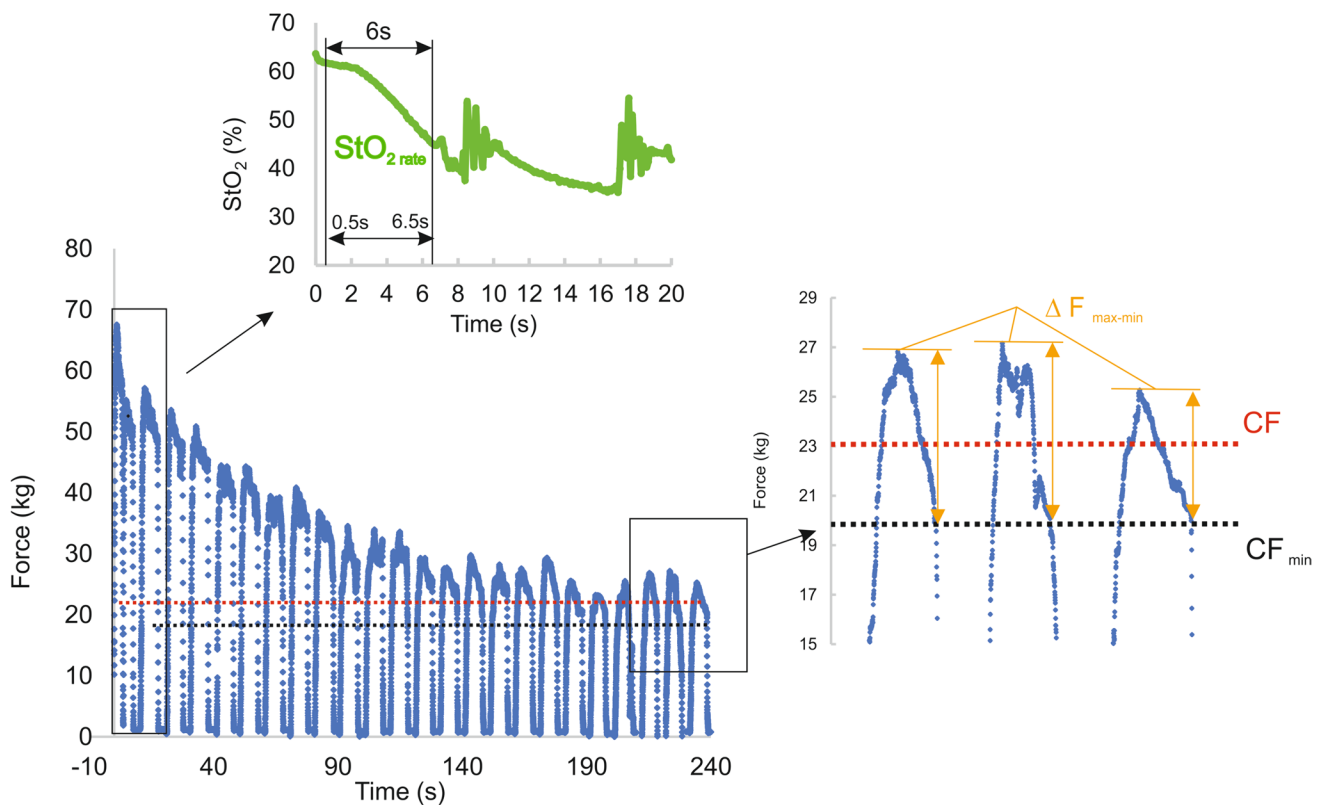
Fig. 1 Illustrative example of the all-out test. Red-dashed line represents critical force (CF) determined by the mean force of last three contractions. Black-dashed line represents critical force (CF_{min}) determined as the mean of end-force from the last three contractions. The green curve represents muscle-oxygen saturation (StO_2) changes during the first two contractions and relief cycles. The calculation of the StO_2 decrease ($StO_{2\ rate}$—%/s) was performed using the middle 6 s part of the first 7 s contraction

Results

All-out test

All participants exhibited a plateau of mean force at the end of the all-out test (Fig. 1). CF, determined from the mean force of last three contractions, was measured at 20.1 ± 5.7 kg, representing $38.8 \pm 8.8\%$ of maximal finger-flexor strength. A noticeable drop in force during the 7 s contraction attained 8.1 ± 3.2 kg in the last three contractions, leading the CF_{min} to be 3.3 kg lower than CF (Table 2). The time of the contraction at the end of the test did not differ ($P > 0.05$) from the overall mean contraction time ranging around 6.6 s. (Table 2), however a significant decrease of RFD was observed from the start to the end of the test ($P < 0.001$; $d = 1.65$).

W and CF normalized to body mass exhibited significant ($P < 0.05$) relationships with climbing ability ($R = 0.661$ for both W and CF). W' did not reach statistical significance ($P > 0.05$; $R = 0.552$). Notably, a stronger relationship to climbing ability was observed for CF_{min} ($R = 0.704$) and CF_{720} ($R = 0.699$) compared to CF. The $StO_{2\ rate}$ explained 44% and 50% of the variability in CF and CF_{min},

respectively, and exhibited a moderate correlation with the fatigue index (Fig. 3).

Verification trials

In the verification trials, the mean time to failure at CF was 440 ± 140 s, with only one participant completing the 720 s task. When the load was continuously lowered (−2 kg, −4 kg, and −6 kg), a greater number of participants (38%, 69%, and 92%, respectively) successfully completed the 720 s task. However, one participant achieved completion only with a load at CF −8 kg (67% of his CF) (Fig. 4).

CF_{720} was found to be significantly lower (−20%, −4 kg; $P < 0.001$) than CF, with only moderate consistency (ICC = 0.691; 95%CI 0.245 to 0.899) between the two variables. Conversely, no significant differences (0.7 kg; $P > 0.05$) and excellent consistency (ICC = 0.912; 95%CI 0.735 to 0.974) were observed between CF_{min} and CF_{720}. The limits of agreement are illustrated at Fig. 5.

The $StO_{2\ end}$ significantly increased from all-out test to CF−6 kg trial ($P = 0.042$, $\mu_p^2 = 0.24$). However, pairwise comparisons revealed the only significant difference between CF−6 kg and CF verification trials (6.6%; $P = 0.011$,
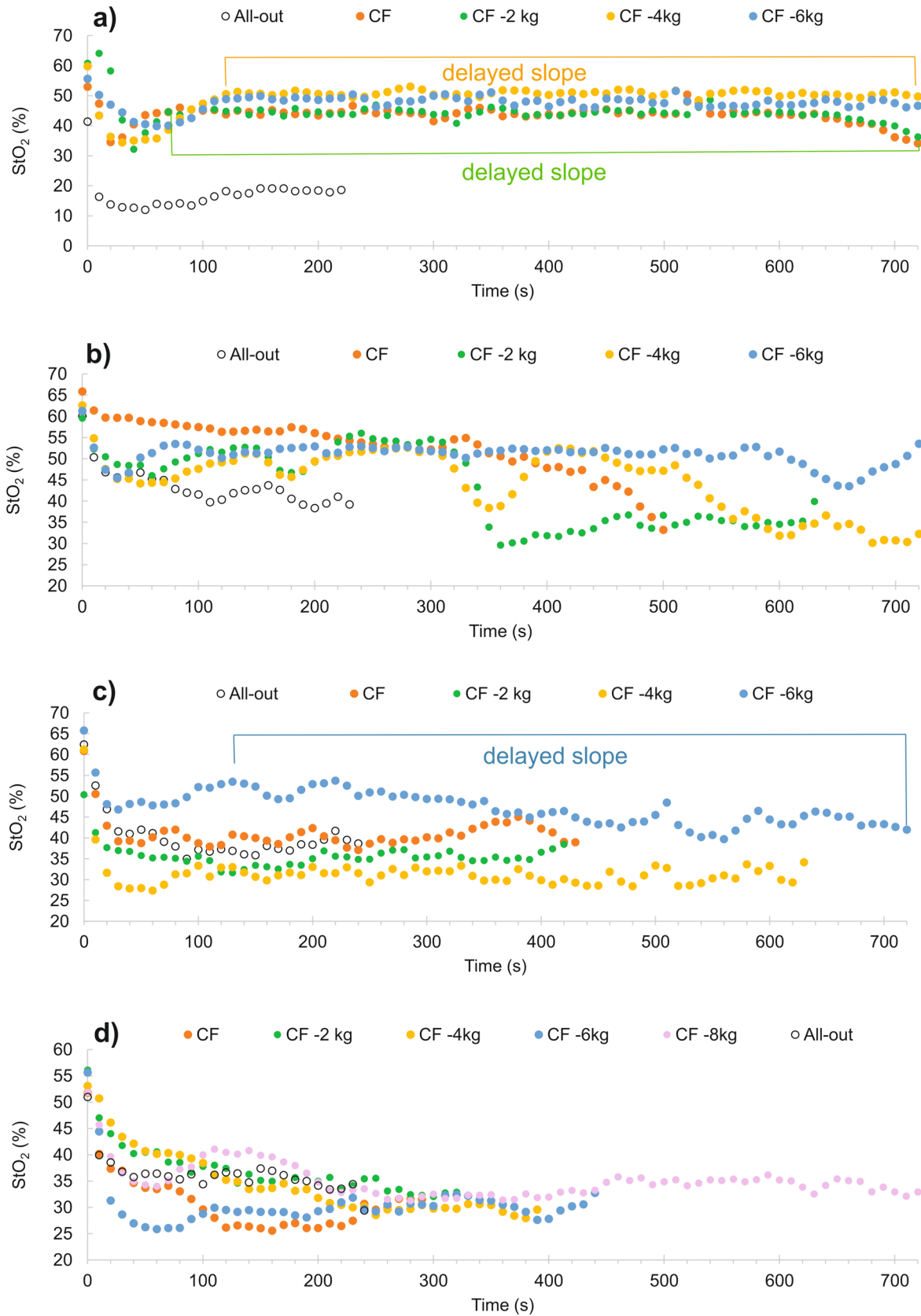
◄**Fig. 2** Illustrative examples of muscle-oxygen saturation (StO_2) from aggregated StO_2 signal (7 s contraction + 3 s rest) during the all-out tests and verification trials with examples of time periods for delayed slope calculations if the 60 s start-point was not used: **a** the only participant tolerating critical force (CF) for 720 s; **b** participant completing the whole verification trial at the intensity CF −4 kg; **c** participant completing the whole verification trial at the intensity CF-6 kg; **d** the only participant who was able to complete the whole verification trial at the intensity CF −8 kg

$d = 1.01$). No other pairwise differences were observed for $StO_{2\,end}$ (Fig. 6). In addition, the $StO_{2\,mean}$ showed a significant increase from the all-out test to CF−6 kg trial ($P = 0.006$, $\mu_p^2 = 0.27$); however, no pairwise comparisons reached significance ($P > 0.05$) (Fig. 6). Finally, StO_2-delayed slope did not exhibit statistically significant differences ($P > 0.05$) between verification trials due to high intraindividual variability, although trending to higher values with easier intensity (Fig. 6). In few participants, the StO_2 development showed irregular drops or increases (Fig. 2b, c), likely due to incontrollable grip and arm positions changes. The mean $StO_{2\,end}$ from the all-out was not related to values from the verification trials to failure at CF ($-2.4 \pm 7.5\%$; $R = 0.444$; $P > 0.05$) and often, lower $StO_{2\,end}$ have been found during verification trials than during the all-out tests (Fig. 2b, c, d). Contrary, in the only participant completing the whole 720 s-long verification trial at CF near exhaustion (RPE = 19), the $StO_{2\,end}$ was 13% higher at the exhaustive verification trial than during the all-out test (Fig. 2a).

Discussion

The study reveals several key findings: 1) CF determined as the mean force from the last three contractions of the 4 min all-out test fails to predict the highest sustainable work rate

Table 2 Mean ($\pm$ SD) force, time, and near infrared spectroscopy variables from the 4 min all-out test

CF – mean force from the last three contractions (kg)	20.1 ± 5.7
W '(kg.s)	1365 ± 512
W (kg.s)	4557 ± 1103
Mean contraction time whole test (s)	6.61 ± 0.19
Mean contraction time last three contractions (s)	6.59 ± 0.41
RFD first three contractions (kg/s)	107 ± 42
RFD last three contractions (kg/s)	57 ± 17
CF_{min} – end-force from the last three contraction (kg)	16.8 ± 5.2
CF_{720} (kg)	16.1 ± 4.4
$\Delta F_{max–min}$ – mean from last three contractions (kg)	8.1 ± 3.2
$StO_{2\,min}$ (%)	28.2 ± 8.7
$StO_{2\,end}$ – last three contractions (%)	37.4 ± 8.1
$StO_{2\,rate}$ – first contraction (%/s)	2.2 ± 0.9
$\Delta StO_{2\,relief}$ (%)—last three contractions	11.9 ± 5.7

CF represents the critical force determined as the mean of the last three contractions. W is the impulse from all contractions, W' is the impulse from all contractions over the CF. RFD refers to the rate of force development. CF_{min} represents the end-force from the last three contractions. CF_{720} was calculated as the highest force that participants were able to tolerate for 720 s

of forearm flexors; 2) CF_{min} determined as the end-force of the last three contractions shows a stronger correlation with sustainable work rate and better predicts sport climbing ability; 3) the initial-StO_2 rate during the all-out test is closely related to CF and inversely related to the fatigue index; 4) mean values or delayed slope of StO_2 are not sensitive enough to discriminate intermittent finger-flexor contractions at intensities ranging from ~0–40% below CF in a sport-specific setting.

Despite the widespread use of the 4 min all-out test, our study does not support its predictive validity for sustainable exercise intensity, aligning with current research trends
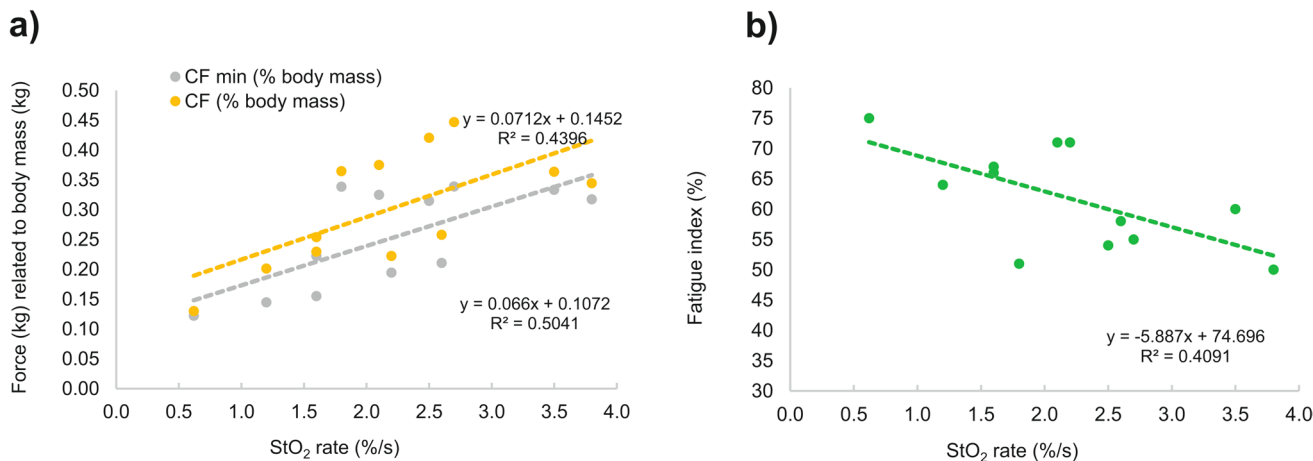

Fig. 3 Relationship between muscle oxygen desaturation during the first 7 s contraction of the 4 min all-out test and **a** critical force (CF) normalized to body mass; **b** fatigue index calculated as % of initial force decrease
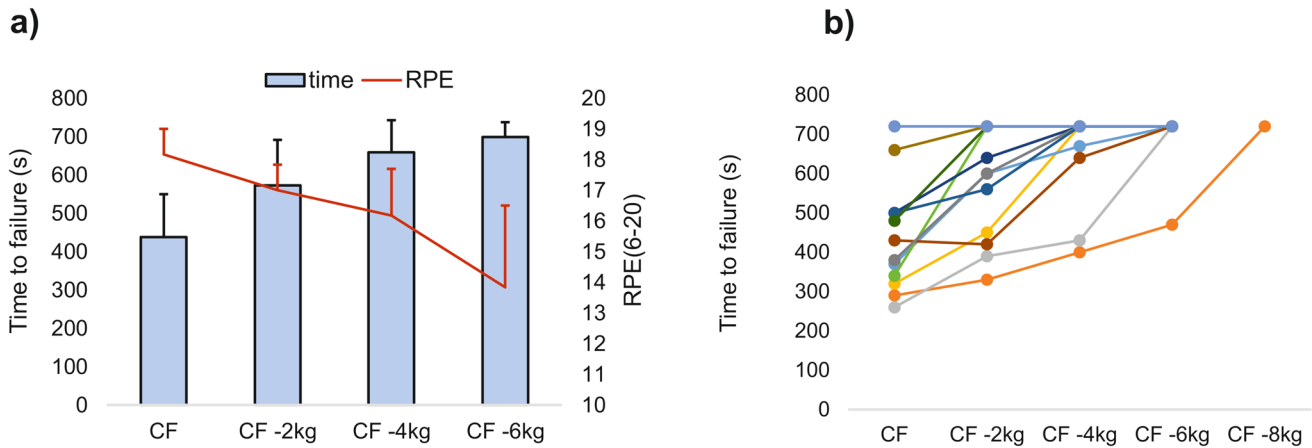
Fig. 4 **a** Mean (± SD) time to failure and rate of perceived exertion (RPE) for intensities at critical force (CF), CF-2 kg, CF−4 kg and CF −6 kg; **b** individual times to failure. Maximum test time was set to 720 s
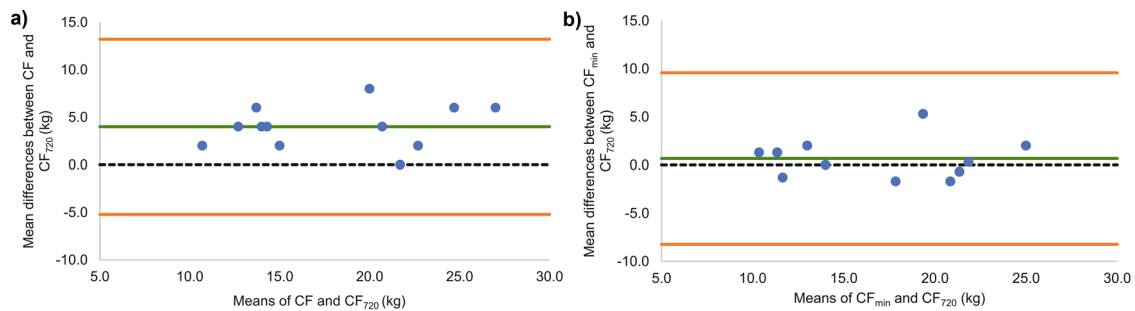

Fig. 5 Bland–Altman plots of mean differences (green line) between **a** critical force determined from the mean of the last three all-out test contractions (CF) and minimal force tolerable for 720 s (CF$_{720}$); **b**

critical force determined from the end-force of the last three all-out test contractions (CF$_{min}$) and CF$_{720}$. Orange lines represent 95% limits of agreement

(Bartram et al. 2017; Bergstrom et al. 2013; Karsten et al. 2014). Research indicates that exercises at CP /speed intensity typically last from 15 to 25 min, occasionally extending to 45–60 min (Dotan 2022; Jones et al. 2019). In our study, the mean exercise time to exhaustion at CF was ~ 7 min. However, Jones et al. (2019) discourage the verification of the CP concept by exercising at CP intensity due to potential reliability errors in CP determination. Therefore, we employed four intensities at and below CF, using 2 kg as minimal, practically distinguishing intensity steps to monitor exercise sustainability, RPE, and muscle-O$_2$ dynamics. This choice was based on previous reliability data for the forearm flexor 4 min all-out test (Giles et al. 2021; McClean et al. 2023).

Initially, Giles et al. (2021) reported excellent test–retest reliability (ICC = 0.96, limits of agreement = −2.45 to 2.4 kg) for a small sample size. However, a recent study by McClean et al. (2023) with a similar population to ours, revealed lower consistency (ICC = 0.848, CV = 21%) The precision of the test for determining CF was questioned due

to significant interindividual variability in the latter study. The only divergence from the initial Giles et al. study (2021) was the allowance of lowering the arm during relief periods, similar to our study, enhancing blood flow, muscle-O$_2$ recovery, and performance (Baláš et al. 2016). This modification likely increased CF during the all-out test, however, the effect on reliability is not obvious. The high-interindividual variability in determining CF may be attributed to low hangboarding experience in participants with substantial test–retest CF variability. Familiarization with the exhaustive protocol seems necessary for obtaining reliable data. Although all participants in our study were familiar with the all-out test, we acknowledge the potential reliability error in data interpretation. Considering an ICC of 0.848 and an SD of CF in our sample (SD = 5.7 kg), the standard error of measurement is 2.2 kg, implying that the all-out test may over- or underestimate CF with this value within ~ 68% of the population.

Our results reveal no underestimation of CF. The participant who completed the 720 s CF trial was nearly exhausted
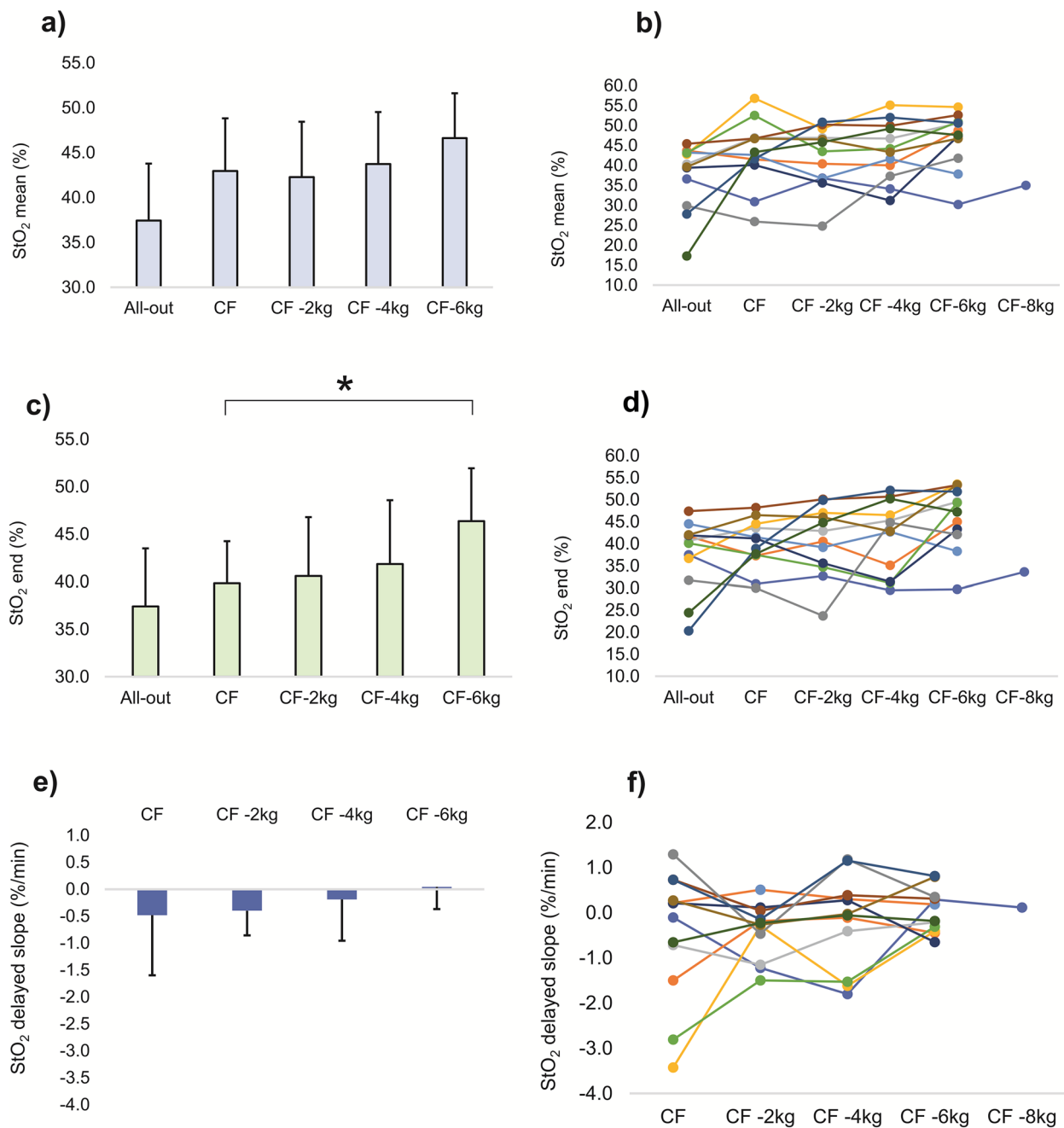
Fig. 6 **a** Mean ($\pm$ SD) and **b** individual muscle-oxygen saturation (StO_2) from the whole test (StO_2 mean); **c, d** from the last 30 s (StO_2 end) of each test; and **e, f** delayed StO_2 slope from all verification trials at the working intensities at the critical force (CF), CF$-$2 kg, CF$-$4 kg and CF $-$6 kg. * indicates significant ($P < 0.05$) differences

at the end. Even considering the reliability error, the intensity of CF $-$4 kg should be sustainable for nearly all participants, yet only 69% completed the 720 s trial, and the mean RPE was only slightly lower than during the CF trial (18.3 vs 16.3). A significant drop in RPE was observed at CF $-$6 kg (RPE = 13.8). RPE is generally lower for localized than for whole-body exercise, and research indicates the RPE for the transition between sustainable and non-sustainable climbing to be $\sim$ 14 on the 6–20 scale (Baláš et al. 2022). This suggests that CF, calculated as the mean force from the end of the test, overestimates CF as an indicator of the transition between sustainable and non-sustainable hangboard exercise. Our findings contradict previous forearm studies using the 10 min and 5 min all-out tests to determine CF, which clearly distinguished sustainable and non-sustainable tasks (Hammer et al. 2020; Kellawan and Tschakovsky 2014).

The length of the all-out protocol, particularly the ratio of work-relief cycles, may contribute to these discrepancies. Previous studies utilized short isometric contractions with 1:2 s and 1.5:1.5 s work:relief cycles, respectively (Hammer et al. 2020; Kellawan and Tschakovsky 2014). In such short contractions, there is no force decrease within a contraction, and blood flow restriction is likely smaller compared to longer contraction as showed previously (Broxterman et al. 2014). Partial vascular occlusion begins at ~20% of MVC, while full blood occlusion is observed at ~50–75% of MVC during handgrip sustained contractions (Barnes 1980; Bergua et al. 2020). Consequently, O_2 delivery is highly limited during all-out contractions and predominantly occurs in the short relief periods between contractions.

The primary limitation of intermittent hangboard performance appears to be O_2 delivery rather than O_2 extraction, as suggested in handgrip exercise with varying work:relief cycles and intensities (Broxterman et al. 2014; Hammer et al. 2020). Enhanced O_2 extraction likely compensates for reduced O_2 delivery even during low-intensity exercise, explaining the lack of significant differences in StO_2 dynamics between all-out tests and verification trials with decreasing intensity in our study. For instance, the StO_2-delayed slope could not distinguish exhaustive from non-exhaustive trials. Arm movement during relief periods was allowed, and participants, with fatigue, could instinctively change their grip and arm position, affecting forearm flexor involvement (Schweizer and Hudek 2011). These factors are inherent in real climbing conditions and challenging to control even in a standardized setting. Consequently, we observed more or less pronounced waves during the StO_2-delayed slope (Fig. 2), making the interpretation of StO_2 data less straightforward. Moreover, the placement of optodes on small forearm muscles may pose an additional challenge compared to voluminous muscles like the vastus lateralis, and even slight rotations of forearm muscles may alter muscle architecture under optodes and StO_2 responses.

Although $StO_{2\ end}$ did not differ between all-out tests and exhaustive verification trials at CF, suggesting that the lowest StO_2 values can predict exhaustion, caution should be exercised due to large intraindividual variability. This is likely attributed to the low reliability of $StO_{2\ end}$ during exhaustive forearm flexor tasks (ICC = 0.437, CV = 23.5%) (Baláš et al. 2018). On the other hand, there was a consistent increase in $StO_{2\ end}$ from CF to CF−6 kg trials, reaching statistical and practical significance at CF−6 kg (+ 6.6% $StO2_{end}$ increase). CF−6 kg might represent a group threshold for sustainable and non-sustainable exercise based on O_2 dynamics. However, individual increases of $StO_{2\ end}$ are not as evident as the whole group means. In summary, due to numerous confounding factors, NIRS may not be sensitive enough to distinguish between steady

and non-steady state conditions in climbing-specific conditions at intensities up to 40% below CF.

Another NIRS indicator, the $StO_{2\ rate}$ from the beginning of the all-out test, exhibited a close association with CF and an inverse relationship with the fatigue index, calculated as the percentage of force decrease during the test. The rapid decrease in StO_2 implies a higher rate of muscle-O_2 extraction, given the absence of changes in blood volume expected during the initial maximal forearm contraction overhead, leading to vascular occlusion. Faster O_2 extraction is possibly linked to increased mitochondrial respiration capacity, justifying its association with CF, even though it lacks the O_2 delivery component (Cardinale et al. 2019). Therefore, we propose considering the initial-StO_2 rate during the all-out test as an additional variable when assessing CF and localized endurance of finger flexors.

The force decrease during each contraction is another factor differing from previous handgrip all-out tests, where no decrease during short contractions was reported (Broxterman et al. 2014; Hammer et al. 2020; Kellawan and Tschakovsky 2014). We observed an ~8 kg-force decrease during the last three contractions. Therefore, we tested whether the end-force might better estimate sustainable intensity. It was shown that CF $_{min}$ was in excellent agreement with CF $_{720}$. Moreover, it more precisely predicted lead climbing ability and was more related to StO_2 rate than CF. All this suggests that the end-force from the last contractions likely more precisely reflects the threshold between sustainable and non-sustainable isometric exercise. However, larger sample size is needed to verify this hypothesis.

RFD significantly decreases during the all-out test, with the initial RFD dropping to half of its values by the end. While this information was not initially part of the objectives and was analyzed to monitor the length and course of each contraction, it is interesting to note. Although not presented, the drop in RFD was not associated with any O_2 dynamics variables, and due to the low sample size, no assessment of the effect of training status or ability could be performed. Both RFD and force variation during contraction have been linked to specific forearm muscle adaptations in boulder and lead climbers (Fanchini et al. 2013; Limonta et al. 2016). Therefore, these parameters may be further explored to assess neuromuscular fatigue in various ability groups of climbers.

Several limitations and strengths need to be acknowledged. First, the recruited sample size was limited, raising questions about the generalizability of the findings. In addition, testing was conducted throughout different menstrual cycles in two female climbers, which may have contributed to higher variability in strength outcomes (Weidauer et al. 2020). However, within this heterogeneous group of climbers, both time to exhaustion and NIRS responses consistently

indicated an overestimation of CF. Furthermore, verification trials employed an absolute load of 2 kg, representing the minimal step, resulting in a slightly varied relative individual intensity under CF for different participants. This pragmatic approach aligns with the feasibility of the study and common practices in hangboard training, where intensity is adjusted by adding or subtracting free weight (Torr et al. 2022). The handgrip contractions were conducted in an ecological setting, enhancing ecological validity while reducing control over all variables (Michailov et al. 2018). This may have contributed to the fluctuation of NIRS signal and reliability of the tests.

Conclusions

Our study challenges the conventional use of CF derived from the 4 min all-out test for forearm flexors. CF, based on the mean force from the last three contractions, does not predict the highest sustainable work rate reliably.

In contrast, determining CF as the end-force of the last three contractions shows a stronger link to sustainable work rate and better predicts sport climbing ability. Focusing on end-force measurement may provide a more accurate representation of sustained effort capacity in climbing.

The initial-StO_2 rate during the all-out test correlates closely with CF and inversely with the fatigue index, indicating its potential utility in understanding metabolic demands and fatigue resistance during climbing-specific tasks. However, caution is needed in interpreting mean values or slopes of StO_2 as discriminatory tools for intermittent finger-flexor contractions around 0–40% below CF in a sport-specific context. Our findings suggest that these conventional metrics may lack the sensitivity required to distinguish nuanced metabolic responses during climbing-related tasks.

Declarations

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