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Title page

Title: Isolated finger flexor vs. exhaustive whole body climbing tests? How to assess endurance in sport climbers?

Running head: Endurance in climbers

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Abstract

Purpose. Sport climbing requires high intensity finger flexor contractions, along with a substantial whole-body systemic oxygen uptake ($\dot{V}O_2$) contribution. Although fatigue is often localised to the finger flexors, the role of systemic $\dot{V}O_2$ and local aerobic mechanisms in climbing performance remains unclear. As such, the primary purpose of this study was to determine systemic and local muscle oxygen responses during both isolated finger flexion and incremental exhaustive whole-body climbing tests. The secondary aim was to determine the relationship of isolated and whole-body climbing endurance tests to climbing ability.

Methods. Twenty-two male sport climbers completed a series of isometric sustained and intermittent forearm flexor contractions, and an exhaustive climbing test with progressive steepening of the wall angle on a motorized climbing ergometer. Systemic $\dot{V}O_2$ and flexor digitorum profundus oxygen saturation (StO_2) were recorded using portable metabolic analyser and near-infra red spectroscopy, respectively.

Results. Muscle oxygenation breakpoint (MOB) was identifiable during an incremental exhaustive climbing test with progressive increases in angle (82±8% and 88±8% $\dot{V}O_2$ and heart rate climbing peak). The peak angle from whole-body treadwall test and impulse from isolated hangboard endurance tests were interrelated ($R^2 = 0.58\text{-}0.64$). Peak climbing angle together with mean $\dot{V}O_2$ and StO_2 from submaximal climbing explained 83 % of variance in self-reported climbing ability.

Conclusions. Both systemic and muscle oxygen kinetics determine climbing specific endurance. Exhaustive climbing and isolated finger flexion endurance tests are interrelated and suitable to assess climbing specific endurance. An exhaustive climbing test with progressive wall angle allows determination of the MOB.

Keywords

Threshold, NIRS, muscle oxygen, intermittent exercise, isometric contraction

Declarations

Funding

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Conflict of interest

It should be noted that one of the authors (DG) is employed by Lattice Training Ltd. who provide climbing coaching and assessment services. The remaining authors have no competing interests to declare and assert that the results of the study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation. The authors declare no conflict of interest.

Availability of data and material

The datasets generated during in the current study are available from the corresponding author on reasonable request.

Authors' contributions

JB and JG conceived and designed the research; JB, JG, DK, TB conducted experiments; JB and JG analysed and evaluated data; JB, AF, DG and SF prepared the manuscript. All authors read and approved the manuscript.

Abbreviations

ATP	Adenosine triphosphate
CI	Confidence interval
GET	Gas exchange threshold
FDP	Flexor digitorum profundus
f_{H}	Heart rate
f_{R}	Respiratory frequency
H^+	Hydrogen cation
MOB	Muscle tissue oxygenation breakpoint

MVC	Maximal voluntary contraction
P	Statistical significance
R	Pearson correlation coefficient
R^2	Coefficient of determination
$\dot{V}CO_2$	Carbon dioxide production
$\dot{V}_E$	Expired minute ventilation
$\dot{V}O_2$	Oxygen uptake
V_T	Tidal volume

Introduction

Sport climbing requires high intensity finger flexor contractions which induce repeated periods of localised ischemia separated by short periods of reperfusion (Michailov 2014; Thompson et al. 2014). These contractions place high demands on both oxidative and non-oxidative metabolic pathways (Bertuzzi et al. 2007) and, indeed, tests of oxidative and anaerobic capacity of the finger flexors have been found to be associated with climbing ability (Fryer et al. 2018; Giles et al. 2020; Michailov et al. 2018). Recently, indices of localised muscle oxygen kinetics have been explored using near infra-red spectroscopy (NIRS). More advanced climbers have shown greater oxygen desaturation of the finger flexors during sustained and intermittent contractions (Fryer et al. 2018; Baláš et al. 2016), and quicker muscle oxygen recovery after arterial cuff occlusion and during exercise compared to lesser ability climbers (Fryer et al. 2018; Macleod et al. 2007; Philippe et al. 2012; Fryer et al. 2015a). These findings demonstrate that indices of localised muscle oxygen kinetics may be used to assess climbing specific endurance or training adaptations.

In practice, intermittent or sustained contractions of the forearm flexors on a climbing specific test apparatus, known as a hangboard or fingerboard, at 40-80 % of maximal voluntary contraction (MVC) have been the primary means used to assess climbing specific endurance (Macleod et al. 2007; Philippe et al. 2012; Vigouroux and Quaine 2006; Fryer et al. 2015a; Michailov et al. 2018). Only recently have exhaustive tests on motorized climbing ergometers (treadwalls) been proposed for the assessment of whole-body climbing specific endurance (Fryer et al. 2018; España-Romero et al. 2009; Limonta et al. 2018). For instance, Fryer et al. (2018) were able to predict 67 % of the variation in climbing ability using a combination of treadwall peak oxygen uptake, muscle oxygen desaturation and recovery, underlying the importance of both whole-body and local aerobic capacity in climbers. On the other hand, the use of indices such as treadwall peak oxygen uptake and muscle oxygen desaturation in the previously reported protocol may have overestimated the aerobic capacity contribution to climbing performance. For instance, greater muscle desaturation have not been accompanied by climbing performance improvement after supplementation of anthocyanins (Fryer et al. 2020b; Fryer et al. 2020a) and treadwall peak oxygen uptake did not distinguish climbing ability groups in another recent study (Limonta et al. 2018).

In the literature, there is no common agreement of methods for endurance testing in climbers. Isolated forearm models (hangboard tests) have received increasing attention, most recently with the application of the critical force model (Giles et al. 2019; Giles et al. 2020). While applicable and useful for assessment and training, isolated forearm assessments may have transfer limitations to actual climbing performance. Exhaustive climbing tests (whole-body model) have been proposed (Fryer et al. 2018; Limonta et al. 2018; Booth et al. 1999; España-Romero et al. 2009), but there is no consistency in task demands (progressive speed versus progressive angle protocols) or measures taken (use of peak oxygen uptake and time to failure mostly). Furthermore, no attempt has been made to ascertain the relationship of systemic and muscle oxygen kinetics in climbing and appearance of metabolic breakpoints. Thus, there is need for the definition of methods for whole-body endurance assessment in climbers using an ecologically valid task, which is representative of the demands found in the sport. Therefore, the primary purpose of this study was to determine systemic and local muscle oxygen responses during both isolated finger flexion and incremental exhaustive whole-body climbing tests. The secondary aim was to determine the relationship of isolated and whole-body climbing endurance tests to climbing ability.

Methods

Experimental plan

All participants visited the laboratory on two occasions. They were asked to refrain from any strenuous physical activity for 48 h, caffeine for 12 h and heavy meals for 3 h prior to testing. On the first visit, participants' MVC of the finger flexors was assessed on a climbing specific dynamometer, followed by tests of sustained and intermittent finger flexor endurance (to volitional exhaustion at 60 % of MVC). Thirty min recovery with 15 min active recovery (brisk walking) was provided between endurance tests. Participants then performed a familiarisation ascent on the treadwall. Lastly, participants conducted a treadmill running test with progressive inclination (%) to failure. On the second visit, participants performed an exhaustive incremental test (progressive steepening of the wall angle) on the treadwall to volitional exhaustion. Each session began with the same warm-up, which consisted of 5 min running, 5 min traversing on a climbing wall and 5 min individual one-arm intermittent hanging on a 30 and 23 mm deep wooden rungs.

Participants

Twenty-two male sport climbers volunteered to participate in the study. Participants were healthy, non-smokers, and were not taking any vascular acting medication. According to their recent (last 3 months) self-reported red-point climbing ability, they were separated into intermediate and advanced groups (Draper et al. 2016). Self-reported climbing ability is a valid, and currently the most common, method for the assessment of climbing ability level (Draper et al. 2011). Anthropometric and training characteristics are depicted in Table 1. The study conformed to the recommendations of the local Research Ethics Committee in accordance with the Declaration of Helsinki. All participants were informed of the experimental risks and provided informed consent prior to the commencement of data collection.

Hangboard tests.

Climbing specific finger flexion strength and endurance were tested using a custom-made dynamometer (1D-SAC, Spacelab, Sofia, Bulgaria) which has been shown to be both reliable and valid (Michailov et al. 2018). The dynamometer was calibrated for a wooden hold 23 mm deep, in order to maximise the activation of the flexor digitorum profundus (FDP) (Schweizer and Hudek 2011). MVC of the dominant finger flexors was completed twice with each attempt being separated by two-min passive rest. Participants were instructed to progressively transfer as much of their weight ("hang") as possible on to the wooden rung for 5 s with their dominant hand. The highest peak value from the two trials was considered maximal finger flexor strength and this was used to determine relative workloads for the following sustained and intermittent tests.

The sustained and intermittent endurance tests were performed at 60 % of MVC. The tests started with an acoustic signal and participants were provided with visual feedback to ensure the correct force was applied. If this force dropped by more than 10 % of the target for more than 1 s, the test was automatically terminated. The intermittent test was conducted with a contraction: relief ratio of 8:2 s. An acoustic signal as well as the visual display marked the start and end of each contraction/relief period.

In-line with previously described methods, all tests were conducted whilst standing with the arm in shoulder flexion (180°) and the elbow slightly flexed to simulate sport specific conditions (Baláš et al. 2014b), and to prevent blood pooling (van Beekvelt et al. 2001). Participants were verbally encouraged to achieve maximal effort throughout. Time to failure (s) and impulse (N·s) were recorded for further analysis

Running test

Maximal aerobic capacity during running was determined using a graded protocol on a treadmill (Quasar, H/P/Cosmos, Germany). The test started at submaximal speed 10 km.h^{-1} without any belt inclination (0 %) for 4 min. After that, a graded step protocol (+ 1.5 % inclination per min) was applied until volitional exhaustion. All participants attained at least two of the following primary peak oxygen uptake ($\dot{V}O_{2\ \mathrm{peak}}$) criteria: a plateau in oxygen uptake, respiratory exchange ratio was greater than 1.1 and heart rate (f_H) higher than 90 % of age predicted-maximum.

Climbing test

The exhaustive incremental climbing test was conducted on a treadwall 3.8 m high (ClimbStation generation, Forssa, Finland) with a 6 m long belt. The climb consisted of 14 hand moves repeated within each belt cycle. The route was graded as 8 on International Rock Climbing Association scale (4+ Sport grade, 5.8 Yosemite Decimal Scale) with a vertical inclination (set as 0° angle). A constant belt speed of 9 $m \cdot min^{-1}$ was applied to minimise static resting positions during the climb and was determined based on several previous trials with climbers of differing ability to simulate climbing on a known route and to elicit high oxygen output (Fryer et al. 2018). The incremental test started at 0° and after each min, the belt was stopped for 10 s to allow climbers dry their hands with chalk and the angle was increased (made steeper) by -5°. During the 10 s rest, climbers were not allowed to touch the ground and were only allowed to shake their hands to enable short recovery. This time was not included in the analysis. The test ended when the climber could not have continued the climb and fell on the mat.

Near-infra red spectroscopy (NIRS)

A continuous-wave NIRS device (Portamon, Artinis Medical System, BV, Netherlands) was placed over the belly of the FDP of the dominant hand in accordance with Fryer et al. (2018). The device was fixed by bi-adhesive tape from interior and black tape and black sleeve from the exterior to limit 1) optode movement during climbing and 2) ambient light penetration. Muscle tissue oxygen saturation (StO_2), deoxy[heme], and total[heme] were used to determine muscle oxygen kinetics during the ascent. Due to the irregular intermittent nature of finger flexor contractions during climbing, NIRS values were averaged over 20 s periods (approx. three moves with one hand) for analyses of mean hemodynamic responses during the treadwall test. To determine muscle oxygenation breakpoint (MOB), the double linear regression method with one inflection point (Fig. 1) for deoxy[heme] was applied (Wang et al. 2006; Boone et al. 2016). From the hangboard tests, only maximal muscle oxygen desaturation ($StO_{2\ \mathrm{min}}$) and changes in StO_2 during relief periods from intermittent contractions ($\Delta\ StO_{2\ \mathrm{relief}}$) were assessed at 10

Hz. The reliability of StO_2 measurement in this setting has previously been deemed satisfactory and the error of measurement stated (standard error of measurement: $StO_{2\ min}$ = 7.2 %; Δ $StO_{2\ relief}$ = 1.2 %) (Baláš et al. 2018).

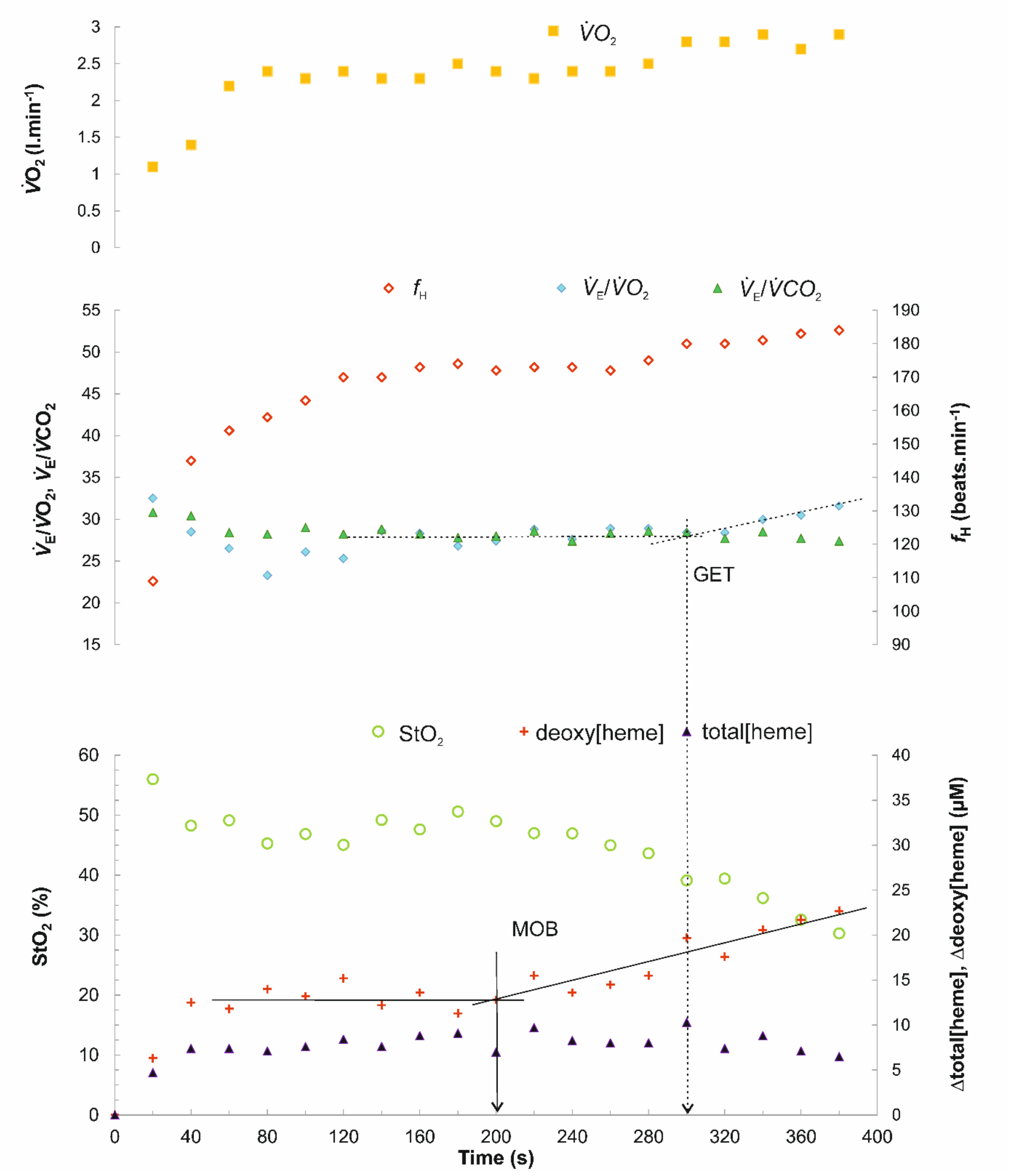

Figure 1 Determination of muscle oxygenation breakpoint (MOB) and gas exchange threshold (GET) during incremental climbing test on a treadwall in a typical climber. Total[heme] and [deoxy[heme] were set arbitrary to zero before the test after 10 min passive rest. StO_2 muscle tissue oxygen saturation, f_H heart rate, $\dot{V}_E$ expired minute ventilation, $\dot{V}O_2$ oxygen uptake, $\dot{V}O_2$ carbon dioxide production.

Gas analysis

Expired minute ventilation ($\dot{V}_E$), oxygen uptake ($\dot{V}O_2$), carbon dioxide production ($\dot{V}CO_2$), respiratory frequency (f_R), and tidal volume (V_T) were measured using portable breath-by-breath indirect calorimetry system (MetaMax 3B, Cortex Biophysic, Germany). The MetaMax 3B was attached onto the chest by a harness. Gas and volume calibration were conducted before each test according to manufacturer's guidelines. The volume calibration was performed using a known 3 l syringe and gas calibration was performed with a known gas mixture of 15 % O_2 and 5 % CO_2. Data was collected continuously from 5 min pre-climb rest and the whole climbing trial to failure. Averaged data over 10 s intervals was exported to Excel for further analysis. f_H was monitored by the MetaMax 3B using a Polar heart transmitter belt (Polar Electro OY, Finland).

From the treadwall exhaustive test, gas exchange threshold (GET) was determined using double linear regression method from $\dot{V}_E/\dot{V}O_2$ ratio, which appeared in all participants (Fig. 1). However, the $\dot{V}CO_2/\dot{V}O_2$ slope method could not have been applied as no clear inflection points were detected during the treadwall test. Similarly, a respiratory compensation point using $\dot{V}_E/\dot{V}CO_2$ was not detected. Further in the manuscript, $\dot{V}_E/\dot{V}O_2$ ratio will be treated as GET, however, the authors question the validity in the Discussion section.

From the treadmill incremental test, GET was determined using the $\dot{V}_E/\dot{V}O_2$ ratio and $\dot{V}CO_2/\dot{V}O_2$ slope method. Respiratory compensation point (RCP) was determined using $\dot{V}_E/\dot{V}CO_2$ ratio. Two blinded investigators independently determined all respiratory thresholds.

Statistical analysis

Descriptive statistics (mean ± SD) were used to characterize anthropometric, training, and performance characteristics in all climbers. All data have been found to be normally distributed, homoscedastic, and of equal variance. The differences between ability groups were assessed using independent *t*-tests. The relationship among endurance test performance, indices of systemic and localised oxygen response and climbing ability was calculated using the Pearson correlation coefficient. A full correlation matrix is provided within the Supplementary material S1. Stepwise linear regression was applied to selected variables with best fit to predict climbing ability. Variables entered in the regression were based on significance to climbing ability and logical reflection. The excluded variables are reported in the Supplementary material S2. Cohen's *d* was used to assess effect size between ability group differences. Statistical significance was set to $P < 0.05$.

Results

Compared to the intermediate climbers, the advanced group was older, had been climbing for longer, spent more time engaging in climbing specific training per week, but spent less of this time focusing on training endurance (Table 1). The advanced climbers had significantly greater finger flexor MVC and greater impulse (N·s) for both the sustained and intermittent hangboard tests (Table 1). There were no ability group differences in muscle oxygen desaturation or recovery during either of the hangboard tests (Table 1). Running time and $\dot{V}O_{2\ \mathrm{peak}}$ for the exhaustive treadmill test were similar between the ability groups, however $f_{\mathrm{H\ peak}}$ was higher for intermediate than advance climbers (Table 1).

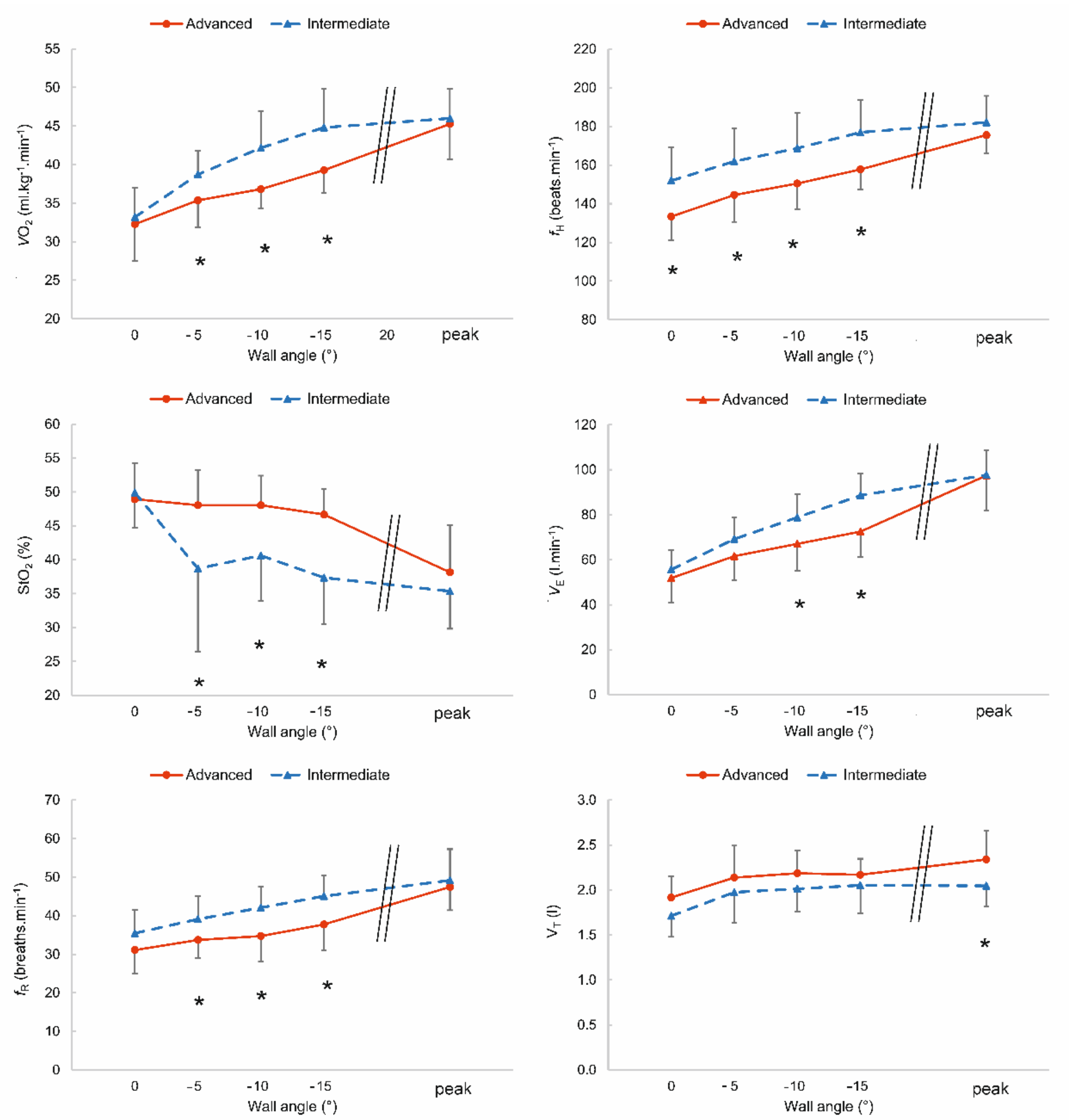

Figure 2 Mean (± SD) cardiorespiratory response and muscle tissue oxygen saturation (StO_2) of flexor digitorum profundus during incremental climbing test on a treadwall in advanced and intermediate climbers. Climbing wall

angle of -15° is the steepest inclination completed by all participants. * designates significant differences between groups at specific wall angle ($P<0.05$). f_H heart rate, f_R respiratory frequency, V_T tidal volume, $\dot{V}_E$ expired minute ventilation, $\dot{V}O_2$ oxygen uptake, RER respiratory exchange ratio.

During the exhaustive incremental climbing test, advanced climbers achieved significantly steeper angles than the intermediate climbers (greater number of angle steps), however all cardiorespiratory and hemodynamic parameters were similar at the peak angle for both ability groups, with the exception of V_T (Table 1, Fig 2). All participants attained the angle of at least -15°, enabling group comparisons at four time points (0, -5, -10, -15°) of submaximal climbing to be made (Fig. 2). Both systemic (f_H, $\dot{V}_E$, $\dot{V}O_2$ and f_R) and local physiological responses (StO_2) were significantly different for -5° (except for $\dot{V}_E$), -10° and -15° between the two ability groups (Fig. 2).

MOB and GET were detected from the data in 18 and 22 participants, respectively. During the treadwall test, MOB preceded the GET by 69 s (95 % CI 55.7-82.0 s) and the systemic response was significantly lower at the MOB than at the GET (Δf_H -9 beats·min^{-1}, $\Delta\dot{V}_E$ -8.9 l·min^{-1}, $\Delta\dot{V}O_2$ -0.2 l·min^{-1} and Δf_R -4 breaths·min^{-1}). MOB represented 88 ± 8 % and 82 ± 8 % of treadwall $f_{H\ peak}$ and $\dot{V}O_{2\ peak}$, respectively. GET treadwall was achieved at 93 ± 6 % and 90 ± 6 % of treadwall $f_{H\ peak}$ and $\dot{V}O_{2\ peak}$, respectively (Table 2). There was no relationship between any treadwall (MOB, GET) and treadmill (GET, RCP) thresholds ($P > 0.05$).

Respiratory peak values (mean from 20 s interval) from treadwall were significantly lower than from treadmill, specifically: Δf_H = -11 beats·min^{-1} (95 % CI -15 to -6 beats·min^{-1}), $\Delta\dot{V}O_2$ = -9.6 ml·kg^{-1}·min^{-1} (95 % CI -13.0 to -6.0 ml·kg^{-1}.min^{-1}); $\Delta\dot{V}_E$ = -52.7 l·min^{-1} (95 % CI -64.7 to -40.8 l·min^{-1}); Δf_R = -6 breaths·min^{-1} (95 % CI -9 to -3 breaths·min^{-1}); ΔV_T = -0.9 l (95 % CI -1.2 to -0.7 l).

From all the endurance tests indicators, the strongest relationship to climbing ability was found for treadwall peak angle ($R^2 = 0.70$). Slightly less variability in climbing ability was explained by treadwall MOB and impulse from sustained and intermittent hangboard tests ($R^2 = 0.66$, $R^2 = 0.56$ and $R^2 = 0.43$, respectively). The relationship with climbing ability remained high even when using partial correlations to control for maximal finger flexors strength (Table 3). Treadwall MOB was in closest relationship with the impulse from the intermittent hangboard test ($R^2 = 0.71$), however, no relationship with maximal strength was found ($R^2 = 0.06$).

Table 1 Anthropometric, training and performance differences between advanced and intermediate climbers. Peak respiratory and oxygen saturation values are reported for incremental tests (mean from 20s interval). IRCRA International Rock Climbing Research Association, StO_2 muscle tissue oxygen saturation, F force, $\dot{V}O_2$ oxygen uptake, RER respiratory exchange ratio, f_H heart rate, f_R respiratory frequency, V_T tidal volume, $\dot{V}_E$ expired minute ventilation.

	Advanced	Intermediate	*Differences*	
	N = 11	N =11	*P*	Cohen's *d*
Anthropometric and training characteristics				
Age (years)	35.5±7.6	27.4±8.2	**0.026**	0.92
Body mass (kg)	70.9±5.3	69.5±6.6	0.599	0.23
Height (cm)	177.8±6.2	177.5±8.3	0.920	0.04
Climbing ability (IRCRA scale)	21±2	14±2	**<0.001**	1.70
Climbing experience (years)	14.8±5.9	7.9±5.9	**0.012**	1.03
Endurance from total climbing time (%)	38.2±16.6	60.0±27.9	**0.038**	0.87
Climbing specific training (hours/week)	6.4±3.2	4.2±2.2	0.071	0.77
Climbing non-specific training (hours/week)	3.2±3.1	3.5±3.7	0.803	0.11
Hangboard tests				
Finger strength (kg) related to body mass (kg)	0.90±0.10	0.75±0.14	**0.006**	1.10
Sustained contraction impulse (N·s)	21129±4332	13073±2930	**<0.001**	1.47
Sustained contraction time (s)	56.8±14.6	43.6±10.3	**0.024**	0.94
Sustained contraction $StO_{2\ min}$ (%)	32.5±9.0	36.2±8.2	0.315	0.44
Intermittent contraction impulse (N·s)	30958±9790	21207±8438	**0.021**	0.95
Intermittent contraction time (s)	82.5±30.2	67.5±27.6	0.238	0.51
Intermittent contraction $StO_{2\ min}$ (%)	32.4±9.0	31.8±8.4	0.882	0.07
Intermittent contraction $\Delta\ StO_{2\ relief}$ (%)	14.4±5.2	13.0±3.4	0.452	0.33
Incremental climbing test				
Time to peak (s)	381±59	263±46	**<0.001**	1.48
Peak angle (°)	29±5	19±4	**<0.001**	1.46
$f_{H\ peak}$ (beats·min^{-1})	176±9	182±14	0.203	0.55
$\dot{V}O_{2\ peak}$ (ml·min^{-1}·kg^{-1})	45.3±4.6	46.0±3.8	0.690	0.18
$\dot{V}_E$ (l·min^{-1})	97.5±15.6	97.7±10.9	0.971	0.02
f_R (breath·min^{-1})	47±6	49±8	0.577	0.25
V_T (l)	2.3±0.3	2.0±0.2	**0.022**	0.95
RER	1.07±0.11	1.07±0.07	0.925	0.04
$StO_{2\ min}$ (%)	30.0±7.4	26.7±5.4	0.248	0.50
Incremental running test				
Time (s)	385±95	434±130	0.329	0.43
Slope (%)	14±3	15±2	0.591	0.24
$f_{H\ peak}$ (beats·min^{-1})	185±5	196±8	**0.002**	1.23
$\dot{V}O_{2\ peak}$ (l·min^{-1})	53.2±5.7	54.7±7.6	0.594	0.23
$\dot{V}_E$ (l·min^{-1})	141.9±29.6	157.9±33.4	0.211	0.54
f_R (breath·min^{-1})	52±8	58±12	0.205	0.55
V_T (l)	3.2±0.3	3.1±0.5	0.706	0.17
RER	1.23±0.08	1.26±0.07	0.377	0.39

To predict climbing ability using data from the exhaustive treadwall test and hangboard sustained and intermittent contractions, stepwise linear regression was used (Table 4). Three predictors from treadwall exhaustive test significantly predicted climbing ability ($R^2 = 0.83$): peak angle, systemic $\dot{V}O_2$ from submaximal climbing ($\dot{V}O_2$ $10°_{treadwall}$) and local muscle tissue StO_2 from submaximal climbing (StO_2 $10°_{treadwall}$). Due to co-linearity (Table 3, Supplementary material S1, S2), all performance and oxygen kinetics variables from hangboard tests were excluded from the model by the regression analysis.

Table 2 Muscle oxygenation breakpoint (MOB), gas exchange threshold (GET) and peak values from exhaustive incremental test on a climbing motorized ergometer (treadwall) and treadmill. Only subjects with detectable MOB and GET from treadwall are included (N=18). StO_2 tissue saturation index, f_H heart rate, f_R respiratory frequency, V_T tidal volume, $\dot{V}_E$ expired minute ventilation, $\dot{V}O_2$ oxygen uptake. ^ significant differences ($P <$ 0.05) between treadwall MOB and GET.

	Treadwall MOB	Treadwall GET	Treadmill GET	Treadmill RCP	Treadwall MOB (% of treadwall peak)	Treadwall GET (% of treadwall peak)	Treadmill GET (% of treadmill peak)	Treadmill RCP (% of treadmill peak)
Time (s)	193±78^	262±75	121±86	223±112	57±13%	78±8%	27±14%	52±19%
StO2 $_{mean}$ (%)	45.0±6.1^	39.8±5.8	N/A	N/A	N/A	88±8%	N/A	N/A
f_H (beats·min^{-1})	158±15^	167±13	153±11	168±8	88±8%	93±6%	80±4%	88±2%
$\dot{V}O_2$ (l·min^{-1})	2.6±0.4^	2.8±0.4	2.5±0.4	2.9±0.5	82±8%	90±6%	66±8%	76±6%
$\dot{V}_E$ (l·min^{-1})	69.2±12.8^	78.1±12.0	67.2±11.2	84.9±14.4	70±10%	79±9%	46±10%	57±10%
f_R (breaths·min^{-1})	37±5^	41.4±6	22±6	34±7#	74±10%	84±10%	58±15%	63±11%
V_T (l)	1.9±0.3	1.9±0.3	2.3±0.4	2.5±0.4#	88±12%	88±12%	71±10%	80±10%

Discussion

The primary purpose of this study was to determine systemic and local muscle oxygen responses during both isolated finger flexion and incremental exhaustive whole-body climbing tests. The secondary aim was to determine the relationship of isolated and whole-body climbing endurance tests to climbing ability. The main findings were: (1) MOB was identifiable during an incremental exhaustive climbing test with progressive increases in angle and was significantly related to the impulse from forearm isolated intermittent contractions. (2) The peak angle from whole-body treadwall test and impulse from isolated hangboard endurance tests were interrelated (R^2 = 0.58-0.64), however, the strongest relationship to climbing ability was found for the peak angle achieved during the exhaustive treadwall test. (3) Using stepwise linear regression, it was shown that both systemic $\dot{V}O_2$ and localised muscle StO_2 from submaximal climbing improve the prediction of climbing ability.

Table 3 Association between climbing ability and common endurance finger flexor tests. Pearson correlation coefficient (normal font) and partial correlation with the control for maximal finger strength (*italic font*) are depicted. Impulse and strength are normalized to body mass (kg^{-1}). * significant relationship at $P < 0.05$; ** significant relationship at $P < 0.01$

	Climbing ability	Treadwall peak inclination	Treadwall MOB	Sustained contraction impulse	Intermittent contraction impulse	Finger strength
Climbing ability (IRCRA)	1	0.835**	0.813**	0.751**	0.656**	0.552**
Treadwall peak angle (°)	_0.769_**	1	0.912**	0.766**	0.763**	0.518*
Treadwall MOB (°)	_0.835_**		1	0.735**	0.845**	0.253
Sustained contraction impulse (N·s·kg^{-1})	_0.663_**			1	0.799**	0.485*
Intermittent contraction impulse (N·s·kg^{-1})	_0.543_*				1	0.459*
Finger strength (N·kg^{-1})						1

Table 4 Stepwise regression models to predict climbing ability from exhaustive incremental treadwall test and hangboard sustained and intermittent contractions. Only three predictors from exhaustive incremental treadwall test significantly predicted climbing ability. StO$_2$ finger flexor muscles oxygen saturation, $\dot{V}O_2$ oxygen uptake, *β* standardized beta coefficient, LCI lower confidence, interval UCI upper confidence interval, SE standard error of estimate, IRCRA International Rock Climbing Research Association.

Model		*β*	*P*	95% LCI	95% UCI	Adjusted R^2	SE (IRCRA grade)
1	(Constant)		0.011	1.416	9.378	0.730	2.0
	Peak angle $_{\text{treadwall}}$	0.864	0.000	0.347	0.659		
2	(Constant)		0.878	-6.705	5.789	0.793	1.8
	Peak angle $_{\text{treadwall}}$	0.675	0.000	0.225	0.561		
	StO$_2$ 10°$_{\text{treadwall}}$	0.327	0.029	0.023	0.366		
3	(Constant)		0.090	-1.888	23.281	0.832	1.6
	Peak angle $_{\text{treadwall}}$	0.510	0.003	0.117	0.477		
	StO$_2$ 10°$_{\text{treadwall}}$	0.325	0.018	0.038	0.349		
	VO$_2$ 10°$_{\text{treadwall}}$	-0.269	0.050	-0.440	0.002		

Finger flexor MOB was assessed using the inflection points of deoxy[heme]. Previous research comparing different NIRS variables suggested that deoxy[heme] better represents muscle deoxygenation changes and O_2 metabolic dynamics, whereas StO_2 can be influenced by changes in perfusion during exercise (Wang et al. 2006). From a physiological perspective, an increase in forearm exercise intensity stimulates recruitment of faster glycolytic motor units with enhanced lactate and H+ production. Excessive H^+ efflux is buffered by bicarbonate, leading to carbonic acid production and its dissociation into water and CO_2. This progressive muscle acidosis accelerates O_2Hb dissociation via the Bohr effect and consequently speeds-up the increase in capillary oxygen extraction (Grassi et al. 1999). Abrupt changes in deoxy[heme] or StO_2 have been associated with gas exchange/first ventilatory or lactate threshold (Grassi et al. 1999; Wang et al. 2006; Van Der Zwaard et al. 2016). Furthermore, an onset of a plateau in deoxy[heme] has been associated with critical power or RCP in the vastus lateralis and medialis, but not in the deep fibres of the rectus femoris (Keir et al. 2015; Okushima et al. 2015). In the current study, we observed only one breakpoint of deoxy[heme] which corresponded to an abrupt decrease in StO_2 (Fig 1). No plateau of deoxy[heme] was observed, indicating that fractional O_2 extraction in the FDP did not reach its limit (Boone et al. 2016). Similar patterns have been found for typically slow twitch motor units or muscles with lower activation (Okushima et al. 2015; Chin et al. 2011). It may be that other important finger flexor muscles, such as flexor digitorum superficialis, would demonstrate a different localised O_2 response. Moreover, it might be speculated that constant reperfusion during recovery periods of intermittent contractions results in no O_2 extraction plateau, but in a local metabolite accumulation that causes muscle failure.

On a systemic level, both an excess of CO_2 and H^+ stimulates central chemoreceptors, increasing $\dot{V}_E$ which results in non-linear increase in the slope of $\dot{V}CO_2$ versus $\dot{V}O_2$ (Beaver et al. 1986). In sports such as climbing, it is questionable to what degree local isometric contractions can stimulate pulmonary responses when peak lactate concentrations after exhaustive climbing are ~5-7 $mmol \cdot l^{-1}$ and systemic acidosis is considered to be low (Watts 2004). It may be that only when the larger muscle groups of the upper-body are used at steeper angles, or the increased leg activation during faster climbing is used, then the changes in compensatory ventilation may occur. In the current study, the $\dot{V}_E/\dot{V}CO_2$ inflection point was detected, however the inflection point was not visible for $\dot{V}_E/\dot{V}CO_2$ or $\dot{V}CO_2/\dot{V}O_2$ slope, unlike for whole body incremental exercise (Beaver et al. 1986). In fact, treadwall $\dot{V}CO_2$ increased linearly with $\dot{V}_E$ until peak values were achieved. The $\dot{V}_E$ at peak angle was relatively low (~99 $l \cdot min^{-1}$) compared to peak running performance (~150 $l \cdot min^{-1}$), which might be due to thoracic compressions from upper body muscular activity at the steeper angles. Considered together with low previously reported values of systemic acidosis, this may explain why no changes in $\dot{V}_E/\dot{V}CO_2$ or $\dot{V}CO_2/\dot{V}O_2$ slope were seen. Although there was a strong relationship ($R^2 = 0.85$) between MOB and GET during the exhaustive incremental climbing test, the mean shift was ~70 s (~ 10°) and it appears that GET does not reflect the metabolic changes in the smaller forearm muscles shown by the localised MOB. Moreover, GET during exhaustive vertical climbing at lower speed or shallower angles may not occur, as large muscle groups would not be involved. Consequently, we do not recommend using GET to control intensity during actual climbing.

Climbing ascent times have been found to vary between 3-10 min (Michailov 2014), consequently the contribution of aerobic metabolism for ATP re-synthesis is elevated (Bertuzzi et al. 2007). The mean time of the current incremental treadwall test averaged ~5.3 min and $\dot{V}O_2$ increased until the peak angle was achieved. No plateau in treadwall $\dot{V}O_2$ was found, which confirms that local fatigue rather than systemic exhaustion was a limiting factor in climbing performance. Previous research suggested that both local muscle and systemic oxygen capacity during exhaustive climbing test are important predictors of climbing ability, and the authors proposed treadwall $\dot{V}O_{2\,\mathrm{peak}}$ to be used as an indicator of climbing specific oxygen capacity (Fryer et al. 2018; Limonta et al. 2018). The use of treadwall $\dot{V}O_{2\,\mathrm{peak}}$ is not supported by the current study's findings, as $\dot{V}O_{2\,\mathrm{peak}}$ was not related to climbing ability. This may be due to relatively narrow ability range of climbers, or due to differences in the exhaustive protocol used and its "specificity" to climbing. Indeed, $\dot{V}O_{2\,\mathrm{peak}}$ from exhaustive protocols with high or increasing speed have been shown to have a positive relationship with climbing ability, while protocols with increasing angles have not (Baláš et al. 2014c; Limonta et al. 2018; Watts and Drobish 1998; España-Romero et al. 2009; Booth et al. 1999). Faster climbing speeds elicit a greater contribution from the lower body musculature, and thus the relationship to climbing ability is likely due to better movement coordination in more advanced climbers rather than systemic exhaustion (Booth et al. 1999). The question arises how "climbing specific" are tests that use climbing speed to assess climbing $\dot{V}O_{2\,\mathrm{peak}}$ and what protocols should be applied for incremental treadwall test? Future studies may consider using speeds and wall angles where the movement coordination is not the limiting factor of failure and predominantly the upper-body and not lower-body muscles are involved.

The determination of exercise intensity domains, instead of only peak values, from an exhaustive test are generally more informative for the prescription of training intensities. Within climbing, the use of traditional exercise intensity indicators such as blood lactate concentrations or f_H have been found ineffective (Watts 2004). Similarly, GET does not reflect any localised metabolic transition zone as found in the current study. However, the use of NIRS appears promising as MOB have been found to correlate with some metabolic breakpoints (Barstow 2019). In the current study, MOB appeared at 88 ± 8 % of treadwall $f_{H\,\mathrm{peak}}$, and it is plausible that the MOB may correspond to disturbances in homeostasis in forearm muscles and indicate transitional metabolic zone from steady- to nonsteady state in climbing. Nevertheless, the use of single location to determine metabolic transition zone has been questioned (Boone et al. 2016). The assessment of other forearm flexors or shoulder muscles may have provided additional information about localised muscle $\dot{V}O_2$ kinetics.

In the current study, FDP MOB was significantly related to climbing ability, and when controlling for maximal finger strength, it was its best predictor ($R^2 = 0.70$). Contrary to this, maximal finger strength explained only 30 % ($R^2 = 0.30$) of the variation in climbing ability. MOB was also closely related ($R^2 = 0.71$) to impulse from intermittent test which supports its use for the assessment of the aerobic capacity of finger flexors (Baláš et al. 2016). On the other hand, MOB was independent to maximal finger strength ($R^2 = 0.06$), however, impulse from both the intermittent and sustained contraction hangboard tests were significantly related to maximal finger strength ($R^2 = 0.21$-24). Therefore, MOB determined by NIRS seems to be more appropriate for the evaluation of the aerobic capacity of finger flexors.

The use of systemic $\dot{V}O_2$ have been proved effective for the assessment of exercise economy/efficiency and climbing ability level during submaximal climbing intensities (Baláš et al. 2014c; Rosponi et al. 2012; Bertuzzi et al. 2007; Limonta et al. 2018). The novel finding of the current study was that, as with systemic $\dot{V}O_2$, StO_2 of the FDP was able to differentiate intermediate from advanced climbers. In lower ability climbers, there was a steeper initial drop in StO_2, however, more advanced climbers showed slower decrease of StO_2 which was probably related to their higher strength and relatively lower MVC % used for maintaining the grip position and due to force distribution on handholds which has been shown lower in more advanced climbers (better climbing economy/efficiency) (Baláš et al. 2014a). Moreover, advanced climbers have been suggested to have structural and metabolic adaptations caused by training which allow faster muscle oxygen delivery, and, therefore, higher level of StO_2 at a specific workload (Thompson et al. 2014). The $StO_{2\ \mathrm{min}}$ was suggested to predict time to failure in various hanging intensities (Feldmann et al. 2020) and differentiate climbing ability groups (Fryer et al. 2018; Fryer et al. 2015b). The current study could not confirm these findings as there was no relationship between $StO_{2\ \mathrm{min}}$ between the treadwall and hangboard tests and $StO_{2\ \mathrm{min}}$ was similar for both intermediate and advanced climbers. There may be several reasons for this: 1) $StO_{2\ \mathrm{min}}$ was found to have relatively high measurement error (Baláš et al. 2018) and using Monte Carlo modelling for $StO_{2\ \mathrm{min}}$ prediction in the previous study may have provided more consistent results (Feldmann et al. 2020); 2) intermediate climbers reported more endurance type training (Table 1) so there may have been structural and metabolic differences leading to lower $StO_{2\ \mathrm{min}}$, irrespective of ability level (Baláš et al. 2016); 3) there were different muscle motor units recruited during hangboard testing and treadwall climbing; or 4) $StO_{2\ min}$ is not a sensitive parameter to predict climbing ability with any degree of accuracy. Nevertheless, mean $\dot{V}O_2$ and StO_2 from the 3rd min (10°) together with peak angle from treadwall test were shown to explain 83 % of variance of climbing ability, which is very high taking into account that only two ability groups were tested. The findings suggest that evaluating both submaximal and maximal systemic and muscle oxygen response during exhaustive incremental climbing test provides sufficient information to assess aerobic capacity in climbers.

Several limitations should be acknowledged. The determination of test-retest reliability for MOB and GET was not performed in the current study, therefore, future studies should verify the consistency of using StO_2 and deoxy[heme] inflection points during exhaustive treadwall protocols. Based on current research in climbing (Philippe et al. 2012; Fryer et al. 2018), only FDP oxygen kinetics were analysed. Due to intra-individual differences in forearm flexor architecture, other flexors such as flexor digitorum superficialis or flexor carpi radialis might have been involved in the NIRS signal, which should, however, have a minimal effect the outcome of the current study as all these flexors are involved in climbing. Assessment of flexor digitorum superficialis or shoulder muscles may have provided additional information about muscle oxygen kinetics during the incremental climbing task. The findings were stated for a technically simple climbing route at defined speed on handholds with relatively same size which may differ from technical rock-climbing ascents. The use of MOB is, therefore, limited for routes using similar handholds configuration and size.

Conclusions

Both whole body and muscle oxygen kinetics determine climbing specific endurance. An exhaustive incremental treadwall test and isolated finger flexor endurance tests are interrelated and suitable to assess climbing specific endurance. Peak climbing angle together with mean $\dot{V}O_2$ and StO_2 from submaximal climbing explained 83 % of variance in self-reported climbing ability. Moreover, exhaustive incremental treadwall test allows for the determination of MOB. On the other hand, GET from the treadwall test does not appear suitable to reflect local metabolic changes and its determination is questioned. This study did not confirm previous findings that treadwall $\dot{V}O_{2\ peak}$ and $StO_{2\ min}$ are good predictors of climbing ability. It was also shown that commonly assessed cardiorespiratory indicators such as f_H and $\dot{V}O_2$ may not be suitable to set training intensities in climbing. Similarly, it was demonstrated that endurance exercise intensity prescription based on a percentage of MVC may be erroneous, as MOB is independent of maximal voluntary contraction.

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