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Abstract	*Purpose:* To validate heart rate (f_H) as an effective indicator of the aerobic demands of climbing, the f_H vs oxygen uptake ($\dot{V}O_2$) relationship determined during cycling exercise and climbing on a circular climbing treadwall was compared. Possible differences in maximum aerobic characteristics between advanced and élite climbers were also assessed. *Methods:* Seven advanced and six élite climbers performed a discontinuous incremental test on a cycle ergometer and a similar test on a climbing treadwall. Cardiorespiratory and gas exchange parameters were collected at rest and during exercise. *Results:* The f_H vs $\dot{V}O_2$ relationship was steeper during cycling than climbing at submaximal exercise for both groups and during climbing in the élite climbers as compared to the advanced. At peak exercise, $\dot{V}O_2$ was similar during both cycling and climbing (3332 ± 115 and 3193 ± 129 ml/min, respectively). Despite similar $\dot{V}O_{2peak}$, the élite climbers had a higher peak workload during climbing (11.8 ± 0.8 vs 9.2 ± 0.3 m/min in élite and advanced climbers, respectively; $P = .024$) but not during cycling (282 ± 13 vs 268 ± 12 W in élite and advanced climbers, respectively). *Conclusions:* Our findings indicate that care should be taken when energy expenditure during climbing is estimated from the f_H vs $\dot{V}O_2$ relationship determined in the laboratory. The level of climbing experience significantly affects the energy cost of exercise. Lastly, the similar aerobic demands of cycling and climbing at peak exercise, suggest that maximum $\dot{V}O_2$may play an important role in climbing performance. Specific training methodologies should be implemented to improve aerobic power in climbers.
Keywords (separated by '-')	Indoor climbing - Treadwall - Oxygen uptake - Heart rate - Lactate - RPE
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ORIGINAL ARTICLE

Cardiovascular and metabolic responses during indoor climbing and laboratory cycling exercise in advanced and élite climbers

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Abstract

Purpose To validate heart rate (f_H) as an effective indicator of the aerobic demands of climbing, the f_H vs oxygen uptake ($\dot{V}O_2$) relationship determined during cycling exercise and climbing on a circular climbing treadwall was compared. Possible differences in maximum aerobic characteristics between advanced and élite climbers were also assessed.
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Keywords Indoor climbing · Treadwall · Oxygen uptake · Heart rate · Lactate · RPE

Abbreviations

f_H	Heart rate
$\dot{V}O_2$	Oxygen uptake
$\dot{V}E$	Expiratory ventilation
f_R	Respiratory frequency
V_T	Tidal volume
$\dot{V}CO_2$	CO_2 production
[La⁻]	Lactate concentration
RPE	Rate of perceived exertion
CR scale	Category ratio scale
SD	Standard deviation
SE	Standard error
ES	Effect-size
CI	Confidence interval
P	Statistical significance for *t* test

Communicated by Jean-René Lacour.

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Introduction

Sport climbing is shortlisted for the Tokyo 2020 Olympic Games additional events, making precise definition of the physiological profile of climbers of pivotal importance to identify specific and effective training protocols.

Climbing requires discontinuous effort in mixed aerobic/anaerobic work (Bertuzzi et al. 2007) due to wall inclination and length, movement sequence (holds shape, size and position), speed of ascent, psychological challenge, and athlete

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ability (Aras and Akalan 2014; Mermier et al. 1997; Booth et al. 1999; de Geus et al. 2006; Draper et al. 2012, 2008; Fryer et al. 2013; Watts and Drobish 1998). The aerobic characteristics of climbers are generally assessed by indirect calorimetry through standard exercise tests carried out in the laboratory during non-specific cyclic activities such as running or cycling (Billat et al. 1995; Watts and Drobish 1998). With the introduction of treadwall ergometers, the physiological characteristics of climbers can be assessed during activities that are more similar to sport climbing (Espana-Romero et al. 2009; Watts and Drobish 1998; Booth et al. 1999). Due to the encumbrance of portable gas analyzers, heart rate (f_H) is usually monitored after being linearly related to pulmonary oxygen uptake ($\dot{V}O_2$) in the laboratory to estimate the aerobic demands of a sports activity (Arts and Kuipers 1994). However, the intermittent nature and the marked involvement of the upper limbs in climbing could affect the f_H vs $\dot{V}O_2$ relationship, making the use of f_H to estimate the aerobic demands of climbers in the field questionable (Ferrauti et al. 2001; Astrand et al. 1968; Michikami et al. 2002). Indeed, different f_H vs $\dot{V}O_2$ relationships were observed for physiological response to indoor climbing as compared to laboratory exercise tests (Balas et al. 2014; Sheel et al. 2003; Mermier et al. 1997; Watts and Drobish 1998; Booth et al. 1999). The disproportionally higher f_H values measured at lower exercise intensities were mainly explained by the marked involvement of the upper limbs that elicits higher cardiovascular responses as compared to exercise involving mainly the lower limbs (Kuepper et al. 2009; Rowell et al. 1996; Kaufman and Forster 1996). Assessment of physiological response to outdoor and laboratory testing during continuous incremental ramp tests (de Geus et al. 2006; Balas et al. 2014; Rodio et al. 2008; Sheel et al. 2003; Michailov et al. 2015; Mermier et al. 1997; Watts and Drobish 1998; Espana-Romero et al. 2009; Booth et al. 1999) generally tends to underestimate the metabolic response at a given work rate due to the fast workload increase. For better physiological evaluation, matching of cardiovascular and metabolic response should be preferably assessed under a steady condition. To date, only one study has compared the physiological response to climbing with treadmill running under a quasi-steady condition, during which subjects exercised for 4 min at a constant f_H at various mechanical work rates (Watts and Drobish 1998). The study found that during exercise at the same f_H, the $\dot{V}O_2$ was lower during climbing than running. However, this comparison was conducted with only one workload and didn't take mechanical power into account.

Lastly, training level and technical skills may also influence cardiorespiratory and metabolic response to treadwall climbing and, in turn, the f_H vs $\dot{V}O_2$ relationship (Balas et al. 2014; Espana-Romero et al. 2009). At the same submaximal climbing slope and velocity, élite athletes were found to exhibit lower $\dot{V}O_2$ and f_H, suggesting that training level and climbing experience may increase exercise economy. To date, the effects of training level and technical skills on the f_H vs $\dot{V}O_2$ relationship have never been assessed under controlled steady conditions.

The aim of the present study was to determine: (1) the possible differences between the f_H vs $\dot{V}O_2$ relationship during climbing under a macroscopic steady condition and that obtained during cycle exercising in the laboratory; (2) the effect of training level and technical skills on the f_H vs $\dot{V}O_2$ relationship. For this purpose, two groups of climbers (advanced and élite) performed a discontinuous, incremental test on a cycle ergometer and a similar discontinuous incremental test on a climbing treadwall. Given the possible effects of technical skills and training status on exercise performance, our hypothesis was that the advanced climbers would show a steeper f_H vs $\dot{V}O_2$ relationship than élite climbers during the specific (climbing) rather than the aspecific (cycling) exercise.

Methods

Participants

Thirteen male national level climbers volunteered to participate in the study. Based on the French climbing grade scale, which provides a reliable measure of performance (Draper et al. 2011, 2012), the participants reported their best climbing grade achieved in the last 2 years in the red-point and on-sight styles (Draper et al. 2011) and were assigned to either the advanced or the élite group (Draper et al. 2012, 2011). Anthropometric characteristics, climbing level and training habits are presented in Table 1. After full receiving an explanation of the purpose of the study and the experimental

Table 1 Anthropometric characteristics, climbing level, and training regime

	Advanced ($n=7$)	élite ($n=6$)
Age (years)	25.2 (3.9)	29.7 (4.9)
Stature (m)	1.79 (0.7)	1.77 (0.7)
Body mass (kg)	68.8 (6.0)	67.2 (4.3)
Body fat (%)	10.6 (1.4)	9.8 (1.2)*
Forearm circumference (cm)	28.7 (0.3)	29.8 (0.6)
Climbing experience (years)	6.8 (3.9)	11.5 (6.8)*
Training frequency (h/week)	11 (4)	14 (3)*
Best red-point level	7a + − 7c	8a − 8b +
Best on-sight level	6c + − 7b	7b − 8a +

Mean ± SD

*$P<.05$ vs advanced

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procedures, the participants gave their written, informed consent form. The study was approved by the local Ethics Committee and carried out in accordance with the principles of the 1975 Declaration of Helsinki. At the time of the study, none of the climbers reported musculoskeletal pathologies of the upper or lower limbs.

Experimental design

During their first visit to the laboratory, the participants were familiarized with the protocol as well as with the climbing and cycling equipment. Test sessions two and three were randomized. One session involved performing a discontinuous incremental test on a cycle ergometer. Since cycle ergometry is minimally influenced by movements of the body centre of mass, it allows for reliable evaluation of exercise economy and, in turn, of the f_H vs $\dot{V}O_2$ relationship. During the other visit, the subjects performed a discontinuous incremental test on a rotating climbing ergometer (Rotor Dynamic Wall, Climblock-Plastic System, Rovereto, Italy).

Tests were performed during the same week at approximately the same time of the day, with at least 48 h in between. The subjects were asked to refrain from all climbing and intense aerobic activities for 48 h prior to testing; they were instructed to have a meal similar to what they usually eat before a climbing ascent about 3 h before the tests and to abstain from any ergogenic beverages for at least 8 h.

Experimental procedures

Cycle test

The cycle ergometric test was carried out in a climate-controlled room at a constant temperature (20 ± 1 °C) and relative humidity (50 ± 5%). The tests were performed on an electrically controlled, mechanically braked cycle ergometer (839E, Monark, Vansbro, Sweden). After 5 min of rest for taking baseline measurements, the discontinuous incremental test started with the same two workloads (50 and 100 W) for all participants. Three more workloads (each lasting 4 min, with 5 min of rest in between bouts) were administered according to individual cardiorespiratory response to reach the maximum aerobic power in five workloads. The subjects were asked to maintain a cadence of 90 ± 3 rpm and the test was considered terminated when the cadence could not be maintained for more than 10 s. Verbal encouragement was given during the effort. The main gas exchange parameters (expiratory ventilation, $\dot{V}E$; respiratory frequency, f_R; tidal volume, V_T; O_2 uptake, $\dot{V}O_2$; CO_2 production) were recorded on a breath-by-breath basis with a portable metabolic system (mod. K4, Cosmed, Rome, Italy). Flow meter and gas analyzers were carefully calibrated before each test with a 3-L syringe (mod. 5530, Hans-Rudolph, Shawnee, KS, USA) and a gas mixture of known concentration (16%O_2, 5%CO_2, balance N_2). f_H was continuously monitored by electrocardiography (mod. Delta VIS, Remco Italia, Cardioline, Vignate, Italy). At rest and at the end of each workload, arterial blood samples (4 µl) were taken from the ear lobe for blood lactate concentration ([La^-]) measurement by spectrophotometry (LT-1710, Lactate Pro, Arkray, Kyoto, Japan). Rate of perceived exertion (RPE) at general (6–20 scale), muscular and respiratory levels (category ratio, CR10 scale) was reported by participants at rest and after each workload.

Climbing test

The indoor climbing test was performed on a rotating drum-shaped treadwall (4 m diameter and 12 m of linear development; Fig. 1), on which resin holds were applied to trace routes similar to those of artificial walls. As a warm-up exercise before the test, the athletes climbed the route they had successfully led during the familiarization session. The discontinuous incremental test started with 5 min of baseline measurements followed by the same two workloads (4.5 and 5.5 m/min) for all participants. Three more workloads

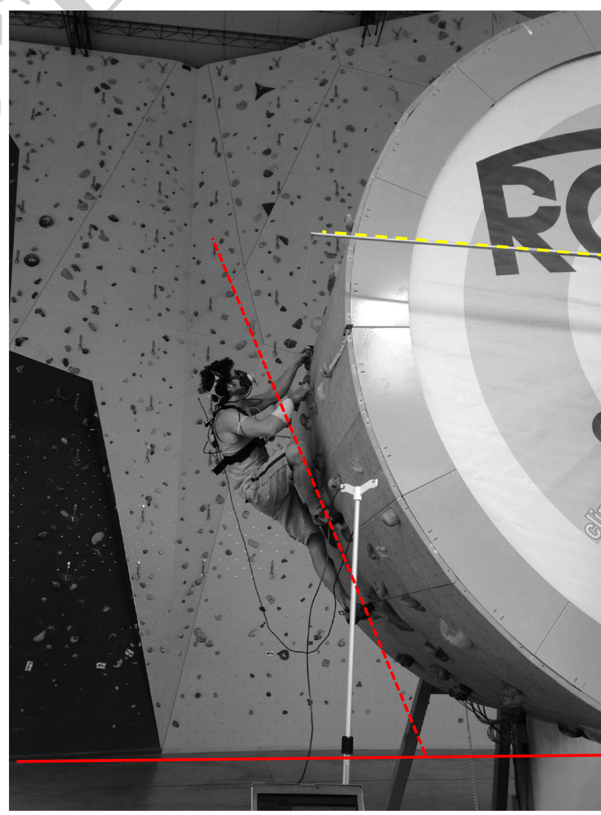

Fig. 1 The rotating treadwall utilized for the indoor climbing test. The dashed yellow line marks the limit they were not allowed to cross when reaching with their hands, thus constraining them to climb at a negative slope between 120° and 125° (dashed red line)

(each lasting 4 min, with 5 min of rest in between each bout) were administered according to individual cardiorespiratory response to reach peak aerobic power in five workloads.

The treadwall is so designed that the participants could perform the exercise uninterruptedly at each required speed. The cylindrical shape permitted to choose the inclination on which to move. During tests, the climbers were not allowed to reach with the hands beyond a horizontal thread positioned parallel to the floor, thus constraining them to climb at a negative slope between 120° and 125° (Fig. 1).

The route was gradable as 6c according to the French scale, with no abrupt technical changes; this was done in order to assess the physical involvement of climbing more than the climber's technical skills. If a fall occurred because of a technical error, the climbers were immediately allowed to resume the trial. The test was considered terminated when a climber failed to maintain the rotating speed of the treadwall. During the exercise, gas exchange parameters were collected breath-by-breath and f_H was continuously monitored. [La$^-$] was determined at rest and at the end of each workload, as were general RPE, muscular and respiratory CR10.

Data analysis and statistics

Cardiorespiratory and metabolic parameters were averaged over the last minute of each workload for both cycling and climbing tests. This averaging was performed to obtain values similar to a steady condition ("macroscopic steady") also for climbing, thus overcoming, at least in part, the intermittent nature of this effort (continuous accelerations and decelerations) that may solicit anaerobic metabolism to a higher extent (Dellal et al. 2010; Scott and Fountaine 2013; Esposito et al. 2004). The f_H vs $\dot{V}O_2$ relationship was then computed.

Statistical analysis was performed using a software package (Sigmaplot ver. 12.5, SysStat Software Inc, San Jose, CA, USA). A Kolgomorov-Smirnov test was applied to verify normal data distribution. A sample size of 13 participants was calculated to ensure a statistical power higher than 0.80. Descriptive statistics [mean; standard deviation (SD); standard error (SE)] were used to describe the study sample characteristics and results. Possible differences between conditions for the whole group were checked using paired Student's t test. To identify differences between groups, for the considered variables, unpaired Student's t test was utilized. The magnitude of changes was assessed using effect-size (ES) statistics with the standard error of ES estimate and the ES lower and upper 95% confidence interval (CI). ES was classified as trivial for values < 0.2, small between 0.2 and 0.6, moderate between 0.6 and 1.2, large between 1.2 and 2.0, and very large > 2.0 (Batterham and Hopkins 2006). The relationship between f_H and $\dot{V}O_2$ was determined by linear regression analysis. Regression lines of different groups were compared by utilizing the individual intercept and slope of each subject. Paired (differences between the two ergometers) or unpaired (differences between the two groups) Student's t test was applied to disclose significant differences in intercept and slope. Statistical significance was set at $\alpha < 0.05$.

Results

Submaximal exercise

When the pooled data from both groups were considered together, the difference between the regression line slopes of the f_H vs $\dot{V}O_2$ relationship for the cycle ($y = 0.022x + 107.1$; $R^2 = 0.68$; $P < .05$) and the treadwall ($y = 0.039x + 52.7$; $R^2 = 0.89$; $P < .05$) exercise, while close, did not achieve statistical significance ($P = .091$, ES = 0.40, CI = 1.14–0.41). However, when the élite and the advanced climbers were considered alone, both groups presented significant differences for intercept and slope between cycle and treadwall exercise (Fig. 2c, d). Differences between the élite and the advanced athletes emerged only for the specific treadwall exercise, where the difference in slope reached statistical significance ($P = .010$, ES = 0.69, CI = − 0.14 to 2.18; Fig. 2b).

When $\dot{V}O_2$ was considered as a function of mechanical power during cycle exercise, no differences were found between the regression line equations for the élite ($y = 8.76x + 1120.4$; $R^2 = 0.95$; $P < .05$) and the advanced ($y = 8.42x + 1240.1$; $R^2 = 0.96$; $P < .05$) climbers. During treadwall climbing, the regression line equations for élite ($y = 130.2x + 1624.2$; $R^2 = 0.83$; $P < .05$) and the advanced ($y = 132.1x + 2226.2$; $R^2 = 0.58$; $P < .05$) climbers paralleled each other and differed significantly only for the intercept.

Peak exercise

The maximum mechanical aerobic power achieved during the cycle test was 282 ± 10 W. When the two groups were compared, the élite and the advanced climbers achieved 291 ± 13 and 270 ± 12 W, respectively ($P = .024$, ES = 0.67, CI = − 0.50 to 1.73). During the climbing exercise, the maximum velocity was 10.9 ± 1.5 m/min (11.8 ± 0.8 for the élite and 9.2 ± 0.3 m/min for the advanced climbers) ($P = .003$, ES = 0.65, CI = 0.41–2.94). The physiological parameters at maximum exercise are shown in Fig. 3. No differences were found at maximum exercise between the two testing modalities for $\dot{V}O_2$ and f_H (Fig. 3a, b). Conversely, lower $\dot{V}E$ (156.9 ± 6.3 and 116.0 ± 4.1 L/min for cycle and climbing, respectively; $P = .000$, ES = 0.49, CI = −3.02 to − 1.12), due to reduced V_T (2.75 ± 0.11 and 2.36 ± 0.05 L for cycle and climbing, respectively; $P = .002$, ES = 0.43, CI = − 2.07 to − 0.39) and f_R (58.2 ± 3.3 and 49.6 ± 1.7 b/min for cycle

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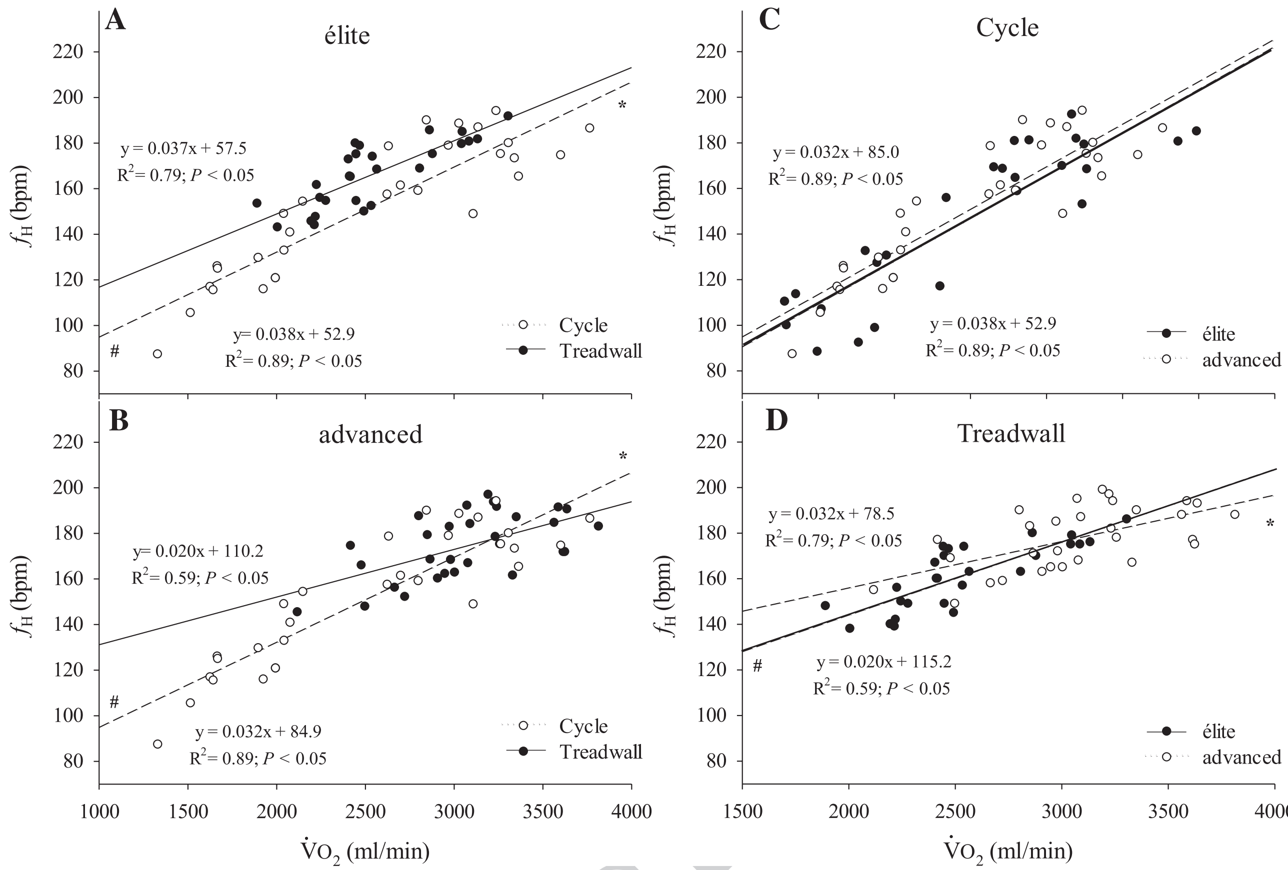

Fig. 2 Heart rate vs oxygen uptake (f_H vs $\dot{V}O_2$) relationship at different exercise intensities during climbing and cycling tests, for the advanced ($n=7$) and the élite ($n=6$) climbers. $^*P<.05$, statistical difference in slope value between the two regression lines (cycling and climbing exercise); $^{\#}P<.05$, statistical difference in intercept value between the two regression lines

and climbing, respectively; $P=.039$, ES = 0.41, CI = − 1.69 to − 0.08) were observed for climbing. Also, lower [La$^-$] values (see Fig. 3c; $P<.000$, ES = 0.61, CI = − 3.29 to − 1.31) were found for climbing. No differences between the advanced and the élite athletes were found.

Lower general RPE ($P=.025$, ES = 0.41, CI = − 1.73 to − 0.11), lower muscular ($P=.017$, ES = 0.41, CI = − 1.78 to − 0.15) and respiratory CR10 ($P=.005$, ES = 0.41, CI = − 1.77 to − 0.15) for climbing than cycling was observed (Fig. 4). The advanced climbers expressed higher scores for general ($P=.040$, ES = 0.60, CI = − 1.98 to 0.30) and muscular ($P=.025$, ES = 0.60, CI = − 2.32 to 0.03) RPE during cycling than the élite athletes.

Discussion

The main finding of the present study was that, when the data from all participants were pooled together, the f_H vs $\dot{V}O_2$ relationship during cycling was steeper than that observed during climbing under a macroscopic steady condition. Higher f_H values were observed during climbing than during cycling at low and medium workload intensities at the same $\dot{V}O_2$. Moreover, a significant difference in the f_H vs $\dot{V}O_2$ slope was found during climbing between the élite and the advanced athletes, suggesting that training level and technical skills may affect that relationship. Interestingly, in spite of the similar peak $\dot{V}O_2$ and f_H values, peak climbing velocity was higher for the élite climbers, indicating a better climbing efficiency at maximum climbing velocity.

Preliminary considerations

The atypical nature of climbing make it very difficult to standardize specific testing protocols approximating real-world climbing conditions. For instance, a speed-controlled climbing ascent may not be representative of true climbing situations as athletes tend to climb at a self-selected pace (Giles et al. 2006). This may seem a limitation of our study. However, the macroscopic steady condition achieved during treadwall climbing was an essential prerequisite to

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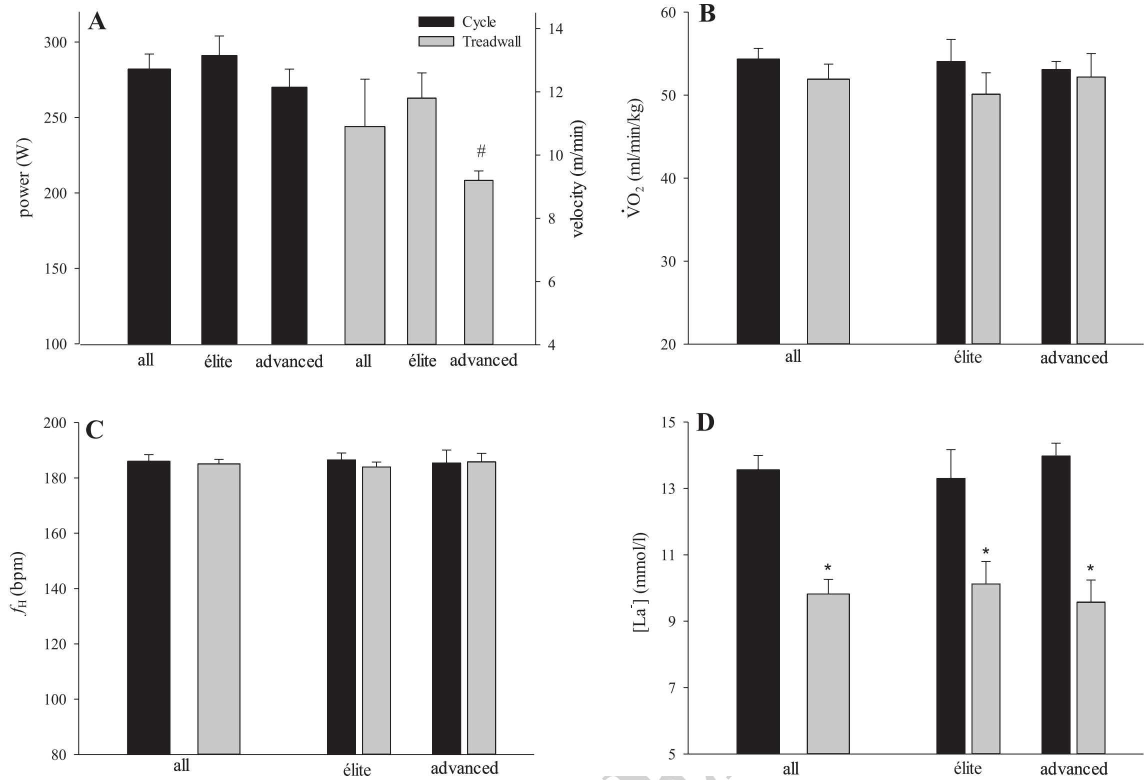

Fig. 3 Physiological parameters at maximal exercise (power or velocity; pulmonary O_2 uptake, $\dot{V}O_2$; heart rate, f_H; blood lactate concentration, $[La^-]$) during climbing and cycling exercise for the whole group and the advanced ($n = 7$) and the élite ($n = 6$) climbers. *$P < .05$ vs cycle

compare cardiovascular and metabolic responses with exercise intensity.

We chose a steadily negative treadwall slope to make the testing protocol more representative of climbing competitions that frequently include routes on overhanging walls (Mermier et al. 1997; Watts and Drobish 1998). For this reason, cardiorespiratory values during the climbing tests were much higher, and the climbing speed slower, than in previous investigations (Mermier et al. 1997; Watts and Drobish 1998; Sheel et al. 2003; de Geus et al. 2006; Giles et al. 2006; Booth et al. 1999). Nevertheless, the speed of ascent in the present study (4–11 m/min) was faster than that reported during usual, self-selected outdoor climbing (3–5 m/min) (Booth et al. 1999).

Physiological responses at submaximal exercise

Cardiovascular and respiratory responses to discontinuous incremental exercise increased with exercise intensity for both testing modalities, providing experimental evidence that mechanical work was higher when climbing treadwall speed was faster, while inclination and difficulty were held constant.

Consistent with previous studies (Mermier et al. 1997; Watts and Drobish 1998; Balas et al. 2014; Sheel et al. 2003; Booth et al. 1999), the relationship between f_H and $\dot{V}O_2$ during climbing differed from that observed in cycling. Disproportionately higher f_H values with respect to $\dot{V}O_2$ were observed when climbing at low and medium velocities. This phenomenon may be explained by longer isometric phases of the forearm muscles when climbing ascent is slow. There is, indeed, a disproportionate rise in blood pressure, cardiac output and f_H under isometric as compared to dynamic actions, especially when the upper limb muscles are involved (Kuepper et al. 2009; Rowell et al. 1996; Astrand et al. 2003; Rowell 1993; Kaufman and Forster 1996). At higher climbing intensities this phenomenon may be attenuated as movement speed increases and, consequently, the isometric phase of the upper limb muscles shortens (Mermier et al. 1997). Moreover, the f_H discrepancy between climbing and cycling may be related to a greater cardiovascular response to exercise typical to when the arms work above the heart level (Rowell et al. 1996; Rowell 1993; Kaufman and Forster 1996). Also, higher psychological stress and/or anxiety in climbing may contribute to explain this phenomenon, especially when f_H is far from its maximum limit (Mermier et al. 1997).

The novelty of the present investigation was the matching of physiological responses to climbing and exercise intensity (treadwall speed) under a macroscopic steady condition of

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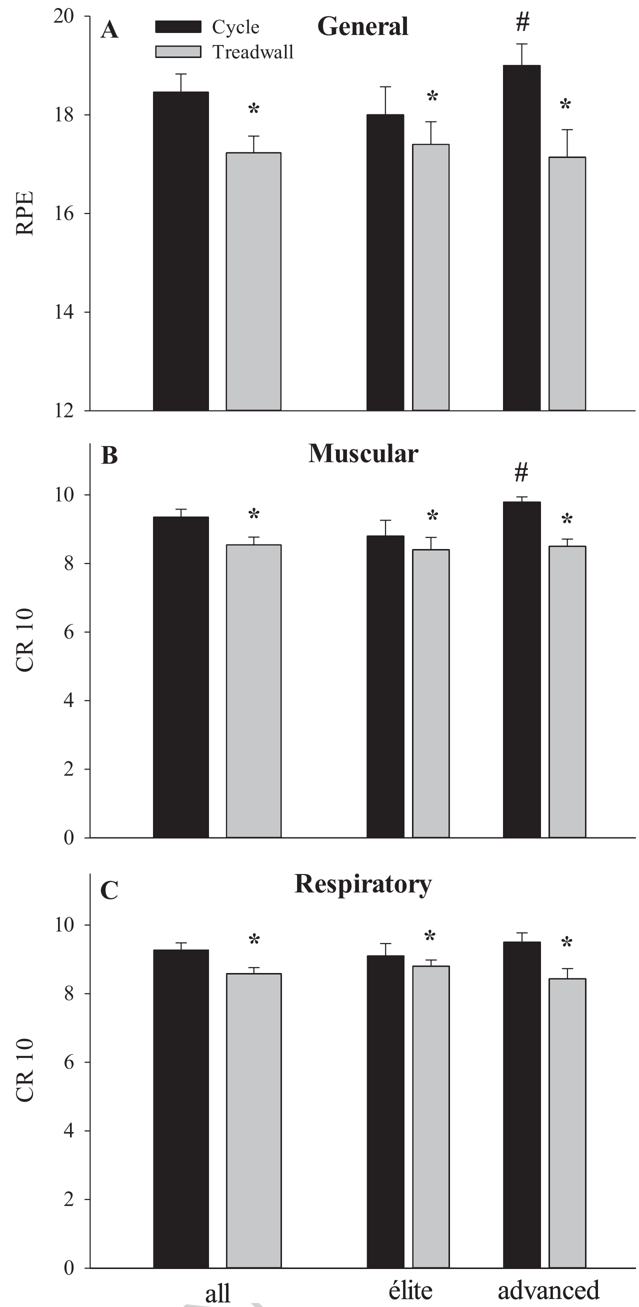

Fig. 4 General rate of perceived exertion (RPE; Borg scale 6–20), muscular and respiratory CR10 during the climbing and cycling tests for the whole group and the advanced ($n=7$) and the élite ($n=6$) climbers. $^{*}P<.05$ vs cycle; $^{\#}P<.05$ vs élite

the discontinuous incremental protocol, thus overcoming the intrinsic limits of ramp protocols. Ramp protocols include changes in work rate that could be faster than cardiorespiratory and metabolic adjustments and so may not represent the best testing modality to achieve mechanical and metabolic power matching (Riboli et al. 2017).

Collectively, our data seem to suggest that f_H shouldn't be considered a good marker of metabolic demands in climbing. Accordingly, it cannot be used adequately to monitor and prescribe climbing training intensities because, despite the macroscopic steady condition, f_H at low climbing velocity was markedly higher than in cycling at the same $\dot{V}O_2$.

Differences in the f_H vs $\dot{V}O_2$ relationship between élite and advanced climbers have been currently investigated. Recent studies observed that élite climbers have an attenuated pressure response to isometric exercise and an increased muscle vasodilator capacity as compared to less experienced climbers (Sheel et al. 2003). Previous data and the present findings show that the slope of the f_H vs $\dot{V}O_2$ relationship during climbing is higher in élite than in advanced climbers. A plausible explanation on the effects of training and experience levels is the difference in pressure response to isometric exercise in élite climbers, who present a lower cardiovascular response to low and moderate exercise intensity during climbing. This was not the case at maximum climbing exercise because the cardiovascular response to exercise in that scenario is very close to its maximum, and therefore may not differ between the two groups.

Lastly, when we considered $\dot{V}O_2$ and f_H as a function of climbing velocity, the élite climbers showed lower $\dot{V}O_2$ and f_H values at the same ascent velocity, with greater exercise economy. This was not the case during cycle exercise, however, suggesting that differences between the two groups existed only for a specific and not a generic testing modality. The greater economy of movement reported for élite athletes during climbing (Balas et al. 2014; Bertuzzi et al. 2007) may depend on better postural control and technical optimization of movements (Bertuzzi et al. 2007). Whether this finding was due to physiological aspects or to greater technical skills still remains an open question.

Physiological and perceptual involvement at peak exercise

At peak exercise, the cardiorespiratory and metabolic commitment was similar for the two exercise modalities. The $\dot{V}O_2$ and f_H at peak climbing exercise were about 96% and 99%, respectively, of those at peak cycle exercise. These findings seem to contradict previous observations in which physiological commitment at peak climbing exercise ranged between 45 and 70% of $\dot{V}O_2$ at maximum treadwall exercise (Balas et al. 2014; Billat et al. 1995; Mermier et al. 1997). Considering also that climbers generally report $\dot{V}O_{2peak}$ values markedly lower than endurance athletes, it was concluded that aerobic capacity plays a secondary role in climbing (Billat et al. 1995; Michailov et al. 2015). As mentioned previously, however, these studies were carried out with continuous incremental ramp tests and not under a macroscopic steady condition, implying that the increase in work rate reported in previous studies was faster than cardiorespiratory and metabolic

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adjustments (Riboli et al. 2017). In addition, the athletes tested in those studies of previous investigations climbed on vertical or slightly overhanging walls, following routes of low difficulty (Balas et al. 2014; Mermier et al. 2000; Watts and Drobish 1998; Espana-Romero et al. 2009) and without being asked to climb at their maximum speed, thus leading unquestionably to reduced physiological demands. In our study, the climbing tests were performed up to maximum climbing velocity on a constant overhanging wall, and each workload was held constant for 4 min (macroscopic steady condition). In previous studies, the lower $\dot{V}O_{2_{peak}}$ in climbers was also ascribed to the small involvement of the upper limb muscle mass as compared to cyclic locomotion modalities (running, pedaling) (Michailov et al. 2015). However, climbing globally involves a greater number of skeletal muscles not only for primary movements but also to maintain a constant postural control in conditions of instability. Therefore, climbing should be considered as a whole-body exercise, as also evidenced by the high percentage of cycle $\dot{V}O_{2_{peak}}$ during climbing.

Collectively, these findings suggest that $\dot{V}O_{2_{peak}}$ needs to be reconsidered as an strategic factor for climbing performance, thus questioning the current belief that maximum aerobic fitness is not an important requirement for climbing.

In line with previous studies (Mermier et al. 1997; Watts et al. 2000), we observed lower maximal [La$^-$] during climbing than cycling. Compared to the large body muscle mass involved in running or cycling, the small size of the active muscles of the upper body utilizing anaerobic metabolism in climbing may have played an important role (Mermier et al. 1997; Watts et al. 2000). Nevertheless, we observed higher [La$^-$] levels at peak climbing exercise than those found previously (Giles et al. 2006; Michailov et al. 2015). This finding could be explained by the relatively long effort at maximum velocity during the last workload in the present protocol (4 min), without rest periods in between bouts. When athletes climb at a self-selected velocity, they generally take short rests on large holds to reduce peripheral muscle fatigue and to allow partial resynthesis of the high-energy phosphate stores (Bertuzzi et al. 2007).

RPE and CR10 values were lower at peak climbing exercise than during cycling at general, muscular and respiratory levels. This finding well reflects the lower f_R during climbing. Indeed, f_R seems to be strongly related not only to respiratory but also to general RPE (Nicolo et al. 2016). Also, the lower [La$^-$] may have influenced muscular CR10 during climbing. Furthermore, the higher confidence and expertise of our subjects with climbing than cycling exercise may have affected RPE and CR10 outcomes.

When the group was divided into élite and advanced climbers, the same dissimilarities between cycling and climbing persisted. Though the two groups did not differ for physiological parameters at peak exercise, including peak $\dot{V}O_2$, the élite athletes achieved a higher peak workload during the climbing test. This observation, together with the lower $\dot{V}O_2$ vs climbing velocity relationship (Fig. 4b), highlight the higher exercise economy in the élite climbers during the specific testing modality. When exercise was aspecific, i.e., during cycling, the difference in exercise economy disappeared.

The advanced climbers reported higher general and muscular RPE only at maximum cycle exercise and similar RPE values at maximum climbing exercise. This could have been due to a less familiarity with fatigue perception and maximum effort during an unusual exercise modality mostly involving the lower rather than the upper limb muscles. Future studies are may better elucidate the role of training and experience level on the central and peripheral aspects of the perception of fatigue. There is also a need to investigate the differential effect of specific and aspecific exercise modalities on RPE.

Practical applications and conclusions

Since sport climbing has recently been included in the next Olympic Games (Tokyo 2020) program, it becomes crucial to appropriately define the physiological profile of this discipline and to assess the determinant factors of climbing performance. Our study results suggest that f_H may not be considered as a good marker of aerobic demands in climbing. Moreover, the élite climbers showed a physiological engagement similar to that in of the advanced athletes but at higher work rates during climbing, indicating better exercise economy during the specific exercise. Lastly, the lack of a difference in $\dot{V}O_2$ at peak exercise between the two exercise modalities indicates that the current belief that $\dot{V}O_{2max}$ is not a prerequisite for climbing performance may be inaccurate. For this reason, specific training components to improve peak aerobic power in climbers should be employed to optimize performance.

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Compliance with ethical standards

Conflict of interest The authors declare no conflict of interest.

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