Original articles

Energy cost of sport rock climbing in elite performers

John Booth, Frank Marino, Chris Hill, Tom Gwinn

Abstract

***Objectives*—To assess oxygen uptake ($\dot{V}O_2$), blood lactate concentration ($[La_b]$), and heart rate (HR) response during indoor and outdoor sport climbing.**

***Methods*—Seven climbers aged 25 (SE 1) years, with a personal best ascent without preview or fall (on sight) ranging from 6b to 7a were assessed using an indoor vertical treadmill with artificial rock hand/foot holds and a discontinuous protocol with climbing velocity incremented until voluntary fatigue. On a separate occasion the subjects performed a 23.4 m outdoor rock climb graded 5c and taking 7 min 36 s (SE 33 s) to complete. Cardiorespiratory parameters were measured using a telemetry system and $[La_b]$ collected at rest and after climbing.**

***Results*—Indoor climbing elicited a peak oxygen uptake ($\dot{V}O_{2climb\text{-}peak}$) and peak HR ($HR_{peak}$) of 43.8 (SE 2.2) ml/kg/min and 190 (SE 4) bpm, respectively and increased blood lactate concentration $[La_b]$ from 1.4 (0.1) to 10.2 (0.6) mmol/l ($p < 0.05$). During outdoor climbing $\dot{V}O_2$ and HR increased to about 75% and 83% of $\dot{V}O_{2climb\text{-}peak}$ and HR_{peak}, respectively. $[La_b]$ increased from 1.3 (0.1) at rest to 4.5 mmol/l ($p < 0.05$) at 2 min 32 s (8 s) after completion of the climb.**

***Conclusions*—The results suggest that for elite climbers outdoor sport rock climbs of five to 10 minutes' duration and moderate difficulty require a significant portion of the $\dot{V}O_{2climb\text{-}peak}$. The higher HR and $\dot{V}O_2$ for outdoor climbing and the increased $[La_b]$ could be the result of repeated isometric contractions, particularly from the arm and forearm muscles.**

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Keywords: rock climbing; performance; oxygen uptake; heart rate; lactate

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Sport climbing is a discipline of rock climbing which is performed indoors and outdoors. Indoor sport climbing is characterised by gymnastic type movements on walls fitted with artificial hand and foot holds and is an internationally contested event. Outdoor sport climbing requires similar movements with the climber guarded from injury during a fall by protection fixed in the rock before ascent. This style of rock climbing and the increased popularity of climbing in recent years have contributed to an increase in the number and difficulty of rock climbing ascents.

Although climbers are characterised by low body fat, exceptional power to weight ratios,[1 2] and forearm circulatory adaptations favouring the performance of isometric work,[3] the physiological factors related to sport climbing remain essentially undefined. Previous research suggests that indoor sport climbing is highly anaerobic in nature given the low fraction (~46%) of running maximum oxygen uptake ($\dot{V}O_{2max}$) required for ascents of three to five minutes' duration.[4] However, no study has reported $\dot{V}O_2$ in well trained climbers at different climbing velocities or $\dot{V}O_2$ as peak oxygen uptake ($\dot{V}O_{2climb\text{-}peak}$) determined during a specific incremental climbing test to exhaustion. Furthermore, no study has reported $\dot{V}O_2$ during an outdoor sport climb or expressed $\dot{V}O_2$ as a percentage of $\dot{V}O_{2climb\text{-}peak}$.

Therefore, the purpose of this study was to investigate oxygen consumption during indoor and outdoor sport climbing. During indoor climbing a rock climbing specific ergometer fitted with artificial hand/foot holds was used and climbing velocity incremented until exhaustion to determine $\dot{V}O_{2climb\text{-}peak}$. During the outdoor climb oxygen uptake and the fractional use of a peak oxygen uptake ($\%\dot{V}O_{2climb\text{-}peak}$) were investigated. In addition, HR and blood lactate concentrations ($[La_b]$) were measured.

Methods

SUBJECTS AND STUDY DESIGN

Six men and one woman volunteered as subjects and were all in good health as reported by a medical screening questionnaire. Table 1 gives descriptive characteristics of the subjects. The mean climbing experience of the group was 8.9 (SE 1.2) years, and for individuals the most difficult outdoor ascent made without preview or fall (on sight ascent) ranged from 6b to 7a. With the numerical scale for climbing difficulty ranging from 5a (novice) to 7c (expert) (UK grading system) the subject sample comprised highly skilled climbers.

On one occasion anthropometric measurements were taken, a capillary (finger prick)

Table 1 Characteristics of subjects. Mean (SE) is given except for †, which represents range

Subject	*Age (years)*	*Climbing experience (years)*	*Best on sight*	*Ht (cm)*	*Body mass (kg)*	*Sum 9 skinfolds (mm)*	*$\dot{V}O_{2climb\text{-}peak}$ (ml/kg/min)*	*Max HR (bpm)*
1	30	15	6c	176.3	56.52	54.6	37.3	185
2	25	5	6b	172.5	68.14	54.4	45.2	185
3	26	10	6c	176.4	65.10	78.9	45.1	200
4*	26	8	6b	164.3	53.56	75.4	39.7	200
5	24	9	7a	183.8	73.17	58.2	43.2	197
6	21	6	6c	171.3	51.12	52.6	55.1	184
7	25	9	6c	185.0	70.31	55.2	41.2	178
Mean	25	8.9	6b†	175.7	62.60	61.3	43.8	190
(SE)	1	1.2	7a	2.7	3.30	4.2	2.2	4

*Subject No 4 was female.

blood sample was collected for the measurement of resting [La_b] and subjects weighed with the telemetry system and dressed in climbing apparel consisting of a T shirt, body tights, waist harness, and shoes specifically for climbing. The subjects then performed a sport climbing specific test of maximal aerobic capacity involving an incremental climbing test to volitional fatigue on a vertical climbing ergometer (Crestville Holdings, Sydney, Australia) fitted with artificial rock hand/foot holds. Large various shaped holds were randomly placed in close formation on the belt surface with their position standardised for all trials. The belt speed of the ergometer was calibrated before each trial and monitored by continuous digital output. The protocol is original and designed to determine steady state climbing $\dot{V}O_2$ and HR at different velocities and a $\dot{V}O_{2climb\text{-}peak}$. The incremental protocol consisted of three trials at increasing velocity with 20 minute rest periods between trials owing to the strenuous nature of the climbing exercise. During recovery, forearm muscle contractile function was assessed, but these data are not reported here. Trials 1 and 2 lasted for five minutes at a climbing velocity of 8 and 10 m/min, respectively. For the third trial the speed was kept at 12 m/min for five minutes and increased to 14 and 16 m/min at five and six minutes, respectively. Climbing on the ergometer required a high degree of skill, particularly at the higher climbing velocities. To minimise the influence of skill on the outcome of the maximal test, climbing speed was not incremented beyond 16 m/min. Furthermore, for trial 3 exhaustion was elicited within eight to 10 minutes, which is optimal for the evaluation of maximal aerobic power.[3 4] During the third trial subjects were verbally encouraged to climb until volitional fatigue, at which point climbing ceased and the subjects were assisted from the ergometer. At the completion of each trial a capillary blood sample was collected immediately. In this study the highest $\dot{V}O_2$ (ml/kg/min) over a one minute interval was used to define $\dot{V}O_{2climb\text{-}peak}$ during climbing.

On a separate occasion the subjects refrained from vigorous exercise, caffeine, and alcohol ingestion at least 48 hours before performing an outdoor sport climb which all subjects had climbed previously. After a resting capillary blood sample was collected for measurement of [La_b], an HR transmitter strap was attached and the subjects were weighed with the telemetry system and dressed in similar climbing apparel as worn during the incremental test. The subjects were secured by a waist harness to a 10 mm dynamic rope fed through a ring bolt at the top of the climb and returned to a belayer at the start of the climb. During the climb no assistance was afforded to the climber by the rope which was kept "slack". Although some variation in hand and foothold selection was inevitable, the general route direction was the same for all climbers and marked by fixed protection placed at about 2 m intervals. At the completion of the climb tension was applied to the rope and the subjects were lowered to the ground and a capillary blood sample collected. Caution was necessary during lowering-off to avoid tangling the climber in a tree and to land them on the narrow cliff ledge, thus time for blood sampling after the climb varied (2 min 32 s (SE 8 s)).

The climb is located at an elevation of 890 m and is 24.4 m long measured from the base of the climb to the top ring bolt housing the fixed rope. On the day of the climb the ambient temperature was 7.8 (SE 0.2)°C. The climb is graded 5c and is overhanging throughout its length (~4 m) with good hand and foot holds and requires more physical than technical prowess.[5] Climb duration was the time which elapsed between the start of the climb (feet off the ground) until the ring bolt was grasped by the subject.

MATERIALS

Skinfold thickness was measured with skinfold calipers (British Indicators Ltd, England) at nine sites (biceps, triceps, pectoral, subscapular, suprailiac, mid-abdominal, thigh, calf, and mid-axilla) as suggested by Norton *et al*.[6] All sites were measured in triplicate with the median value recorded. Height was measured using a stadiometer to the nearest 0.1 cm. Body mass was measured to the nearest 10 g using an electronic precision balance (HW-100KAI, GEC, Avery Ltd, Australia).

Blood lactate was measured from a capillary (finger prick) blood sample using a portable Accusport lactate analyser (Boehringer Mannheim, Germany). At lactate concentrations of 1.0–15 mmol/l, the accuracy and linearity of the Accusport compared with standard enzymatic methods was r=0.98 and r=0.99, respectively.[7] In our laboratory the Accusport provides a coefficient of variation of 0.05%. HR was recorded with a Sports Tester (Polar Electro, Oy, Finland) at rest and at 15 second intervals.

A portable telemetry system (Cosmed K2) was used to collect expired gas, with ventilation and oxygen consumption ($\dot{V}O_2$) measured at 15 second intervals. The accuracy of the K2 for measurement of $\dot{V}O_2$ during physical movement has been described elsewhere,[8–10] with no significant difference in $\dot{V}O_2$ measured by Douglas bag[8 9] or online oxygen analysis.[10] Furthermore, the K2 has been used in various studies in which conventional gas analysis was either difficult or not practical.[8 11] The K2 was calibrated before each trial against inspired

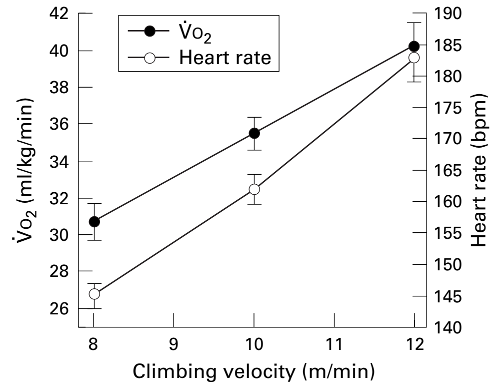

Figure 1 The mean oxygen uptake ($\dot{V}O_2$) and heart rate as a function of climbing velocity; number of subjects = 7. Values are means (SE).

air assumed to have a fractional oxygen concentration of 20.9%. Volume was calibrated by a turbine flowmeter with a 2 litre syringe (Hans Rudolph). The reproducibility of the measurement of a standard gas containing 15.9% oxygen ranged from 15.7 to 16.2% for five trials giving a coefficient of variation of 1.2%. Although the reproducibility of $\dot{V}O_2$ may be limited by the accuracy of the K2, this apparatus is currently the only practical method available for use in a field setting such as in this study. During climbing, the telemetry system was housed in a pack worn on the participants' back (combined weight 3 kg) secured at the shoulders and the waist.

The data were analysed by analysis of variance with repeated measures on time. Significant differences were located with the Student-Newman-Keuls test. Pearson's bivariate correlations were computed for HR and $\dot{V}O_2$. The relation between HR, $\dot{V}O_2$, and climbing rate was determined by regression analysis. Statistical significance was set at $p<0.05$. Values are given as means (SE).

Results

RESPONSES TO SUBMAXIMAL AND MAXIMAL ERGOMETER CLIMBING

All subjects completed the five minute climb at 8, 10, and 12 m/min. Figure 1 shows the oxygen consumption and HR as a function of climbing velocity at 8, 10, and 12 minutes. As expected the $\dot{V}O_2$ and HR responses were similar and increased linearly with climbing rate. Linear regression analysis to predict the $\dot{V}O_2$ and HR response for climbing velocity yielded the following equations: $\dot{V}O_2 = (11.8 + 2.36) \times$ climbing velocity ($r^2=0.98$, $p<0.01$) and HR = $(70.3 + 9.32) \times$ climbing velocity ($r^2=0.97$, $p<0.01$). Blood lactate increased ($p<0.05$) from 1.43 (0.1) mmol/l at rest to 4.54 (0.46) mmol/l and 6.50 (0.69) mmol/l after five minutes' climbing at 8 and 10 m/min, respectively. Steady state HR and $\dot{V}O_2$ were significantly correlated during climbing at 8, 10, and 12 m/min ($r=0.76$, $p<0.05$). The time to exhaustion for the third trial with the climbing velocity incremented from 12 to 16 m/min was 7 min 44 s (40 s). Climbing to exhaustion yielded a $\dot{V}O_{2climb\text{-}peak}$ and peak HR (HR_{peak}) of 43.8 (2.2) ml/kg/min, and 190 (4) bpm, respectively, with an [La_b] of 10.2 (0.6) mmol/l (see table 2).

Table 2 $\dot{V}O_{2climb\text{-}peak}$, HR_{peak}, [La_b] and climbing duration for (a) the incremental climbing test to exhaustion, (b) the outdoor sport climbing and, (c) values expressed as a percentage of the peak values determined during the incremental climbing test to exhaustion. Values are means (SE) for seven subjects

$\dot{V}O_{2climb\text{-}peak}$ (ml/kg/min)	HR_{peak} (bpm)	[La_b] (mmol/l)	Climb duration (min, s)
(a) 43.8 (2.2)	190 (4)	10.2 (0.6)	7 min 44 s (40 s)
(b) 32.8 (2.0)	157 (8)	4.51 (0.5)	7 min 36 s (33 s)
(c) 75 (4) %	83 (4) %	44 (4) %	7 min 36 s (33 s)

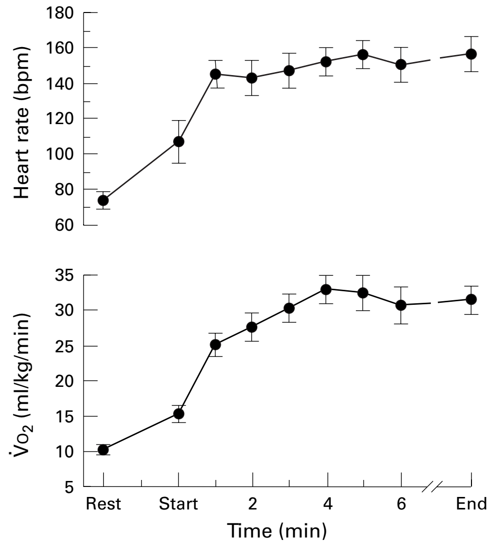

Figure 2 The mean oxygen uptake ($\dot{V}O_2$) and heart rate (HR) during outdoor sport rock climbing. At all times the number of subjects was seven, except at six minutes where the number was six. Values are means (SE). From one minute, HR and $\dot{V}O_2$ were significantly greater than at the start of the climb at all times ($p<0.05$).

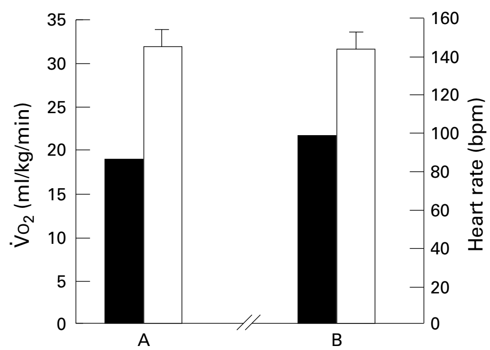

Figure 3 (A) The predicted oxygen uptake ($\dot{V}O_2$, filled bar) for outdoor climbing and the mean $\dot{V}O_2$ at five minutes during the outdoor climb; (B) the predicted heart rate (HR, filled bar) for outdoor climbing and the mean HR at five minutes during the outdoor climb. Number of subjects = 7. Values are means (SE).

RESPONSES TO OUTDOOR CLIMBING

The duration of the outdoor rock climb was 7 min 36 s (33 s) (range 6 min 28 s to 9 min 54 s) with all subjects completing the ascent without a fall. The mean climbing velocity was 3.2 (0.2) m/min. Figure 2 shows the data for $\dot{V}O_2$ and HR during the outdoor climbing trial. The resting HR of 74 (5) bpm was increased to 107 (12) bpm at the start of the climb ($p<0.05$) and further increased to 145 (10) bpm after one minute ($p<0.05$). Heart rate was not significantly different throughout the remainder of the climb, increasing to 157 (8) bpm after five minutes' climbing, this being about 83% of HR_{peak}. The $\dot{V}O_2$ of 15.2 (1.2) ml/kg/min at the start of the climb was significantly ($p<0.05$) increased at one minute and throughout the remainder of the climb. After four minutes $\dot{V}O_2$ reached 32.8 (2.0) ml/kg/min, representing about 75% of $\dot{V}O_{2climb\text{-}peak}$. Blood lactate was increased from 1.3 (0.1) mmol/l at rest to 4.5 (0.5) mmol/l at 2 min 31 s (8 s) after the completion of the climb ($p<0.05$). Using the regression equation for $\dot{V}O_2$ versus climbing velocity and HR versus climbing velocity, the predicted $\dot{V}O_2$ and HR at the outdoor climbing velocity of 3.2 (0.2) m/min were 19.4 ml/kg/min and 100 bpm, respectively (fig 3).

Discussion

Despite the increased popularity of sport climbing in recent years, the physiological factors related to this activity remain relatively undefined with no data for outdoor sport climbing. In this study a K2 portable telemetry system was used to measure $\dot{V}O_2$ continuously during an outdoor rock climb and expressed as a percentage of $\dot{V}O_{2climb\text{-}peak}$. The K2 is a reliable method for measuring $\dot{V}O_2$ during exercise[9–11] and useful when conventional gas analysis is difficult or impractical.[8 11]

The finding that the outdoor sport climb required a significant portion of the $\dot{V}O_{2climb\text{-}peak}$ (about 75%) suggests that outdoor climbing might require a large fraction of the climber's peak oxygen uptake. Although these findings are somewhat different from those of previous work,[4] the differences can partly be explained by the method used to express climbing $\dot{V}O_2$ as a percentage of pulling (~ 95%) or running $\dot{V}O_{2max}$ (~ 38%).[4] As $\dot{V}O_{2max}$ is directly related to the amount of contracting muscle,[12 13] pulling and running protocols have limited application to sport climbing. A more meaningful expression of climbing $\dot{V}O_2$ is as a fraction of the climber's peak aerobic power determined during a specific sport climbing test. In our study $\dot{V}O_{2climb\text{-}peak}$ was assessed during exhaustive climbing on a vertical ergometer fitted with artificial hand/foot holds. Although no data exist for $\dot{V}O_{2climb\text{-}peak}$ in elite climbers, pulling and running $\dot{V}O_{2max}$ were respectively 22 and 55 ml/kg/min in competitive sport climbers.[4] While similar running $\dot{V}O_{2max}$ values occur for other non-endurance trained elite athletes (for example, gymnasts, wrestlers), values as low as 50 ml/kg/min have been reported for this group.[14] In the present study climbing on artificial hand/foot holds might be expected to use more contracting muscle than a maximal pulling protocol, and less than a running protocol. Accordingly, maximal climbing exercise elicited a $\dot{V}O_{2climb\text{-}peak}$ of ~ 44 ml/kg/min. Although localised muscle fatigue in the upper limbs might have been a primary factor for fatigue during maximal climbing, the $[La_b]$ of about 10 mmol/l and HR within 10% of the age predicted maximum suggests that the subjects were working maximally when the highest $\dot{V}O_2$ was measured.[15 16]

At an outdoor climbing velocity of 3.2 m/min, $\dot{V}O_2$ and HR were predicted to reach 44% and 53% of the HR_{peak} and $\dot{V}O_{2climb\text{-}peak}$, respectively. However, during the outdoor climb $\dot{V}O_2$ and HR reached about 75% and 83% of the HR_{peak} and $\dot{V}O_{2climb\text{-}peak}$, respectively. One contribution to the greater energy expenditure during outdoor climbing might be the increased isometric contraction time of the upper limbs as the climber's weight is supported intermittently for a considerable period of time. Immobilisation time was not recorded during the outdoor climb, but isometric contraction time during sport climbing can account for more than one third of the total ascent time.[4] Thus during climbing, the muscles, and in particular muscles of the arm and forearm, are subject to extensive isometric loading.[17] On steeper climbs, such as in this study, isometric loading of the upper limb muscles would be further increased as more of the climber's weight is forced onto the arms with less support by the legs. Consequently, repeated isometric contractions during the outdoor climb might be expected to cause a steep rise in heart rate and blood pressure and augment oxygen uptake.[18 19] The possibility that isometric contractions mediate the HR and $\dot{V}O_2$ response during outdoor climbing is suggested by the lower correlation for HR and $\dot{V}O_2$ during outdoor ($r=0.57$) compared with indoor climbing ($r=0.76$). These results are similar to those reported by Mermier *et al*,[20] who showed that $\dot{V}O_2$ and HR appear to be non-linearly related during indoor rock climbing. These authors suggested that isometric exercise elicited a disproportionate rise in HR in relation to $\dot{V}O_2$. However, the HR response during climbing may be strongly influenced by increased psychological stress in the form of anxiety or fear from falling.[21] Although psychological stress was not measured in the present study, it is unlikely that it influenced our results given the considerable climbing experience of the participants and their prior knowledge of the outdoor climbing route.

Although the effect of static positioning time during ascent on $\dot{V}O_2$, HR, and $[La_b]$ are yet to be defined, the maintenance of static positions is essential in rock climbing so that the climbing route can be negotiated with some degree of efficiency and certainty. Furthermore, the isometric contractions accompanying static positions would cause restrictions in localised blood flow to contracting muscle, which might be a limiting factor of climbing endurance. For example, occlusion of forearm blood flow has been documented at handgrips exceeding 70% of maximal voluntary handgrip strength.[22 23] During climbing, the support of the climber's weight would repeatedly evoke near maximal isometric contractions with greatly attenuated blood flow to the forearm and this could be increased on steeper climbs. Thus the increased $[La_b]$ of 4.5 mmol/l after outdoor climbing might be largely the result of repeated isometric contractions, in particular, by the arm and forearm muscles. Similar $[La_b]$ values have also been reported after indoor climbing of a comparative difficulty.[4] However, caution must be used when interpreting these results given the delayed blood sampling time of about three minutes after the completion of climbing. Although climbers adapt to isometric exercise by developing decreased blood pressure and an enhanced forearm vasodilatation capacity,[3] climbing performance might be improved by minimising immobilisation time during ascent. Certainly, during the outdoor performance, climbing velocity varied between climbers, with a trend for lower $[La_b]$ for faster ascents. A particularly relevant finding was that during continuous climbing on the vertical ergometer, and in the absence of repeated isometric contractions, more work was performed before $[La_b]$ reached a similar concentration compared with outdoors. That is, during continuous climbing on the ergometer the vertical distance climbed was 40 m compared with the outdoor distance of 24 m for an $[La_b]$ of 4.5 mmol/l.

In conclusion, the results of this study suggest that for elite climbers a moderately difficult outdoor sport rock climb requires a significant portion of $\dot{V}O_{2climb\text{-}peak}$. An increased $[La_b]$ suggests a contribution by the anaerobic energy system, which is probably the result of repeated isometric contractions, particularly from the arm and forearm musculature. Although the contribution from each energy system would vary depending on the route profile and difficulty, the current belief that aerobic fitness is not a requirement for climbing may be inaccurate. Indeed, specific training for climbing, such as laddermill work as used in this study, should be considered in order to improve the $\dot{V}O_{2climb\text{-}peak}$.

We acknowledge the inspiration provided by Professor John Sutton—a friend, inspirational scientist, and adventurer—who died suddenly on 7 February 1996. The authors acknowledge Dr Martin Thompson for use of the telemetry system and the Sydney Indoor Climbing Centre for use of their facilities. We also gratefully acknowledge the whole hearted cooperation of the subjects in these experiments.

Contributors

John Booth initiated and formulated the study hypothesis and discussed the core ideas related to the energy requirements of sport climbing and participated in data collection, analysis, and writing of the paper. He also designed the protocol for the outdoor and indoor climb. Frank Marino provided technical assistance, participated in data collection, analysis and interpretation, and writing of the paper. Chris Hill provided the technical input and assistance with the equipment and data collection out in the field. Tom Gwinn provided the intellectual input and assisted with data collection for the indoor climbing protocol and assisted in the data analysis.

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Take home message

Although the energy requirement during climbing would be dependent on the route, difficulty, and environmental conditions, the present results indicate that climbers may benefit significantly from a higher aerobic fitness. We suggest that aerobic training using graded laddermill work should be included in a climber's training programme.