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The cardiorespiratory demands of elite-level competitive rock climbing

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ABSTRACT

Introduction. Rock climbing has become a mainstream sport, contested on the Olympic stage. The work/rest pattern of bouldering is unique among disciplines, and little is known about its physiological demands. This study characterized the cardiorespiratory responses to a simulated competition. **Methods.** Eleven elite boulderers (7 male/4 female) volunteered to participate (age=23.3±4.5 y; mass=68.2±9.7 kg; stature=1.73±0.06 m; bodyfat %=10.4±5%). Subjects completed incremental exercise on a treadmill for the determination of maximal capacities. On a separate day, they undertook a simulated Olympic-style competition comprising five boulder problems, each separated by 5-min rest. Pulmonary ventilation, gas exchange, and heart rate were assessed throughout using a portable system. **Results.** Total climbing time was 18.9±2.7 min. Bouldering elicited a peak $\dot{V}O_2$ of 35.8±7.3 mL·kg^{-1}·min^{-1} (~75% of treadmill maximum) and a peak heart rate of 162±14 b·min^{-1} (~88% of maximum). Subjects spent 22.9±8.6% of climbing time above gas exchange threshold. At exercise cessation, there was an abrupt and significant increase in tidal volume (1.4±0.4 vs. 1.8±0.4 L; p=0.006, d=0.83) despite unchanged minute ventilation. Cardiorespiratory parameters returned to baseline within 4 min of the rest period. **Conclusion.** Competitive bouldering elicits substantial cardiorespiratory demand and evidence of tidal volume constraint. Further studies are warranted to explore the effect of targeted cardiorespiratory training on climbing performance.

Key words: bouldering; heart rate; oxygen uptake; respiratory; rock climbing; sport climbing; ventilation.

Key findings

- Competitive bouldering evokes substantial cardiorespiratory demand including a high fraction of $\dot{V}O_2$ max and a prolonged time above GET
- Climbing appears to impose a constraint on tidal volume expansion such that ventilation is achieved primarily via elevated respiratory frequency
- Cardiorespiratory indices in elite climbers return to baseline within 2 – 4 min of the rest period

INTRODUCTION

Rock climbing has transitioned from a niche activity to mainstream sport contested on the Olympic stage. The Olympic discipline comprises 3 events, all with markedly different activity profiles: lead climbing (roped ascents of routes in excess of 15 m); speed climbing (timed sprints of a standardised, pre-determined route); and bouldering (rope-free, very short-duration ascents typically requiring greater muscular effort).

Rock climbing is characterized by high-intensity, intermittent contractions of the upper-limbs (Billat et al. 1995; Michailov et al. 2009), and has been more closely compared to resistance rather than aerobic exercise (Kuepper et al. 2009). Research suggests that longer duration, lead/roped climbing imposes a substantial cardiorespiratory requirement. For example, during submaximal efforts on familiar routes, elite climbers exhibited a mean oxygen uptake of 22.7 ± 3.7 mL kg^{-1} min^{-1} and heart rate of 144 ± 14 b min^{-1} (Sheel et al. 2003). In highly-trained climbers, a ‘competition-style’ route elicited a peak oxygen uptake and heart rate of 31.9 ± 5.3 mL kg^{-1} min^{-1} and 162 ± 17 b·min^{-1}, respectively (Watts et al. 2000), while others report values as high as 44.1 ± 5.8 mL kg^{-1} min^{-1} (84 ± 12.4% maximum) and 175 ± 14 b·min^{-1} (91.4 ± 9.8%maximum; [de Geus et al. 2006]). Despite variability in the climbing tasks imposed and the ability of subjects, these data suggest that lead/roped ascents evoke considerable perturbations of the cardiovascular and respiratory systems, although this has yet to be comprehensively investigated in a competitive setting.

Studies to date have focussed exclusively on the responses to lead/roped climbing (Billat et al. 1995; Watts et al. 2000; Sheel et al. 2003; de Geus et al. 2006) and climbing-specific ergometry (Watts and Drobish 1998). However, the markedly different activity profile of bouldering would suggest that it evokes distinct physiological demands. For example, lead/roped competition climbing requires single, sustained efforts lasting 4 – 6 min (Arbulu et al. 2015). By contrast, competition bouldering comprises numerous boulder problems contested in 5-min ‘attempt intervals’, each interval requiring multiple and successive un-roped climbs of ~4.5 m lasting 30 – 40 s (White and Olsen 2010; Medernach et al. 2016). This work/rest pattern is unique among competitive climbing disciplines. Given that aerobic contributions to energy metabolism increase with successive bouts of high-intensity exercise (Bogdanis et al. 1996), and that aerobic pathways provide the primary means of replenishing the ATP-PCr system (Taylor et al. 1983; McMahon & Jenkins, 2002), cardiorespiratory capacity is likely to be an important determinant of bouldering performance, as might be the ability to recover between successive climbs. It has also been speculated that isometric contractions of the upper-limbs during climbing may impact on breathing patterns and mechanics (Kuepper et al. 2009; Baláš et al. 2014). However, both of these hypotheses are yet to be tested.

To the authors’ knowledge, only two studies have assessed the cardiac responses to bouldering. During a simulated competition, La Torre *et al.* observed peak heart rates of ~93% age-predicted maximum (La Torre et al. 2009), while Callender *et al.* reported values of ~92% age-predicted maximum during a single, moderately difficult boulder problem (Callender et al. 2020). Neither study, however, reported data on pulmonary ventilation, gas exchange, or respiratory patterns. There is also a paucity of data in subjects of a consistently elite standard in any discipline of climbing, and tasks previously employed have been inconsistent in their difficulty relative to an individual’s capacity for peak performance (Sheel et al. 2003). Accordingly, with impending Olympic inclusion, research is needed to elucidate the physiological responses to competition bouldering, especially in elite populations. Such data may help identify novel targets for training interventions and allow better cardiorespiratory risk stratification of the sport. Accordingly, the aims of this study were to characterize the cardiorespiratory demands of an elite-standard bouldering competition, to assess the recovery rate of key physiological variables in the post-climb rest period, and to examine the degree to which climbing exerted control over respiratory patterns.

METHODS

Subjects

Eleven elite climbers volunteered to participate (see Table 1 for characteristics). Their most recent climbing grades were: male (n=7), mean redpoint grade Fontainebleau 8b (IRCRA 28 ± 2.2); female (n=4), mean redpoint grade Fontainebleau 7c+ (IRCRA 25 ± 1.3), which had them classified as *Higher-Elite Male* and *Elite female*, respectively (Draper et al. 2016). Ten subjects were experienced competitors at international level and, at the time of testing, 6 were current members of the GB Bouldering Team. The group had a mean 12.6 ± 3.6 y of climbing experience (9.3 ± 4.2 y competing in bouldering at any level) and were engaged in 1.3 ± 1.5 h of non-climbing aerobic exercise per week. Following approval from the institution's Research Ethics Committee, subjects provided written, informed consent. Prior to testing, subjects abstained from food for 3 h, alcohol and caffeine for 12 h, and intense exercise for 48 h. Due to scheduling constraints, the female subjects were not tested during a standardized phase of the menstrual cycle.

Experimental Design

Subjects attended the laboratory on two occasions, separated by at least 48 h. At the first visit, they completed basic anthropometry via bioelectrical impedance (InBody 720, Seoul, Korea), a test of finger-flexor strength, and a maximal incremental exercise test on a motorized treadmill. At the second visit, subjects undertook a simulated, Olympic-format bouldering competition comprising five boulder problems, with physiological responses assessed throughout.

Visit 1

Finger strength. Finger-flexor strength was assessed independently in each arm using bespoke apparatus comprising a 19 mm, flat wooden hold with a 2 mm edge radius, attached to an S-Type load-cell orientated in the horizontal position (Weone YZC-516; Guangdong, China. Range 0 – 100 kg, hysteresis 0.1%, sensitivity 0.02%). Subjects were required to grip the wooden hold with fingers in the half-crimp position, with the upper-arm restrained, and the elbow in 90-degrees of flexion (see Image, Supplementary File 1, which illustrates the apparatus setup). The force signal was amplified using a Wheatstone Bridge interface (PhidgetBridge, Phidgets Inc.; Calgary, Canada) and sampled at 60 Hz. The peak value attained from the best-of-three efforts was recorded and expressed in both absolute terms (N) and relative to body mass (N kg^{-1}).

Maximal incremental exercise. To determine maximal aerobic capacities, subjects completed a ramp incremental exercise test on a motorized treadmill (Saturn, h/p/cosmos; Traunstein, Germany). Following seated rest for 3 min, exercise commenced at 8 $km \cdot hr^{-1}$ for 4 min at a 1% incline (warm-up), after which the speed was increased by 1 $km \cdot hr^{-1}$ each minute until volitional fatigue. The test was designed to elicit maximal capacities within 8 - 12 min. Pulmonary ventilation and gas exchange were measured on a breath-by-breath basis (Metalyzer 3b, Cortex; Leipzig, Germany), heart rate (f_C) was measured via telemetry (Polar H7, Polar Electro; Finland), and maximal values were calculated as the highest 30 s mean. Following the test, gas exchange threshold (GET) was identified using the V-slope method (Beaver et al. 1986).

Visit 2

Simulated Competition. The simulated competition followed International Federation for Sport Climbing (IFSC) regulations. Subjects attempted five different boulder problems set by an experienced IFSC-accredited route-setting team and scored by a single, experienced competition judge. The competition wall ranged from 80 degrees (slab) to 150 degrees (steep overhang). Each subject attempted the boulder problems 'on-sight' without prior knowledge of the climb. The format allowed a 5 min *attempt interval* during which participants had unlimited tries to complete the allocated problem, followed by 5 min passive rest before progressing to the next climb. During the between-interval rest period, participants remained seated, facing away from the competition wall, and were reminded not to speak unless to convey important information. Where participants completed a boulder problem within the allocated 5-min, the remaining time was added to the rest-period. For this reason, exercise time and rest time have been analysed independently. Participants were instructed to treat the simulation as a real competition.

Measures. Pulmonary ventilation and gas exchange were assessed on a breath-by-breath basis throughout the simulated competition (including recovery periods) using a portable gas analyser, collectively weighing ~600 g (MetaMax 3b, Cortex; Leipzig, Germany) (Fig. 1). The peak and nadir means were calculated using the highest and lowest 30 s values. Heart rate was recorded continuously via telemetered chest strap (Polar H7). In an effort to quantify the degree to which climbing influenced respiratory patterns, we assessed tidal volume (V_T), respiratory frequency (f_B), and mean inspiratory and expiratory flow (V_T/T_I & V_T/T_E) in the work-to-rest transition. Specifically, we compared values in the eight respiratory cycles occurring immediately before the cessation of exercise in the final climb (peak-exercise), to eight respiratory cycles performed immediately after the cessation of exercise when external loads on the torso were zero but minute ventilation (V_E) was assumed to remain elevated (Tiller et al. 2017a). Blood lactate concentration [BLa] was sampled from the earlobe (Lactate Pro 2, Arkray; Japan) immediately before and after each attempt interval. Rating of perceived exertion (RPE, Borg 6-20 scale; Borg 1982) for whole-body (RPE_{Body}) and forearm ($RPE_{Forearm}$) were recorded immediately prior to the blood sample.

Statistics:

Data were analysed using SPSS Version 26 (IBM; New York, USA). Normality of distribution was assessed using the Shapiro-Wilk test. Oxygen uptake ($\dot{V}O_2$), minute ventilation ($\dot{V}_E$), heart rate (f_C), blood lactate concentration [BLa], and ratings of perceived exertion (RPE_{Body} and $RPE_{Forearm}$) during the 5-min recovery period following the final climb were assessed using a repeated-measures ANOVA. Bonferroni-adjusted post-hoc tests were performed on significant interactions relative to baseline. Respiratory patterns (V_T and f_B) and mean inspiratory and expiratory flow (V_T/T_I & V_T/T_E) at the end of the final climb and immediately upon exercise cessation were compared using a related-samples Wilcoxon Signed Rank test. Effect size (Cohen's *d*) was used to quantify the magnitude of the difference between group means (0.2 = small; 0.5 = medium; 0.8 = large; Cohen 1988). Data are presented as mean ± SD, and critical alpha level was set at 0.05.

RESULTS

Visit 1

Finger strength. Group mean finger-flexor strength was 574.4 ± 110.3 N (0.88 ± 0.13 N kg^{-1}) and 567.8 ± 106.2 N (0.90 ± 0.14 N kg^{-1}), on the right- and left-side, respectively. Force readings were not significantly different between sides ($p > 0.05$, $d = 0.031$). In males, force was similar in the right- and left-side (615.0 ± 110.7 versus 621.0 ± 88.6 N), but was slightly disparate in females (503.3 ± 73.7 versus 474.8 ± 61.2 N). When comparing between the sexes, males exhibited higher values than females on the left side (621.0 ± 88.6 versus 474.8 ± 61.2 N), and right side (615.0 ± 110.7 versus 503.3 ± 73.7 N), although the low number of female subjects precluded a statistical comparison.

Maximal incremental exercise. Peak physiological responses to incremental treadmill exercise are shown in Table 2. The group mean $\dot{V}O_2$max was 47.9 ± 7.8 mL kg^{-1} min^{-1}. Maximal oxygen uptake was higher in males compared to females (53.0 ± 4.1 vs. 39.0 ± 1.6 mL kg^{-1} min^{-1}), and was equivalent to 111 and 104% of the respective predicted norms (Kaminsky et al. 2015). The group mean GET occurred at 55 ± 7% of $\dot{V}O_2$max (51 and 60% $\dot{V}O_2$max for males and females, respectively). Resting [BLa] was 0.9 ± 0.02 mmol L^{-1}, and this peaked at 10.6 ± 2.0 mmol L^{-1} at 4 – 6 min post-exercise.

Visit 2

Simulated competition. Physiological responses to simulated competition (excluding rest intervals) are shown in Table 3. Competition duration (from commencement of the initial attempt of the first problem to cessation of exercise on the final problem) was 44.2 ± 0.7 min with a cumulative exercise time of 18.9 ± 2.7 min. Subjects made 4.2 ± 2.2 attempts per problem (range 1 – 12), and a cumulative 21.0 ± 4.7 attempts throughout (range 14 – 25). Climbing evoked a $\dot{V}O_2$peak of 35.8 ± 7.3 mL·kg^{-1}·min^{-1} which was equivalent to 75 ± 1.2% of $\dot{V}O_2$max achieved during the maximal treadmill test (males = 38.0 mL·kg^{-1}·min^{-1} [71% $\dot{V}O_2$max]; females = 31.9 mL·kg^{-1}·min^{-1} [82% $\dot{V}O_2$max]). Minute ventilation reached 67.2 ± 20.1 L·min^{-1} which was equivalent to 58.1 ± 15.4% $\dot{V}_E$max (males = 69.6 ± 24.0 L·min^{-1} [54.1 ± 15.3% $\dot{V}_E$max]; females = 62.8 ± 12.2 L·min^{-1} [65.0 ± 15.1% $\dot{V}_E$max]). Heart rate reached 162 ± 14 b·min^{-1} which was equivalent to 88 ± 0.1% HRmax (males = 165 ± 10 b·min^{-1} [91 ± 0.1% HRmax]; females = 155 ± 19 b·min^{-1} [83 ± 0.1% HRmax]). Subjects spent 22.9 ± 8.6% of climbing time above GET. A representative (single-subject) trace showing the temporal response of heart rate (panel A) and $\dot{V}O_2$ (panel B) for the competition period as a whole, is shown in Fig. 2.

Recovery Period. Selected cardiorespiratory responses during the 5-min post-climb rest period are shown in (Fig. 3). A repeated-measures ANOVA revealed main-effects for all measured variables (p <0.001), with the results of post-hoc analyses summarized below:

Oxygen uptake. Compared to pre-exercise values (6.9 ± 1.5 mL·kg^{-1}·min^{-1}), $\dot{V}O_2$ remained significantly elevated at 1-min post-exercise (30.9 ± 6.3 mL·kg^{-1}·min^{-1}, p <0.001, d = 14.9), 2-min post-exercise (16.2 ± 3.5 mL·kg^{-1}·min^{-1}, p <0.001, d = 5.84), and 3-min post-exercise (10.8 ± 2.1 mL·kg^{-1}·min^{-1}, p = 0.01, d = 2.34) but was not different to baseline at 4-min or 5-min post-exercise (p > 0.05).

Minute ventilation. Compared to pre-exercise values (14.9 ± 3.3 L·min^{-1}), $\dot{V}_E$ remained significantly elevated at 1-min post-exercise (58.0 ± 15.9 L·min^{-1}, p = <0.001, d =

13.02), 2-min post-exercise (36.7 ± 7.2 L·min^{-1}, p = <0.001, d = 6.59), 3-min post-exercise (26.9 ± 5.6 L·min^{-1}, p = 0.001, d = 3.64), and 4-min post-exercise (21.8 ± 5.1 L·min^{-1}, p = 0.019, d = 2.09) but was not different to baseline at 5-min post-exercise (p > 0.05).

Heart rate. Compared to pre-exercise values (88 ± 15 b·min^{-1}), f_C remained significantly elevated at 1-min post-exercise (149 ± 12 b·min^{-1}, p <0.001, d = 3.99), and 2-min post-exercise (113 ± 9 b·min^{-1}, p = 0.001, d = 1.66), but was not different to baseline at 3-min, 4-min, or 5-min post-exercise (p > 0.05).

Blood lactate concentration. Compared to pre-exercise vales (1.3 ± 0.4 mmol L^{-1}), [BLa] remained significantly elevated at 1-min post-exercise (4.0 ± 2.3 mmol L^{-1}, p = 0.009, d = 1.99) and was still elevated at 5-min post-exercise (3.2 ± 1.5 mmol.L^{-1}, p = 0.003, d = 2.02).

Rating of perceived exertion. Compared to pre-exercise values (6.6 ± 0.8), RPE$_{\text{Forearm}}$ remained significantly elevated at 1-min post-exercise (15 ± 2.5, p < 0.001, d = 2.59) and was still elevated at 5-min post-exercise (11.6 ± 2.2, p < 0.001, d = 3.30). Compared to pre-exercise values (6.5 ± 0.9), RPE$_{\text{Body}}$ remained significantly elevated at 1-min post-exercise (15.6 ± 1.6, p < 0.001, d = 3.63) and was still elevated at 5-min post-exercise (11.5 ± 1.9, p < 0.001, d = 3.51).

Respiratory Patterns. Respiratory patterns (V_T & f_B) at the transition point from climbing to rest are shown in Fig. 4. A related-samples Wilcoxon Signed Rank test revealed that f_B decreased significantly immediately post-exercise (47 ± 10 to 37 ± 7 br·min^{-1}; p = 0.01, d = 0.78) with a large and significant increase in V_T (1.4 ± 0.4 to 1.8 ± 0.4 L; p = 0.006, d = 0.83). Minute ventilation remained unchanged (61.6 ± 15.8 versus 65.0 ± 23.3 L·min^{-1}; p = 0.594, d = 0.16). There were no statistically significant changes in peak- to post-exercise mean inspiratory flow (1.8 ± 0.5 versus 2.2 ± 1.0 L·s^{-1}; $p = 0.327$, $d = 0.35$) or mean expiratory flow (2.2 ± 0.7 versus 2.0 ± 0.8 L·s^{-1}; $p = 0.263$, $d = 0.40$).

DISCUSSION

The aims of this study were to characterize the cardiorespiratory demands of an elite-standard bouldering competition, to assess the recovery rate of key physiological variables in the post-climb rest-period, and to examine the degree to which climbing exerted control over respiratory patterns. We made several key observations: i) competitive bouldering evokes substantial cardiorespiratory demand, as evidenced by a high fraction of $\dot{V}O_2$ max and a prolonged time above GET; ii) climbing appears to impose a constraint on tidal volume expansion such that ventilation is maintained via elevated respiratory frequency; iii) cardiorespiratory parameters recover to baseline within 2 – 4 min of the rest period.

Simulated competition

To our knowledge, this is the first study to examine cardiorespiratory function during competitive bouldering, but also during competitive climbing of any discipline. Our data suggest that competition bouldering is associated with a considerable cardiorespiratory demand. The attempt intervals (a cumulative intermittent exercise period of 18.9 ± 2.7 min) evoked a mean $\dot{V}O_2$ of 22.3 ± 3.1 mL kg^{-1} min^{-1} (~47% $\dot{V}O_2$max), $\dot{V}_E$ of 43.6 ± 7.6 L min^{-1} (~38% $\dot{V}_E$max), and f_C of 138 ± 9 b min^{-1} (~75% HRmax). Peak values reached higher fractions of treadmill-determined values ($\dot{V}O_2$ = ~75% $\dot{V}O_2$max; $\dot{V}_E$ = ~58% $\dot{V}_E$max; f_C = ~88% HRmax; Table 3 & Fig. 2). Moreover, subjects spent the majority of exercise time close to the individual GET, with 23 ± 9% of total attempt-interval time above the GET. For an activity requiring relatively brief but repeated periods of high-intensity muscular effort (30 – 40 s; White and Olsen 2010; Medernach et al. 2016), peak values were remarkably similar to those reported during difficult lead/roped climbing of much greater durations (150 – 240 s; Watts et al. 2000; de Geus et al. 2006).

An important related observation was that, despite aerobic exercise constituting a very small proportion of weekly training volume in our group (1.3 ± 1.5 h·wk^{-1}), treadmill-determined $\dot{V}O_2max$ was above the age- and sex-specific predicted norm; males, particularly, exhibited values of 53 ± 4.1 mL kg^{-1} min^{-1} which was 111% predicted (Kaminsky et al. 2015) (Table 2). These values are similar to those seen in highly-trained lead climbers (de Geus et al. 2006; Magalhaes et al. 2007), trained games players (Hamilton et al. 1991), and only slightly below values measured by some in trained distance runners (McLaughlin et al. 2010). Thus, our elite boulderers exhibited impressive aerobic capacities, even though climbing is typically considered a resistance-based activity (Kuepper et al. 2009). Our data, therefore, support the notion that aerobic energy pathways might make an important metabolic contribution during climbing, alongside the phosphocreatine system in particular (de Moraes Bertuzzi et al. 2007). It is also likely that bouldering itself confers a potent aerobic training stimulus, similar to that observed during longer-duration climbs (Mermier et al. 1997; Rodio et al. 2008).

During the simulated competition, each 5-min attempt interval required a mean 4.2 ± 2.2 discrete efforts, with very brief between-effort respites of <30 s (White and Olsen 2010; Medernach et al. 2016). Aerobic contributions to energy metabolism tend to increase with successive bouts of intense exercise (Bogdanis et al. 1996). Thus, the basis for the high cardiorespiratory demands observed presently may lie in the requirement for successive high-intensity efforts, particularly since our data show minimal recovery of cardiorespiratory parameters in the first 60 s of rest (see below).

Recovery period

We assessed selected cardiorespiratory parameters ($\dot{V}O_2$, $\dot{V}_E$, and f_C) during seated rest following the final attempt interval, and while there was minimal recovery in the first 60 s, these metrics reflected baseline values by 4-min (Fig. 3). Oxidative metabolism is an important component in the replenishment of phosphocreatine following high-intensity exercise (Taylor et al. 1983; McMahon and Jenkins 2002), and likely explains the elevated aerobic requirement we observed during recovery. That the recovery period was assessed following the final climb of the final interval, suggests that highly-trained climbers will generally recover cardiorespiratory function in-between the attempt-intervals. Our data also indicate that a superior cardiorespiratory fitness (in combination with local muscular factors) may be an important mediator of competitive bouldering performance, although this requires further investigation.

Perceived exertion did not recover with the same rapidity. After 5 min rest, $RPE_{Forearm}$ and RPE_{Body} remained significantly elevated above baseline (11.6 ± 2.2 and 11.5 ± 1.9, respectively). Given the rapid recovery of cardiorespiratory variables, the elevated perceptual scores at this juncture likely reflect a high degree of peripheral neuromuscular effort. Blood lactate concentration also remained significantly elevated above baseline after 5 min rest (3.2 ± 1.5 vs. 1.3 ± 0.4 mmol L^{-1}). This was somewhat expected, given that it can take at least 30 min for lactate clearance to return values towards baseline following exercise intervals above the lactate threshold (Menzies et al. 2010). Lactate removal may have been facilitated by active recovery during rest (Watts et al. 2000), but this would likely have impinged on recovery of cardiorespiratory parameters (Watts et al. 2000; Yamagishi and Babraj 2019).

Respiratory patterns

The thoracic muscles function to ventilate the lungs while simultaneously stiffening the spine (Hodges et al. 2001, 2005) and maintaining upper-torso/arm position during exercise (Celli et al. 1988). Strenuous upper-body exercise is thought to exacerbate competition for the ventilatory and non-ventilatory functions of respiratory muscles (Tiller et al. 2017a), thereby influencing respiratory function. In an effort to quantify the degree to which climbing influenced breathing patterns, we compared the data from eight respiratory cycles at peak-exercise, to eight respiratory cycles immediately after the cessation of exercise when external loads on the torso were zero but minute ventilation was assumed to have remained elevated. When the high thoracic loads imposed by climbing were relinquished, we noted an abrupt and significant increase in V_T (1.4 ± 0.4 to 1.8 ± 0.4 L) with a large effect (*d* = 0.83), while $\dot{V}_E$ remained unchanged (Fig. 4). These findings are congruent with previous observations that $\dot{V}_E$ during upper-body exercise is achieved primarily via increases in respiratory frequency rather than V_T (Takano 1993; Tiller et al. 2017b). Our data show, for the first time, that climbing likely imposes a degree of constraint on the ribcage, precluding the effective expansion of V_T.

Our respiratory data also support the contention that isometric contractions associated with holding static positions during climbing may disrupt normal respiratory patterns (Baláš et al. 2014). We would anticipate this to be even more marked during steeper boulder problems during which greater activation of trunk muscles would be required to maintain position on hand- and foot-holds (Grzybowski et al. 2014). Indeed, recent data recorded during bouldering shows intermittently-raised mouth pressures, congruent with elevated blood pressures, which is characteristic of periodic breath-holds or Valsalva-like manoeuvres (Callender et al. 2020). Such breathing patterns may function to elevate thoracoabdominal pressure (Hodges et al. 2005) which would, in turn, provide postural support to the trunk, as observed during heavy resistance exercise (Hackett and Chow 2013). Irrespective, ventilatory equivalents ($\dot{V}_E/\dot{V}O_2$ and $\dot{V}_E/\dot{V}CO_2$) where relatively well-preserved, and actually increased above the normal range at peak exercise (Koch et al. 2009). Thus, there is no evidence of ventilatory insufficiency during climbing. It is possible, therefore, that tidal volume constraint and/or periodic breath-holding may be a normal (even important) response to strenuous climbing manoeuvres, particularly as evidence of this phenomena has been observed independent of climbing difficulty (Callender et al. 2020).

Technical considerations

There are several considerations that should predicate the interpretation of our findings. First, we assessed maximal aerobic capacities in our climbers via an incremental exercise test performed on a motorized treadmill. Treadmill exercise is generally considered to evoke higher values for $\dot{V}O_2$peak during exercise testing than cycle ergometry (Ross et al. 2003), likely due to the larger muscle mass active during the former. We observed higher values during maximal treadmill running than those derived from highly-trained climbers during maximal cycle ergometry (~46 mL·kg^{-1}·min^{-1}; Sheel et al. 2003) or arm-crank ergometry (37 mL·kg^{-1}·min^{-1}; de Moraes Bertuzzi et al. 2007). Moreover, while the treadmill test does not replicate the movement patterns of climbing, Watts et al. *(1998)* observed higher values for $\dot{V}O_2$peak during an incremental treadmill test when compared to values achieved during a specially-designed climbing test performed on a vertical treadmill (50.5 ± 7.0 versus 31.7 ± 4.6 mL kg^{-1} min^{-1}). Thus, while the treadmill is not considered to be mode-specific, we are confident that our data reflect the *true* maximal aerobic capacities of elite rock climbers.

Second, it is worth noting that we utilized a mixed-sex cohort. Given the discrepancies in anthropometric and physical attributes between male and female climbers, we decided to report group mean values in addition to means for the male and female subgroups. Because our female cohort comprised only four subjects, we were unable to make statistical comparisons between groups, and larger studies into sex-differences among highly-trained climbers would likely prove insightful.

Finally, simulated conditions rarely replicate those of a real contest, and there is substantial variation in the style and steepness of boulder problems across competitions. Indeed, blood lactate concentrations are different between real and simulated bouldering competitions, even when matched for standard (La Torre et al. 2009). Nevertheless, we made a concerted effort to replicate several key factors of Olympic-format bouldering, including the environment, wall structure, and technicalities of the boulder problems. Our subjects were also of the standard who typically compete in international competition and were encouraged to treat the simulation as a formal contest. Accordingly, our data provide the most accurate representation to date of the cardiorespiratory responses to elite-level bouldering.

In conclusion, the high peak fractions of $\dot{V}O_2$max, prolonged time above the GET, and rapid recovery of cardiorespiratory function, suggest that bouldering requires a considerable aerobic contribution to energy metabolism. We also report evidence of tidal volume constraint at peak exercise, the implications of which require further study. Further studies are also warranted to explore the effect of targeted cardiorespiratory training on climbing performance.

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Authors' contributions NAC, TNH and NBT conceived the research, NAC, TNH and NBT conducted all experiments. NAC and NBT analysed data, NAC and NBT drafted the manuscript. All authors read and approved the manuscript.

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Table 1. Subject characteristics.

Subject	Age (y)	Mass (kg)	Stature (m)	Body fat (%)	BMI (kg·m^2)
1 (m)	22.7	66.6	1.73	9.1	22.3
2 (m)	21.3	88.4	1.83	6.1	26.4
3 (m)	23.9	62.8	1.70	9.1	21.7
4 (m)	33.1	59.9	1.72	9.0	20.2
5 (m)	20.2	61.3	1.68	4.0	21.7
6 (m)	20.9	70.3	1.80	5.8	21.7
7 (m)	21.3	68.1	1.83	6.2	20.3
8 (f)	22.3	67.8	1.71	14.3	23.2
9 (f)	23.9	60.7	1.65	16.6	22.3
10 (f)	21.0	65.9	1.65	18.9	24.2
11 (f)	18.9	65.3	1.73	15.0	21.8
Mean (m)	23.3	68.2	1.76	7.0	22.1
SD	4.5	9.7	0.06	2.0	2.1
Mean (f)	21.5	64.9	1.76	16.2	22.9
SD	2.1	3.0	0.04	2.0	1.1
Mean (group)	**22.7**	**67.0**	**1.73**	**10.4**	**22.4**
SD	**3.8**	**7.8**	**0.06**	**5.0**	**1.8**

Table 2. Peak cardiorespiratory responses to ramp incremental treadmill test.

	Rest	Max. (group)	Max (m)	Max (f)
$\dot{V}O_2$ (L min^{-1})	0.4 ± 0.1	3.2 ± 0.7	3.6 ± 0.5	2.5 ± 0.1
$\dot{V}O_2$ (ml kg^{-1} min^{-1})	4.8 ± 1.3	47.9 ± 7.8	53.0 ± 4.1	39.0 ± 1.6
$\dot{V}CO_2$ (L min^{-1})	0.3 ± 0.1	3.6 ± 0.7	4.1 ± 0.4	2.9 ± 0.2
RER	0.9 ± 0.1	1.14 ± 0.07	1.14 ± 0.06	1.13 ± 0.09
f_C (b min^{-1})	73 ± 14	186 ± 11	185 ± 14	187 ± 5
$\dot{V}_E$ (L min^{-1})	11.9 ± 3.6	116.6 ± 17.9	127.2 ± 8.4	98.1 ± 14.6
V_T (L)	0.8 ± 0.3	2.2 ± 0.4	2.4 ± 0.4	1.9 ± 0.2
f_R (br min^{-1})	17.5 ± 4.4	53.6 ± 8.1	54.4 ± 6.8	52.2 ± 11.0
V_T/T_I (L s^{-1})	0.5 ± 0.2	3.8 ± 0.7	4.2 ± 0.3	3.1 ± 0.4
$\dot{V}_E/\dot{V}O_2$	32.9 ± 5.6	36.8 ± 4.9	35.7 ± 3.3	38.9 ± 4.3
$\dot{V}_E/\dot{V}CO_2$	37.6 ± 4.7	32.4 ± 3.2	31.3 ± 2.0	34.4 ± 4.3

Mean ± SD (n=11). m = male; f = female; $\dot{V}O_2$ = O_2 uptake; $\dot{V}CO_2$ = CO_2 output; RER = respiratory exchange ratio; f_C = cardiac frequency; $\dot{V}_E$ = minute ventilation; V_T = tidal volume; f_R = respiratory frequency; V_T/T_I = mean inspiratory flow; $\dot{V}_E/\dot{V}O_2$ = ventilatory equivalent for O_2 uptake; $\dot{V}_E/\dot{V}CO_2$ = ventilatory equivalent for CO_2 expired.

Table 3. Physiological responses to simulated climbing (excluding rest-intervals).

	Rest	Mean	Peak
$\dot{V}O_2$ (L min^{-1})	0.5 ± 0.1	1.49 ± 0.24	2.39 ± 0.51
$\dot{V}O_2$ (ml kg^{-1} min^{-1})	6.9 ± 1.5	22.3 ± 3.1	35.8 ± 7.3
$\dot{V}CO_2$ (L·min^{-1})	0.4 ± 0.0	1.27 ± 0.20	2.09 ± 0.60
RER	0.9 ± 0.1	0.83 ± 0.03	0.84 ± 0.06
f_C (b·min^{-1})	88 ± 15	138 ± 9	162 ± 14
$\dot{V}_E$ (L·min^{-1})	14.9 ± 3.3	43.6 ± 7.6	67.2 ± 20.1
V_T (L)	0.8 ± 0.2	1.33 ± 0.26	1.74 ± 0.46
f_R (br·min^{-1})	21.7 ± 5.7	35.2 ± 4.8	40.1 ± 6.4
V_T/T_I (L·s^{-1})	0.6 ± 0.8	1.5 ± 0.3	2.2 ± 0.6
$\dot{V}_E/\dot{V}O_2$	32.6 ± 5.3	29.4 ± 3.9	28.0 ± 3.9
$\dot{V}_E/\dot{V}CO_2$	37.7 ± 4.6	34.2 ± 3.2	32.2 ± 2.6
[BLa] (mmol·L^{-1})	1.3 ± 0.4	3.2 ± 1.5	4.4 ± 2.1
$RPE_{Forearm}$	6.6 ± 0.8	13.0 ± 1.7	15.7 ± 2.2
RPE_{Body}	6.45 ± 0.9	13.4 ± 1.1	16.2 ± 1.0

Mean ± SD (n=11). $\dot{V}O_2$ = O_2 uptake; $\dot{V}CO_2$ = CO_2 output; RER = respiratory exchange ratio; f_C = cardiac frequency; $\dot{V}_E$ = minute ventilation; V_T = tidal volume; f_R = respiratory frequency; V_T/T_I = mean inspiratory flow; $\dot{V}_E/\dot{V}O_2$ = ventilatory equivalent for oxygen; $\dot{V}_E/\dot{V}CO_2$ = ventilatory equivalent for carbon dioxide; [BLa] = blood lactate concentration; RPE = rating of perceived exertion.

FIGURES

Fig. 1. Pulmonary ventilation and gas exchange were sampled throughout the simulated competition using a portable gas analyser. The analyser, sample line, and facemask collectively weighed ~600 g.

Fig. 2. Representative heart rate (panel A) and $\dot{V}O_2$ (panel B) traces for the competition period (including rests). The attempt-intervals are highlighted (1 - 5). Note the considerable exercise time spent above gas exchange threshold (GET), and the within-attempt nadirs owing to failed climbs. (NB: the apparently inconsistent rest-period durations are artefacts of variations in the number of recorded data points in the breath-by-breath analysis).

Fig. 3. Oxygen uptake (panel A), minute ventilation (panel B), and heart rate (panel C) in the 5-min recovery period immediately following the final climb. *significantly different versus pre-exercise values, $p < 0.05$.

Fig. 4. Tidal volume (panel A), respiratory frequency (panel B), and minute ventilation (panel C) during eight breaths at peak-exercise (Peak-ex) versus eight breaths immediately after the abrupt cessation of exercise (Post-ex). *significantly different versus peak-exercise values, $p < 0.05$.

Image, Online Resource 1. Finger strength testing apparatus.