Title

The exercise pressor response to indoor rock climbing

Journal

Journal of Applied Physiology, 129(2)

ISSN

8750-7587

Authors

Callender, Nigel A
Hart, Peter W
Ramchandani, Girish M
et al.

Publication Date

2020-08-01

DOI

10.1152/japplphysiol.00357.2020

Peer reviewed

Case-Studies in Physiology: The exercise pressor response to indoor rock climbing

Nigel A. Callender[1, 2], Peter W. Hart[3], Girish M. Ramchandani[4], Parminder S. Chaggar[5], Andrew J. Porter[6], Charlie P. Billington[7], Nicholas B. Tiller[8].

[1]Department of Anaesthetics, Northumbria Specialist Emergency Care Hospital, Cramlington, UK.

[2]School of Clinical and Applied Sciences, Leeds Beckett University, Leeds, UK.

[3]Department of Anaesthetics and Critical Care, Bradford Teaching Hospitals Foundation Trust, Bradford, UK.

[4]Academy of Sport and Physical Activity, Sheffield Hallam University, Sheffield, UK.

[5]Department of Cardiology, Royal Cornwall Hospital, Truro, UK.

[6]Newcastle University Protein and Proteome Analysis, Newcastle University, Newcastle, UK.

[7]Department of Anaesthetics, Dumfries and Galloway Royal Infirmary, Dumfries, UK.

[8]Division of Pulmonary and Critical Care Physiology and Medicine, Lundquist Institute for Biomedical Innovation at Harbor-UCLA Medical Center, Torrance, CA, USA.

Correspondence: Dr. Nigel Callender, Department of Anaesthetics, Northumbria Specialist Emergency Care Hospital, Northumbria Way, Cramlington, Northumberland, NE23 6NZ, UK | nigelcallender@gmail.com | Orchid ID: https://orcid.org/0000-0001-9658-5266

Conflict of interest: NC is the owner of a commercial climbing gym. There are no other competing interests in relation to the described research.

ABSTRACT

Introduction. This paper assessed the blood pressure, heart rate, and mouth-pressure responses to indoor rock climbing (bouldering) and associated training exercises. **Case Presentation.** Six well-trained male rock climbers (mean ± SD age = 27.7 ± 4.7 y; stature = 177.7 ± 7.3 cm; mass = 69.8 ± 12.1 kg) completed two boulder problems (6b and 7a+ on the Fontainebleau Scale) and three typical training exercises (Maximum voluntary contraction [MVC] isometric pull-up, 80% MVC pull-ups to fatigue, campus-board to fatigue). Blood pressure and heart rate were measured via an indwelling femoral arterial catheter, and mouth pressure via a mouthpiece manometer. Bouldering evoked a peak systolic pressure of 200 ± 17 mmHg (44 ± 21% increase from baseline), diastolic pressure of 142 ± 26 mmHg (70 ± 32% increase), mean arterial pressure of 163 ± 18 mmHg (56 ± 25% increase), and heart rate of 157 ± 20 b min^{-1} (81 ± 30% increase). The highest systolic pressure was observed during the campus-board exercise (218 ± 33 mmHg), although individual values as high as 273/189 mmHg were recorded. Peak mouth pressure during climbing was 31 ± 46 mmHg, and this increased independent of climb difficulty. **Conclusions**. Indoor rock climbing and associated exercises evoke a substantial pressor response, resulting in high blood pressures that may exceed those observed during other resistance exercises. These findings may inform risk stratification for climbers.

Keywords: blood pressure; pressor response; cardiovascular disease; heart rate; rock climbing.

NEW & NOTEWORHY

This case-study provides original data on the exercise pressor response to indoor rock-climbing and associated training exercises, through the use of an indwelling femoral arterial catheter. Our subjects exhibited systolic/diastolic blood pressures that exceed values often reported during resistance exercise. Our data extend the understanding of the cardiovascular stress associated with indoor rock climbing.

INTRODUCTION

Rock climbing is characterized by short periods of high-intensity, intermittent muscle contractions (2, 22). The demands of climbing are more comparable to resistance rather than aerobic exercise (15), thereby evoking a disproportionate increase in heart rate relative to oxygen uptake at a given intensity (21, 28). Rock climbing, therefore, would be expected to induce a significant exercise pressor response and large increases in blood pressure (BP) to optimize oxygen delivery to working muscle (27), but there are currently no data on the magnitude of the response.

Indoor rock climbing is to be contested at the Olympic Games in 2021. Accordingly, data on the typical pressor response may be important for climbing-related risk stratification. This is particularly pertinent given that high peripheral vascular resistance increases stress on the myocardial wall, and has been deemed the principal stimulus for left ventricular hypertrophy in the pressure-overloaded heart of strength and power athletes (13, 23).

Only two studies provide any data on blood pressure responses in trained climbers, both during submaximal forearm exercise. Using the volume clamp method (6) and sphygmomanometry (20), climbers exhibited peak systolic pressures of 160 – 170 mmHg. However, the blood pressure response to isolated forearm exercise is unlikely to reflect the complex nature of rock climbing which involves movements of both upper- and lower-limbs, in addition to co-contractions of the various trunk stabilizers. Breath-holding or Valsalva-like efforts during climbing tasks would also be expected to increase the pressor response via transmission of intrathoracic and intraabdominal pressures to the aorta and heart (24). Studies evaluating the BP responses to dynamic, whole-body climbing would, therefore, be informative. The aforementioned studies are limited by their use of non-invasive measures, with sphygmomanometry shown to underestimate systolic pressure by ~13% (31).

We propose the use of arterial catheterization to record blood pressure responses in climbers. Arterial catheterization has been used to record accurate blood pressures during dynamic exercise like weightlifting (19) and rowing (4). Relative to other methods, arterial catheters have the advantage of beat-by-beat sampling, and provide data on the temporal BP response during climbing in which isometric muscle contraction times can be brief (~8 s [29]). Finally, given that subjects are expected to breath-hold and/or perform Valsalva-like efforts during difficult maneuvers, we propose to assess the magnitude of the mouth-pressure response as a possible mechanism influencing blood pressure during climbing. Therefore, the aim of this case-study was to assess the acute effects of indoor rock climbing, and common training exercises, on the magnitude of the blood pressure, heart rate, mouth pressure response in well-trained climbers.

CASE PRESENTATION

Subjects

Six well-trained male rock climbers volunteered to participate (Table 1). All had a minimum of five years climbing experience, were engaged in 11.3 ± 3.1 h of climbing or sports-specific training per-week (range 6 - 15 h), and were of a moderate-to-high proficiency (IRCA mean 25 ± 3.5; range 21 - 30 redpoint[6]). The study was approved by the institutional Research Ethics Committee and conformed to the principles outlined in the Declaration of Helsinki. Before participation, subjects provided written, informed consent and completed a pre-test medical questionnaire. Subjects were free from pre-diagnosed cardiovascular disease and were not taking medication. Subjects abstained from intense exercise for 48 h, alcohol and caffeine for 12 h, and food for 3 h prior to testing.

Experimental Overview

Subjects attended the laboratory on a single occasion. Basic anthropometry was performed via bioelectrical impedance (InBody 720, Seoul, Korea). Subjects subsequently completed two bouldering problems (short climbing tasks not requiring a rope) and three training exercises, each separated by ~5 min to reflect the rest-periods of a typical climbing session. Intra-arterial blood pressure, heart rate, and mouth pressure were continuously assessed.

Boulder Problems

Boulder problems were created by an internationally-accredited climbing route setter, and were designed to prevent excessive perturbations in the phlebostatic axis. Each route was six moves in length, was previously unattempted by our subjects, and performed above in-situ safety matting. The difficulty and subjective intensity of the boulder problems was agreed by consensus of three expert climbers, and equated to 6b and 7a+ on the Fontainebleau scale for climb one and two, respectively (IRCRA scale 17 & 21 [6]). Both problems had an overhanging angle of 45 degrees, with minimal requirement for flexion of the right hip. The intended sequence of moves was described to subjects prior to their first attempt, and each climb was attempted once. Duration of ascent was measured from the moment contact was lost with the floor and terminated when the subject fell or reached the finishing hold with both hands.

Training Exercises

Maximum voluntary contraction (MVC) isometric pull-up. A maximal isometric pull-up was performed on a pull-up bar with the elbow at 90 degrees of flexion. A waist harness was attached to anchor the subject to an immovable point directly below, in-series with a load-cell, and MVC was expressed as the peak force from the load cell, in addition to the total mass including the arterial line, manometer, giving set, rucksack, and body mass.

80% MVC pull-up. Subjects performed isotonic pull-ups to fatigue from straight arms to a position whereby the chin was above the level of the bar. Mass was added via the waist harness to achieve a load equivalent to 80% of the MVC isometric pull.

Campus-board. Subjects undertook a three-movement footless 'laddering' sequence on a standard campus-board (23 mm holds at 21 cm spacing, on a 20-degree overhanging board), repeating the sequence up and down to fatigue (defined as contact with the floor). Duration and movement number were recorded from a single attempt.

Measurements

Blood Pressure and heart rate. Following 5 min quiet sitting, normotension was confirmed via arm-cuff sphygmomanometry (Boso Varius, Jungingen, Germany). Thereafter, the right femoral artery was located using ultrasound and cannulated aseptically with an 8 cm, 20 G Teflon-coated catheter (Vygon Leadercath, Vygon, Ecouen, France). The femoral artery was chosen to allow uninhibited movement of the arms during the physical assessments, and to facilitate a pressure trace that most accurately reflected central haemodynamics. The catheter was connected to an arterial line with incorporated transducer (DPT-6000, Codan, Forstinning, Germany; range −300 to +300 mmHg; sensitivity ± 1%; hysteresis 1.66%), which was aligned with the presumed level of the right atrium. The line contained 0.9% sodium chloride, running at 3 ml·hr^{-1} from a pressurized 500 ml reservoir bag which was stored in a small rucksack (total 1.94 kg) worn by the subject. Beat-by-beat blood pressure and heart rate were obtained via the arterial line, and the system was zeroed while subjects were in a standing position immediately before each task. Mean arterial pressure (MAP) was automatically calculated as the average of all data points sampled in each waveform. Heart rate was taken as the peak-to-peak pressure interval and averaged every three waveforms.

Mouth Pressure. In an effort to estimate the increases in intrathoracic and intraabdominal pressures, and any potential influence on BP, mouth pressure was obtained using a digital manometer (Amecal ST-8890, Newcastle, UK; sensitivity 0.03%) attached to a well-sealing mouthpiece and contained within the rucksack. After coaching, subjects were asked to maintain an open glottis during any periods of breath-holding or straining, as per MacDougall *et al.*(19), thus allowing transmission of the intrathoracic air column to the transducer via the mouthpiece. In-task pressures were compared to atmospheric conditions (i.e., 0 mmHg gauge-pressure).

Data Processing

Blood pressure and heart rate signals were amplified using a Powerlab Amplifier and Powerlab 4/35 data acquisition system (ADInstruments, Dunedin, New Zealand), sampled at 200 kHz, and displayed digitally in LabChart (ADInstruments). Mouth pressure was sampled at 1 Hz and recorded via the manometer's proprietary software to the same laptop computer used for blood pressure and heart rate. All digital signals were aligned in Microsoft Excel from their individual timestamps recorded in relation to the computer's internal clock. Force data during the MVC isometric pull was recorded using an S-type load cell (Weone YZC-516, Guangdong, China; range: 0-100kg, sensitivity: 0.02%, hysteresis: 0.1%) amplified by a USB-run Wheatstone bridge amplifier (PhidgetBridge, Phidgets Inc., Calgary, Canada) and recorded to a laptop computer running a bespoke program. All values are expressed as mean ± SD.

RESULTS

Boulder problems

Blood pressure, heart rate, and mouth pressure responses to the boulder problems and training exercises are shown in Table 2. All subjects completed boulder problem 1 in 6.0 ± 0.0 moves and in a mean duration of 14.2 ± 3.3 s (range 9.3 – 17.7 s). Three subjects successfully completed boulder problem 2 (all 6 moves), and the group mean (n = 6) for total moves was 5.0 ± 1.1 moves (range 3 – 6) and duration was 17.2 ± 2.5 s (range 13.2 – 19.8 s). Pre-task systolic BP for boulder problem 1 was 126 ± 13 mmHg, and this peaked at 175 ± 27 mmHg (an increase of 40 ± 25%). Pre-task systolic BP for boulder problem 2 was 141 ± 14 mmHg, and peaked at 200 ± 17 mmHg (an increase of 44 ± 21 %). The individual systolic BP response range was 142/88 – 213/145 mmHg for boulder problem 1, and 181/110 – 223/185 mmHg for boulder problem 2. Mean arterial pressure, heart rate, and mouth pressure all increased substantially above pre-task values (Table 2).

Training Exercises

MVC isometric pull-up. Peak force delivered to the load cell was 553 ± 186 N (range 295 - 800 N), equating to a total suspended mass of 126.1 ± 26.7 kg (range 97.1 - 171.5 kg; Table 1). Mean time to peak force during the maneuver was 5.5 ± 2.1 s (range 3.9 – 9.5 s). Peak systolic pressure increased above pre-task values by 50 ± 27 % (Table 2). The individual BP response range was 157/92 – 245/163 mmHg.

80% MVC Pull-Up. Subjects achieved 3.3 ± 1.4 repetitions (range 2 – 6). The mean total mass lifted was 102.5 ± 21.4 kg (range 77.65 – 137.2 kg). Data from one subject was omitted due to sample line occlusion. Peak systolic pressure increased above pre-task values by 51 ± 22 % (Table 2). The individual BP response range was 173/113 – 273/189 mmHg.

Campus-board. The campus-board task elicited the longest task duration of 29.7 ± 13.7 s (range 6.9 – 44.4 s) with subjects performing 20.0 ± 12.7 distinct hand movements (range 6.0 – 42.0).

Peak systolic pressure increased above pre-task values by 67 ± 30 % (Table 2). The individual BP response range was 166/118 – 260/177. For the five subjects who performed the campus-board task for longer than 20 s, data were divided into quartiles based on time (Q2 versus Q4). Relative to Q2, there was an increase in Q4 systolic pressure (201 ± 31 vs. 221 ± 29 mmHg) and heart rate (154 ± 24 vs. 173 ± 21 $b.min^{-1}$). Similarly, there was an increase in Q2 to Q4 diastolic pressure (132 ± 22 vs 147 ± 20 mmHg), and MAP (160 ± 24 vs. 175 ± 21 mmHg).

DISCUSSION

This study assessed the exercise pressor response to indoor rock climbing and associated training exercises. During the various tasks, we observed large increases in arterial BP in the region of 40 – 67%, relative to pre-task values. We also found that mouth pressure was periodically elevated throughout. These data indicate that indoor climbing and associated exercises induce a substantial pressor response which may partly be underpinned by increases in intrathoracic pressures.

Our use of an indwelling arterial catheter to record the BP response is novel among climbing-related research, and demonstrates that the technique may be a viable and safe method for obtaining temporal BP data during climbing. Arterial catheterization is a sensitive means of assessing BP, and records beat-by-beat values at very high frequencies. According to the Association for the Advancement of Medical Instrumentation (AAMI), intra-arterial measures are considered to be the ‘gold standard’ in the assessment of resting BP (11). A disadvantage of the technique is that as the measurement site is moved peripherally from the aorta (to brachial and radial arteries), the pulse wave-form changes in morphology and is amplified, thereby potentially overestimating systolic pressure (3, 25). The femoral artery was chosen because it provided a pressure trace that most accurately reflected central hemodynamics, and because the location was safely accessible and allowed uninhibited movement of the arms during the physical assessments. We are confident, therefore, that our data are the closest representation to date of the *true* BP response to climbing activities.

The highest group systolic BP relative to pre task values was recorded during the campus board task (218 ± 33 versus 132 ± 13 mmHg), with one subject exhibiting peak pressures of 260/171 mmHg (Fig. 1). The highest individual BP was 273/189 mmHg, exhibited during the 80% MVC pull-up. Not only are these values higher than those reported in climbers during isolated forearm exercise (6, 20), but they exceed the peak pressures observed during other high-intensity exercises including rowing (192 ± 20 mmHg; [5]), and upper-limb 1-RM weight-lifting (197 ± 6 mmHg; [8]). Our values are also comparable to those observed during upper-limb exhaustive weight-lifting (255/190 mmHg; [18]).

There may be several mechanisms that underpin these high exercise blood pressures during climbing and related activities. First, given that the campus-board elicited the longest exercise duration (29.7 ± 13.7 s), and that systolic BP increased from 201 ± 31 to 221 ± 30 mmHg in the second-through-final time quartiles, BP cannot be explained exclusively by mechanical forces acting on the vascular tree and muscle mechanoreflex. Longer exercise durations are associated with greater stimulation of Group III & IV afferent fibers (27), and the large BP response was likely associated with the muscle metaboreflex and/or an increase in centrally-mediated sympathetic output, both of which warrant further study in climbers of mixed ability.

Second, we identified periodic increases in mouth pressure, used as a non-invasive surrogate for intrathoracic pressure (19). Despite the simplicity of our measurement technique, it is well accepted that the Valsalva Maneuver plays a major role in augmenting the BP response (12, 18, 19, 24), and we present the first evidence that well-trained climbers exhibit a degree of breath-holding and/or Valsalva-like efforts during climbing movements, manifesting as mouth pressures that were intermittently raised (mean 31 ± 46 cmH_2O). Forceful contractions of various trunk muscles will increase thoracoabdominal pressure (10) which, in turn, stiffens and stabilizes the trunk to provide postural support (1), as observed during weight lifting (8). Breath-holding, therefore, may serve an important function in supporting climbing-specific movements, particularly on overhanging wall inclines. While not directly assessed in this study, the transmission of intrathoracic pressures to the aorta and heart was a likely contributor to the arterial pressures observed (12, 18, 24). Despite the lower effort required for boulder problem 1 relative to problem 2, breath-holding was exhibited by our group during both climbs, suggesting that the phenomenon is somewhat independent of exercise intensity. Collectively, we propose that the large blood pressures observed presently may result from a combination of the high-intensity effort, the large active muscle mass including trunk musculature, and the elevated mouth pressures attributable to Valsalva-like efforts and/or breath-holding.

With respect to heart rate, all tasks evoked a degree of prehension prior to exercise; i.e., active readiness before the commencement of the task. We observed the highest peak heart rate (169 ± 21 b·min^{-1}) during the campus-board task, perhaps because it evoked the single longest exercise duration (29.7 ± 13.7 s). The second boulder problem, the more difficult of the two, elicited peak values of 157 ± 20 b·min^{-1}. Peak heart rate responses were below that seen in other climbing studies using tasks of longer duration; e.g., intermittent climbing to exhaustion (185 ± 11 b·min^{-1}[25]), and simulated bouldering competition (93% HRmax [15]). Notwithstanding, the observation that heart rate is substantially elevated during climbing, congruent with high femoral arterial pressures, suggests that rock climbing and associated activities are likely to evoke considerable myocardial demand.

High-intensity, intermittent activities that evoke periods of elevated vascular resistance, with little-to-no change in cardiac output, have been proposed to stimulate modifications in cardiac size and shape (23), including myocardial hypertrophy (14) and temporarily affect vascular reactivity (13). It is plausible that chronic exposure to the blood pressures we have observed during climbing may be sufficient to induce myocardial and vascular remodeling. While the clinical significance of such long-term adaptations continue to be debated (9, 29), echocardiographic studies in sport climbers would be informative, particularly in guiding physician/athlete decisions on sports participation at the recreational and elite levels (17).

In conclusion, this is the first report of the blood pressure responses to indoor rock climbing in healthy, trained subjects. Indoor climbing and associated training exercises induce a pronounced exercise pressor response that substantially elevates both intra-arterial pressure and heart rate. The responses are likely attributable, at least in part, to elevated intrathoracic pressures associated with Valsalva-like efforts. More research is needed to elucidate the effect of chronic training on cardiovascular structure and function and its clinical implications.

Acknowledgements: We wish to thank the participants who generously gave their time for the study, ADInstruments for the loan of equipment, Vygon UK for the donation of consumables and The Climbing Works (Sheffield, UK) for the use of their venue. We also wish to thank Dr Sam Oliver and Dr Jamie Macdonald for their comments on an early draft of the proposal.

Author contributions:

Study concept and design: NC, NBT, PWH, PC & AJP. Acquisition of data: NC, NBT, PWH & CB. Analysis of data: NC, NBT, GR, AJP & CB. Drafting and critical review of manuscript: NC, NBT, PWH, GR, PC, AJP & CB. All authors have reviewed and approved the final version.

Financial/material support: This study received the donation of consumables and loan of equipment from Vygon UK and ADInstruments respectively. No external funding was received.

Disclosure statement: NC is the co-owner of a commercial climbing wall. Other authors: None.

REFERENCES

1. **Abraham KA**, **Feingold H**, **Fuller DD**, **Jenkins M**, **Mateika JH**, **Fregosi RF**. Respiratory-related activation of human abdominal muscles during exercise. *J Physiol* 541: 653–663, 2002.
2. **Billat V**, **Palleja P**, **Charlaix T**, **Rizzardo P**, **Janel N**. Energy specificity of rock climbing and aerobic capacity in competitive sport rock climbers. *J Sports Med Phys Fitness* 35: 20–24, 1995.
3. **Bruner JM**, **Krenis LJ**, **Kunsman JM**, **Sherman AP**. Comparison of direct and indirect measuring arterial blood pressure. *Med Instrum* 15: 11–21, 1981.
4. **Clifford PS**, **Hanel B**, **Secher NH**. Arterial blood pressure response to rowing. *Med Sci Sports Exerc* 26: 715–719, 1994.
5. **Draper N**, **Giles D**, **Schöffl V**, **Konstantin Fuss F**, **Watts P**, **Wolf P**, **Baláš J**, **Espana-Romero V**, **Blunt Gonzalez G**, **Fryer S**. Comparative grading scales, statistical analyses, climber descriptors and ability grouping: International Rock Climbing Research Association position statement. *Sport Technol* 8: 88–94, 2015.
6. **Ferguson RA**, **Brown MD**. Arterial blood pressure and forearm vascular conductance responses to sustained and rhythmic isometric exercise and arterial occlusion in trained rock climbers and untrained sedentary subjects. *Eur J Appl Physiol Occup Physiol* 76: 174–180, 1997.
7. **Fleck SJ**, **Dean LS**. Resistance-training experience and the pressor response during resistance exercise. *J Appl Physiol* 63: 116–120, 1987.
8. **Hackett DA**, **Chow C-M**. The Valsalva maneuver: its effect on intra-abdominal pressure and safety issues during resistance exercise. *J Strength Cond Res* 27: 2338–2345, 2013.
9. **Haykowsky MJ**, **Dressendorfer R**, **Taylor D**, **Mandic S**, **Humen D**. Resistance Training and Cardiac Hypertrophy. *Sport Med* 32: 837–849, 2002.
10. **Hodges PW**, **Eriksson AEM**, **Shirley D**, **Gandevia SC**. Intra-abdominal pressure increases stiffness of the lumbar spine. *J Biomech* 38: 1873–1880, 2005.

11. **Association for the advancement of medical instrumentation**. *American National Standard for Electronic or Automated Sphygmomanometers*. 1st ed. Arlington: Association for the Advancement of Medical Instrumentation, 1992.

12. **Iwamoto GA**, **Mitchell JH**, **Mizuno M**, **Secher NH**. Cardiovascular responses at the onset of exercise with partial neuromuscular blockade in cat and man. *J Physiol* 384: 39–47, 1987.

13. **Jurva JW**, **Phillips SA**, **Syed AQ**, **Syed AY**, **Pitt S**, **Weaver A**, **Gutterman DD**. The effect of exertional hypertension evoked by weight lifting on vascular endothelial function. *J Am Coll Cardiol* 48: 588–589, 2006.

14. **Kasikcioglu E**, **Oflaz H**, **Akhan H**, **Kayserilioglu A**, **Mercanoglu F**, **Umman B**, **Bugra Z**. Left ventricular remodeling and aortic distensibility in elite power athletes. *Heart Vessels* 19: 183–188, 2004.

15. **Kuepper T**, **Morrison A**, **Gieseler U**, **Schoeffl V**. Sport climbing with pre-existing cardio-pulmonary medical conditions. *Int J Sports Med* 30: 395–402, 2009.

16. **La Torre A**, **Crespi D**, **Serpiello FR**, **Merati G**. Heart rate and blood lactate evaluation in bouldering elite athletes. *J Sports Med Phys Fitness* 49: 19, 2009.

17. **Levine BD**, **Baggish AL**, **Kovacs RJ**, **Link MS**, **Maron MS**, **Mitchell JH**. Eligibility and disqualification recommendations for competitive athletes with cardiovascular abnormalities: task force 1: classification of sports: dynamic, static, and impact: a scientific statement from the American Heart Association and American Colle. *J Am Coll Cardiol* 66: 2350–2355, 2015.

18. **MacDougall JD**, **McKelvie RS**, **Moroz DE**, **Sale DG**, **McCartney N**, **Buick F**. Factors affecting blood pressure during heavy weight lifting and static contractions. *J Appl Physiol* 73: 1590–1597, 1992.

19. **MacDougall JD**, **Tuxen D**, **Sale DG**, **Moroz JR**, **Sutton JR**. Arterial blood pressure response to heavy resistance exercise. *J Appl Physiol* 58: 785–790, 1985.

20. **MacLeod D**, **Sutherland DL**, **Buntin L**, **Whitaker A**, **Aitchison T**, **Watt I**, **Bradley J**, **Grant S**. Physiological determinants of climbing-specific finger endurance and sport rock

climbing performance. *J Sports Sci* 25: 1433–1443, 2007.

21. **Mermier CM**, **Robergs RA**, **McMinn SM**, **Heyward VH**. Energy expenditure and physiological responses during indoor rock climbing. *Br J Sports Med* 31: 224–228, 1997.

22. **Michailov ML**, **Mladenov L V**, **Schöffl V**. Anthropometric and strength characteristics of world-class boulderers. *Med Sport* 13: 231–238, 2009.

23. **Mihl C**, **Dassen WRM**, **Kuipers H**. Cardiac remodelling: concentric versus eccentric hypertrophy in strength and endurance athletes. *Netherlands Hear J* 16: 129–133, 2008.

24. **Narloch JA**, **Brandstater ME**. Influence of breathing technique on arterial blood pressure during heavy weight lifting. *Arch Phys Med Rehabil* 76: 457–462, 1995.

25. **O'Rourke MF**. What is blood pressure? *Am J Hypertens* 3: 803–810, 1990.

26. **Schöffl VR**, **Möckel F**, **Köstermeyer G**, **Roloff I**, **Küpper T**. Development of a performance diagnosis of the anaerobic strength endurance of the forearm flexor muscles in sport climbing. *Int J Sports Med* 27: 205–211, 2006.

27. **Secher NH**, **Amann M**. Human investigations into the exercise pressor reflex. *Exp Physiol* 97: 59–69, 2012.

28. **Sheel AW**, **Seddon N**, **Knight A**, **McKenzie DC**. Physiological responses to indoor rock-climbing and their relationship to maximal cycle ergometry. *Med Sci Sports Exerc* 35: 1225–1231, 2003.

29. **Spence AL**, **Naylor LH**, **Carter HH**, **Buck CL**, **Dembo L**, **Murray CP**, **Watson P**, **Oxborough D**, **George KP**, **Green DJ**. A prospective randomised longitudinal MRI study of left ventricular adaptation to endurance and resistance exercise training in humans. *J Physiol* 589: 5443–5452, 2011.

30. **White DJ**, **Olsen PD**. A time motion analysis of bouldering style competitive rock climbing. *J Strength Cond Res* 24: 1356–1360, 2010.

31. **Wiecek EM**, **McCartney N**, **McKelvie RS**. Comparison of direct and indirect measures of systemic arterial pressure during weightlifting in coronary artery disease. *Am J Cardiol* 66:

1065–1069, 1990.

TABLES AND FIGURES

Table 1. Subject Characteristics.

Table 2. Blood pressure, heart rate, and mouth-pressure responses to boulder problems and training exercises.

Fig. 1. Representative blood pressure (panel A) and heart rate (panel B) responses to the campus-board task in a single subject. The peak data points are highlighted: systolic pressure = 260 mmHg; diastolic pressure = 171 mmHg; heart rate = 193 b min^{-1}.