Title Page

Forearm oxygenation and blood flow kinetics during a sustained contraction in multiple ability groups of rock climbers

Running head: Haemodynamic kinetics in elite rock climbers

Key words: rock climbing, blood flow, hand grip, haemodynamics, oxidative capacity

Abstract

Currently the physiological mechanisms which allow elite level climbers to maintain intense isometric contractions for prolonged periods of time are unknown. Furthermore, it is unclear whether blood flow or muscle oxidative capacity best governs performance. This study aimed to determine the haemodynamic kinetics of two forearm flexor muscles in three ability groups of rock climbers. Thirty-eight male participants performed a sustained contraction at 40% of MVC until volitional fatigue. Oxygen saturation and blood flow was assessed using near infrared spectroscopy and Doppler ultrasound. Compared to control, intermediate and advanced groups, the elite climbers had a significantly ($p < 0.05$) higher strength-to-weight ratio (MVC/N), de-oxygenated the flexor digitorum profundus significantly ($p < 0.05$) more (32, 34.3 and 42.8 vs. 63% O_2 respectively), and at a greater rate (0.32, 0.27 and 0.34 vs. 0.77 $O_2\%\cdot s^{-1}$ respectively). Furthermore, elite climbers de-oxygenated the flexor carpi radialis significantly ($p < 0.05$) more, and at a greater rate than the intermediate group (36.5 vs. 14.6% O_2 and 0.43 vs. 0.1$O_2\%\cdot s^{-1}$ respectively). However, there were no significant differences in total forearm Δ blood flow. An increased MVC/N is not associated with greater blood flow occlusion in elite climbers therefore, oxidative capacity may be more important for governing performance.

Introduction

Early investigations into rock climbing focused on characterizing accident rates and injury occurrences across the United Kingdom and the United States of America (Bowie, Hunt, & Allen 1988; Rooks, Johnston, Ensor, McLntosh, & James, 1995). Research focus began to shift in the mid-1990's when rock climbing emerged as a competitive sport on the international stage, spurring growth in participation levels and enhancements in performance. Studies attempted to identify the anthropometric make-up of rock climbers, (Watts, Martin, & Durtschi, 1993), and to focus on strength characteristics (Köstermeyer & Weineck, 1995; Watts, Newbury, & Sulentic, 1996), particularly in elite level performers. Unfortunately, many of the methodological practices were not specific to the unique nature of the sport (Fryer et al., 2012). One of the most important examples of methodological error was the use of handgrip dynamometry as a measure of rock climbers grip strength. Not until 2008 did Watts et al. (2008) highlight this lack of sport specificity during an investigation into forearm electromyography responses during both rock climbing and hand grip dynamometry. The authors reported significantly higher electromyography readings during rock climbing

compared to hand grip dynamometry, suggesting that hand grip dynamometry lacks practical application to rock climbing.

Recently, in an attempt to understand finger flexor performance in individual groups of rock climbers, MacLeod et al. (2007) and Philippe, Wegst, Müller, Raschner, and Burtscher (2011) used a sport specific handgrip device and near infrared spectroscopy to measure tissue oxygenation. Near infrared spectroscopy works by assessing changes (absorption) in infrared waves within the wavelength range 650-1000nm, this change is affected by the presence of haemoglobin (Sako, Hamaoka, Higuchi, Kurosawa, & Katsumura, 2001). More specifically, one wavelength is sensitive to oxy haemoglobin and another wavelength is sensitive to de-oxy haemoglobin. Since light passed through the large vessels is mostly absorbed, light that reaches the detector on the optode comes mainly from the small blood vessels (arterioles, capillaries and venules) (Chance, Dait, Zhang, Hamaoka, & Hagerman, 1992; Dinler et al., 2007). Therefore, the signal provides a dynamic balance of information between the oxygen (O_2) supply and consumption within the tissues, in this case within the flexor digitorum profundus and the flexor carpi radialis.

Sport climbing ascents typically take 60 – 180s, and involve large periods of time where the forearm flexors are in isometric contraction (Fryer et al., 2012; MacLeod et al., 2007; Schweizer, Schneider, & Goehner, 2007). Surprisingly, only three known studies (Ferguson & Brown, 1997; MacLeod et al., 2007; Philippe et al., 2011) have assessed forearm haemodynamics during an isometric contraction, of which only two used sport-specific apparatus (MacLeod et al., 2007; Philippe et al., 2011). No known study has attempted to determine both oxygenation and blood flow kinetics either during or after the contraction protocols. Consequently, it is not understood whether blood flow or O_2 uptake is more important to forearm flexor performance. Therefore, the aim of the current study was twofold: 1) to determine whether muscle oxidative capacity or forearm blood flow is the limiting factor for governing performance, and 2) to assess the sport specific strength and endurance characteristics in three different ability groups of rock climbers.

Materials and Method

Participants

Forty-four, young male participants were recruited. After the initial data screening was completed (post-exercise testing), six participants were removed due to technical errors with the near infrared spectroscopy equipment. Consequently a total of 38 participants were categorised into the four groups: control (n = 9), intermediate (n = 9), advanced (n = 10) and elite (n = 10) (Table 1). Participants were placed into the ability groups defined by Draper et al. (2011a), using the self-report methods described and validated by Draper et al. (2011b). The groups were matched for age, height, weight and physical activity level. Ethical approval which adhered to the Helsinki Declaration was granted by the Institutional Review Board. Informed consent was obtained from the participants after they were given a detailed description of the procedures.

Procedures

The test sessions were performed between the hours of 7am and 11am to reduce circadian variation. All participants were asked to report to the laboratory, having refrained from strenuous exercise for 48 hours prior to testing. Participants were also asked not to consume caffeine or take any medications with known vascular actions prior to testing. Participants were excluded from the study if they were prescribed medications with known vascular actions. All stages of testing were performed in a climate-controlled laboratory setting.

Fingerboard apparatus

The fingerboard apparatus was developed at the University of Canterbury, New Zealand and was based on the design used by MacLeod et al. (2007) and Philippe et al. (2011). The apparatus was designed as a rock climbing specific handgrip ergometer, which could measure strength and endurance during an open crimp contraction. In order to determine the reliability of the device, 15 male participants performed three maximal voluntary contraction (MVC) trials on two separate days. The between-day coefficient of variation was 0.5 %. For comparison to MacLeod et al. (2007) and Philippe et al. (2011), the modifications consisted of removing grip tape from the wooden board and replacing this with a modular rock climbing hold (Uprising Ventures, Christchurch, New Zealand).

Exercise protocol

The warm-up and familiarisation exercises comprised of four main components. The first part consisted of six sustained sub-maximal contractions (5kg load on the hold) on the fingerboard. Each sustained contraction was held for a 10s period. A series of stretches and

mobilisation exercises were then performed. Three sets of ten intermittent contractions with the same 5kg load were then completed. This was followed by a further set of stretches and mobilisation exercises. Following this, the MVC trials were conducted. Each participant had three MVC attempts, each separated by a 30s rest period. If the highest score occurred on the third attempt, then a fourth contraction was allowed. Following the warm-up and familiarisation, participants were provided a few more minutes to mobilise and stretch before beginning the sustained protocol. The contraction was sustained at 40% of MVC until volitional fatigue occurred. If the participants force deviated by more than 5% above or below the 40% of MVC for more than 2s then the test was automatically terminated. During the trial, participants were verbally encouraged to contract for as long as possible.

Near infrared spectroscopy

The current study used NONIN 7600 (Plymouth, Minnesota, USA) which has previously been validated for measuring changes in regional tissue oxygenation (Lobbestael, Roth, & Prior, 2009; MacLeod & Ikeda, 2009), as well as oxygenation dynamics specifically in the forearm flexors (Schober & Schwarte, 2011). The device provides a stable, real time, near instantaneous measure of O_2 saturation, which is subsequently transferred via a wireless RS-232 serial port using eVision Patient Management Data Software. A host computer (Sony, Vaio E-series 14P) then extracted and stored CSV data files in Microsoft Excel. An extraction program written in R used the data points to plot the time constant upon which the de-oxygenation $\cdot s^{-1}$ and maximal de-oxygenation (Δ) were determined.

Near infrared spectroscopy optodes were held in place with medical tape and a crepe bandage to ensure no light interference. The effectiveness of the optodes is affected by the presence of excessive adipose tissue in the body. However, mean body fat percentage was only 21%, 22%, 15% and 13% for the control, intermediate, advanced and elite groups respectively. Furthermore, the forearms are not a major site of fat storage within the body. Therefore, it can be safely assumed that excessive adipose tissue had no interference with data.

Flexor locations

The flexor digitorum profundus is suggested to be the most important flexor muscle in the forearm for rock climbers as it bends the last (distal) joints of fingers two, three, four and five (used in the open crimp position) (Philippe et al., 2011). To locate the flexor digitorum

profundus, a line was drawn on the anterior side of the forearm from the carpus to the medial epicondyle of the humerous, in accordance with Philippe et al. (2011). Each participant performed a contraction on the climbing apparatus to locate the area of greatest contraction. The flexor carpi radialis is also an important finger flexor in the forearm; it attaches to the second and third fingers, and is also used during the open crimp. The flexor carpi radialis was located using the same technique as the flexor digitorum profundus; however, the line was drawn on the posterior side of the forearm between the crease of the elbow and the carpus.

Ultrasound

Brachial artery diameter, blood velocity and blood flow measurements were made using a SonoSite Micromax duplex Doppler unit (FujiFilm, Washnigton, USA), equipped with a 13-6 MHz linear array transducer (HFL38e). The dominant arm was scanned in the longitudinal plane 3-7 cm proximal to the antecubital fossa.

Diameter measurements

Care was taken to ensure that the vessel clearly extended across the entire (un-zoomed) imaging plane to minimise the likelihood of skewing the vessel walls. Magnification and focal zone settings were then adjusted to optimise imaging of the proximal and distal vessel walls. Ultrasound global (acoustic output, gain, dynamic range, gamma, and rejection) and probe-dependent (zoom factor, edge enhancement, frame averaging, and target frame rate) settings were standardised in accordance with (Stoner, West, Cates, & Young, 2011). Moving Picture Experts Group-2 recordings were captured using a Toshiba Laptop PC equipped with a with video capture device (ADS technologies, Cerritos, California). Video files collected at 30 frames ·s and were converted into JEPG images and subsequently used to make 30 diameter measurements ·s. The JPEG images provide comparable accuracy for ultrasound image measurements compared to the Digital Image and Communications in Medicine standard (Hangiandreou, James, McBane, Tradup, & Persons, 2002). Three 10s movies were taken for each stage of testing. Images were measured offline using semi-automated edge-detection software custom written to interface with the LabVIEW data acquisition platform (version 8.1, National Instruments, Austin, Texas) (Sabatier, Stoner, Reifenberger, & McCully, 2006; Stoner et al., 2006). Custom written Excel Visual Basic code was used to fit peaks and troughs to the diameter waveforms in order to calculate diastolic, systolic, and mean diameters (Stoner & Sabatier, 2012a). Mean diameters were used for analysis.

Velocities

Sonication angle was kept constant (between 45-60°) and the sample volume included most of the vessel. Pulse repetition frequency was adjusted between stages of testing to prevent aliasing. The blood velocity spectra was continuously recorded using a video capture device, as described above. Semi-automated software custom written to interface with MatLab calculated time averaged maximum blood velocities across the cardiac cycle. Time averaged maximum blood velocities are more reliable than time averaged mean blood velocities (Stoner & Sabatier, 2012a, 2012b).

Blood Flow

The 30 diameter measurements ·s were aggregated to 1 ·s, and synchronised with blood velocities. Blood flow was calculated as the product of brachial artery cross-sectional area and the time averaged maximum velocity.

Statistical analysis

Descriptive data is presented as mean (SD). **For meaningfulness confidence intervals (CI) are reported at 95%.** Analysis was performed using Statistical Package for Social Sciences (SPSS, Version 20.0), R-Project, and Microsoft Excel (2007). For all statistical analysis the critical α-level was set at 0.05. All variables were assessed for normal distribution using the Kolmogorov-Smirnov goodness-of-fit test, as well as checking for equal variance by visually examining the change in variance across the means (if the maximum variance was less than three times the minimum variance then equal variance was assumed). If equal variance was not assumed then data was log transformed to ensure the assumptions of ANOVA remained robust. For each independent variable a series of ANCOVA's were performed, the covariates were: height, weight, age, skeletal muscle mass and body fat percentage; none of which were shown to be significant. A series of ANOVAs were used to assess between-group differences in each independent variable. Where a significant effect was found, post-hoc least significant difference testing was used to explore the source of the between-group differences, whilst controlling for error rate. Bonferroni correction was used to adjust the *p* statistic.

Results

Climbing groups were checked for balance across age, gender, height and weight (Table 1). As shown within Table 1, significant between-group differences were reported for body fat percentage, years climbing, climbs per week, hours climbing per week, lead experience and best lead on-sight and red point climbing grades.

	Control	Intermediate	Advanced	Elite	One-way ANOVA		
	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	*F* value (df 3,37)	*P* value	% variance
Age	26 (6)	29 (4)	27 (5)	30 (9)	0.530	0.665	5
Height	178 (7)	178 (9)	179 (7)	175 (7)	0.593	0.624	5
Weight	78.8 (11.2)	79.6 (13)	71.8 (10.3)	69.3 (5.4)**	2.344	0.090	17
Body fat %	19 (11)	20 (4)	13 (4)**	12 (3)*,**	4.002	0.015	31
Years climbing	N/A	6.3 (4.7)	7 (3.9)	13.4 (7.5)**,***	4.659	0.019	26
Climbs per week	N/A	1.3 (0.7)	2.4 (0.67)**	2.9 (0.9)**	10.310	0.001	44
Hours per week	N/A	2.9 (1.7)	5.7 (2.3)*	8 (2.9)**,***	10.616	< 0.0005	45
Years leading	N/A	5.6 (5)	6.2 (4.1)	12.9 (7.8)**,***	4.723	0.018	27
Best on-sight lead (Ewbank)	N/A	18.7 (1.3)	21.7 (1.3)*	24.9 (0.7)**,***	72.661	< 0.0005	85
Best red point lead (Ewbank)	N/A	19.3 (1.2)	22.6 (1.9)*	27.7 (2)**,***	46.049	< 0.0005	79

Table 1 Mean (SD), *F* and *P* values for participant's demographic and anthropometric data.
NB % variance is the estimated variance explained by the mean effects within each group for the named variable.

* Shows the group is significantly different ($p < 0.05$) from the control group.
** Shows the group is significantly different ($p < 0.05$) from the intermediate group.
*** Shows the group is significantly different ($p < 0.05$) from the advanced group.

Strength and endurance characteristics

In accordance with MacLeod et al. (2007) and Philippe et al. (2011) the force time integral was used as a measure of climbing specific endurance. The force time integral was determined using the equation 'force time integral = 0.4 x length of contraction (s) x force (N)'. Table 2 shows that mean (SD) force time integral was marginally higher in all climbing groups compared to the control group; however, the variance relative to the mean is large, revealing a spread of force time integral s within each ability group. The MVC and MVC/body weight increased with rock climbing ability. The length of sustained contraction varied across the ability groups; however, as with the force time integral the variance is large relative to the mean.

Table 2 Mean (SD), *F* and *P* values for forearm strength and endurance characteristics in all ability groups.

	Control	Intermediate	Advanced	Elite	One-way ANOVA		
	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	*F* value (df 3,37)	*P* value	% Variance
MVC (N)+	245 (60)	273 (72)	299 (57)	412 (141)*,**	5.787	0.009	36
MVC/body mass (N/kg)+	3.2 (1)	3.4 (0.6)	4.2 (0.6)	5.9 (1.8)*,**,***	10.924	< 0.0005	49
Length of contraction (s)	107.1 (43)	175.1 (105.3)	141.2 (56.4)	102.4 (39)	2.476	0.312	17
Force time integral (0.4 x N x s)	10799 (5882)	17391 (5933)	16826 (7435)	15605 (4830)	2.199	0.649	14

NB % variance is the estimated variance explained by the mean effects within each group for the named variable. + Shows data that has been log transformed.

* Shows the group is significantly different ($p < 0.05$) from the control group
** Shows the group is significantly different ($p < 0.05$) from the intermediate group
*** Shows the group is significantly different ($p < 0.05$) from the advanced group

After log transformation, one-way ANOVA (Table 2) was used to assess for differences in MVC, MVC/body weight and force time integral between the four ability groups. As shown within Table 2, post-hoc least significant difference indicated that the elite group had a significantly greater MVC than the control (mean difference = 167, CI 55 – 279) and intermediate groups (mean difference = 139, CI 27 – 251), but not the advanced (mean difference = 113, CI 4 – 223) group. After MVC was normalised to body weight the elite group was significantly stronger than the control (mean difference = 2.7, CI 1.3 – 4.1), intermediate (mean difference = 2.5, CI 1.1 – 3.9) and advanced (mean difference = 1.7, CI 0.4 – 3) groups. There were no significant or meaningful differences between the control, intermediate and advanced groups for either MVC or MVC/Kg.

Near infrared spectroscopy

Figure 1 demonstrates example near infrared spectroscopy traces for each group during baseline and, exercise. Within the flexor digitorum profundus, during the sustained contraction, the degree of oxygenation drop increased with climbing ability (Table 3). Within the flexor carpi radialis, the degree of oxygenation drop was lower than the flexor digitorum profundus in all ability groups. The differences between the flexor digitorum profundus and flexor carpi radialis appeared to be smallest within the control group.

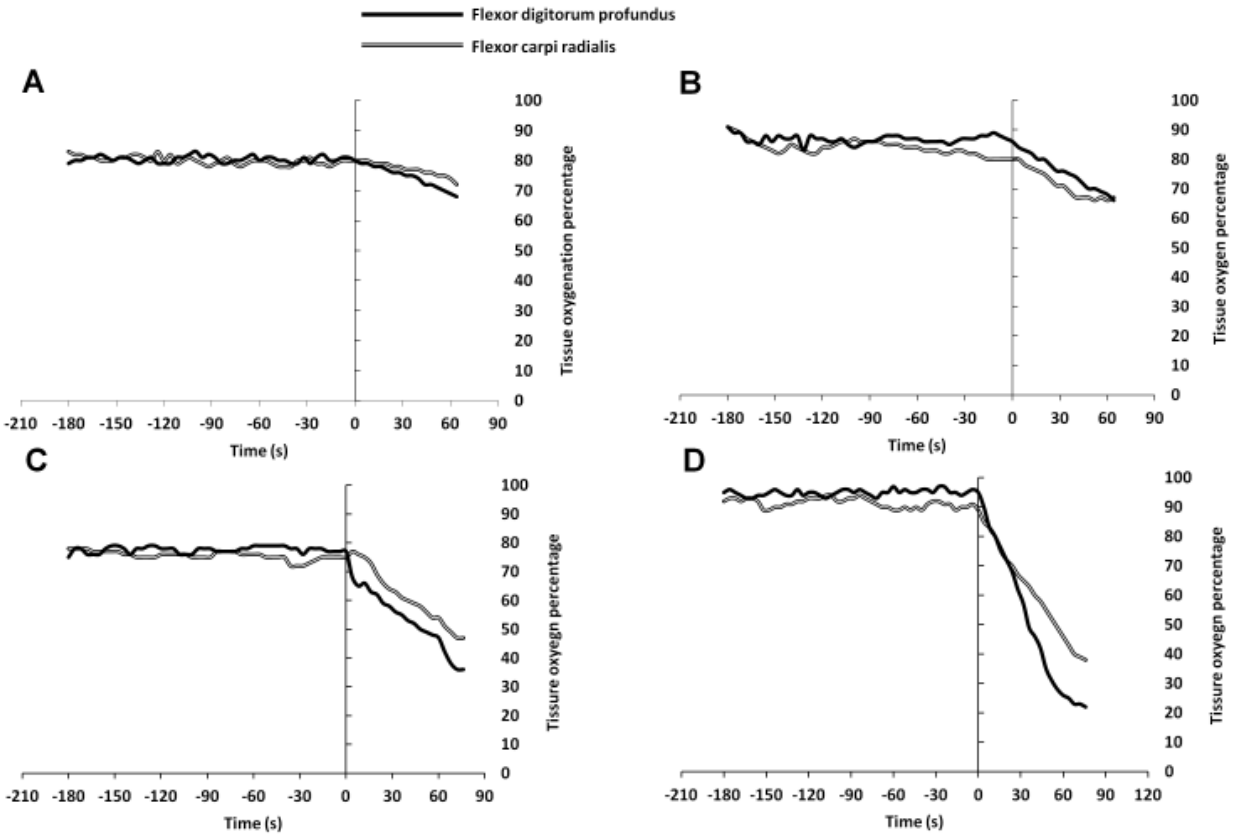

Figure 1 Example near infrared spectroscopy traces during the baseline and exercise in control (A), intermediate (B), advanced (C) and elite (D) participants. Time point '0' represents the start of contraction

The $O_2\%\cdot s^{-1}$ within the flexor digitorum profundus, for the control, intermediate and advanced groups was similar throughout the contraction (Table 3); however, the elite group used notably greater $O_2\%\cdot s^{-1}$. For all groups the $O_2\%\cdot s^{-1}$was lower in the flexor carpi radialis compared to the flexor digitorum profundus. Similar to the flexor digitorum profundus, the flexor carpi radialis in the elite group used the greatest $O_2\%\cdot \mathbf{s}^{-1}$.

Table 3 Mean (SD) tissue de-oxygenation (O_2 %) characteristics during a sustained contraction in the flexor digitorum profundus and flexor carpi radialis of intermediate, advanced and elite climbers as well as non-climbers.

	Control	Intermediate	Advanced	Elite	One-way ANOVA		
	Mean O_2% (SD)	Mean O_2% (SD)	Mean O_2% (SD)	Mean O_2% (SD)	*F* value (df 3,37)	*P* value	% Variance
FDP							
Total drop (Δ)	32 (14.3)	34.3 (9.5)	42.8 (9.3)	63.1 (17.6)*,**,***	11.115	< 0.0005	50
Total drop ·s^{-1}	0.32 (0.14)	0.27 (0.22)	0.34 (0.14)	0.77 (0.6)*,**,***	5.133	0.01	31
FCR							
Total drop (Δ)	22.7 (16.8)	14.6 (7.8)	29 (15)	36.5 (0.4)**	4.715	0.014	29
Total drop ·s^{-1}	0.23 (0.16)	0.1 (0.06)	0.23 (0.16)	0.43 (0.26)**	5.429	0.008	32

NB *% variance* is the estimated variance explained by the mean effects within each group for the named variable.
Δ represents the difference in the % of O_2 saturation between the start of contraction and the lowest % of O_2 attained during the sustained contraction.

* Shows the group is significantly different ($p < 0.05$) from the control group.
** Shows the group is significantly different ($p < 0.05$) from the intermediate group.
*** Shows the group is significantly different ($p < 0.05$) from the advanced group.

As shown in Table 3 a series of ANOVAs revealed significant between-group differences for both de-oxygenation percentage (Δ) and the O_2% ·s^{-1} within the flexor digitorum profundus and flexor carpi radialis muscles. Post-hoc least significant difference indicated that the flexor digitorum profundus de-oxygenated significantly more in the elite group compared to the control (mean difference = 31.1, CI 14.7 – 47.5), intermediate (mean difference = 28.8, CI 12.4 – 45.1) and advanced (mean difference = 20.3, CI 4.4 – 36.2) groups. For the flexor carpi radialis post-hoc analyses indicated that the elite group de-oxygenated (Δ) significantly more than the intermediate (mean difference = 21.9, CI 5.6 – 38.3) but not the control (mean difference = 2.5 – 30.2) or advanced (mean difference = 7.6, CI 8.4 – 23.6) groups.

As shown in Table 3, post-hoc least significant difference indicated that in the flexor digitorum profundus the elite group de-oxygenated significantly more ·s compared to the control (mean difference = 0.45, CI 0.56 – 0.84), intermediate (mean difference = 0.5, CI 0.10 – 0.89) and advanced (mean difference = 0.43, CI 0.41 – 0.81) groups. For the flexor carpi radialis post-hoc least significant difference indicated that the O_2% drop ·s^{-1} of the elite group was significantly greater than the intermediate group only (mean difference = 0.32, CI 0.10 – 0.55).

Blood flow

As shown in Table 4 a series of one-way ANOVAs revealed no-significant between-group differences for velocity and blood flow.

Table 4 Mean (SD), *F* and *P* values for the change in velocity, blood flow and heart rate measured in the brachial artery during the last minute of sustained contraction.

	Control	Intermediate	Advanced	Elite	One-way ANOVA		
	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	*F* value (df 3,30)	*P* value	% variance
Change (Δ) in velocity (mm ·s)	18.8 (9.2)	18 (10.1)	26 (13.6)	27.8 (17.2)	1.333	0.284	10
Change (Δ) in blood flow (mL·min^{-1})	156 (79)	179 (113)	270 (162)	262 (193)	1.359	0.276	13

NB the Δchange in velocity and blood flow is the difference between baseline values and those sampled during the last minute of exercise

Discussion

The major findings of the current study were: 1) elite and advanced rock climbers are able to de-oxygenate both the flexor digitorum profundus and flexor carpi radialis to a greater extent than intermediate climbers and non-climbers during a sustained contraction, and 2) there are no between-group differences in blood flow during the contraction, suggesting vessel occlusion may not be a limiting factor for muscle performance as previously suggested.

MVC and strength-to-weight ratio

This is one of only a few studies which measured MVC using a sport specific handgrip ergometer (Grant et al., 2003; López-Rivera & González-Badillo, 2012; MacLeod et al., 2007; Philippe et al., 2011; Schweizer & Furrer, 2007). Unlike previous studies, the elite group not only had a significantly higher MVC than all other groups, but there was a continually increasing trend in MVC with the concurrent increase in rock climbing ability. These findings suggest that when MVC is obtained using a sport specific ergometer, it can be used as a sensitive measure of rock climbing performance in a range of different ability groups. As previously suggested (Mermier, Janot, Parker, & Swan, 2000; Philippe et al., 2011; Watts, Joubert, Lish, Mast, & Wilkins, 2003) the usefulness of MVC when discriminating between groups may be further enhanced by its expression relative to mass (MVC explained 36% of the variance, and strength-to-weight (MVC/Kg) explained 49% of the variance).

Climbing specific finger endurance

Time-to-failure did not significantly differ by ability group. Previous studies which have assessed endurance times in non-climbers found a shorter isometric endurance with those who had a greater MVC (Carlson, 1969; Carlson & McCraw, 1971; Ferguson & Brown, 1997). In the current study the absence of this negative relationship between MVC and endurance is more likely caused by the elite group being able to contract for a longer period of time, as opposed to the lower level groups contracting for a shorter period of time. Previous studies, including those using climbing specific finger strength equipment, have suggested that blood flow may be occluded in more advanced performers however, these studies either did not measure blood flow (MacLeod et al., 2007), or did not measure blood flow during the contraction (Ferguson & Brown, 1997). The current study did not find blood flow to be significantly different between ability groups, suggesting that muscle oxidative capacity may be more important than blood flow for governing muscle performance in elite rock climbers. This increased ability for elite and advanced climbers to maintain a contraction at 40% MVC and oppose blood flow occlusion could be due to an increased presence of the metaboreflex. The metaboreflex consists of heightened cardiac output, stroke volume, pressor response and heart rate (O'Leary, 1993). These factors would allow for a greater perfusion pressure and/or an increased vascular conductance, therefore improving the capacity to deliver blood during an isometric contraction. However, as Ferguson and Brown (1997) showed there was an attenuated pressor response in climbers, other factors such as an increased cardiac output, or increased capillarity may have contributed to a prolonged contraction time. Figure 1 and Table 3 show that an increased capillarity may have driven the increased oxygen perfusion within the muscle itself. However, further research assessing components of the metarboreflex reflex, capillary density and vascular conductance is required to clarify the driving factors associated with this increase in performance.

Determinants of the force time integral

There was a decline in tissue oxygenation in both the flexor digitorum profundus and flexor carpi radialis with the onset of contraction, with the elite climbers demonstrating a much greater response (see example shown in Figure 1). The elite climbers had a significantly greater total O_2% drop, as well as a significantly greater drop in O_2% $\cdot s^{-1}$ (Table 3) suggesting both an increase in capillary density, as well as an enhanced capability for the muscle to perfuse O_2. These oxygenation responses were more pronounced in the flexor digitorum profundus than the flexor carpi radialis within all ability groups, likely due to the flexor

digitorum profundus contributing to the flexion of a greater number of digits than the flexor carpi radialis. Like previous maximal effort studies, this de-oxygenation tended to level off near the point of failure, suggesting that the muscle had reached its maximal capacity for extracting O_2 from the perfusing blood (Pereira, Gomes, & Bhambhani, 2007). Furthermore, the small variance values seen in the elite group suggests that they were close to the human physical limit for perfusing O_2 from the muscle.

As Philippe et al. (2011) reported a significantly greater force time integral in World Cup climbers, it was expected that the force time integral would have been greater in the elite group of the current study. However, the lack of significant change may be due to the difference in performance grades used in the two studies. In the current study the elite climbers were defined as having a best lead on-sight grade of > 25 (Ewbank), whereas the World Cup climbers in the Philippe et al. (2011) study were defined as > 29 (Ewbank). A difference of four performance grades at this high level of climbing is considerable, and as such separated the top twenty places in the 2012 World Cup competition. The higher level climber presented by Philippe at al. (2011) may have had muscular adaptations not seen in the current study. However, as the current study revealed an increasing trend in blood flow with ability group, but no significant difference in blood flow or force time integral (Table 4), further investigation of forearm blood flow kinetics in World Cup climbers (> 29 Ewbank) is warranted.

Conclusion

Sport specific grip strength, and strength-to-weight ratio appear to be accurate measures of performance and are able to distinguish between ability group's rock climbers. Interestingly, it would appear that an increased MVC may not be associated with greater blood flow occlusion in elite level climbers, as previous research has suggested. As rock climbing ability increases, climbers are able to de-oxygenate both the flexor digitorum profundus and the flexor carpi radialis significantly faster and to a greater extent, suggesting that muscle oxidative capacity and the ability to perfuse O_2 may be more important than blood flow for governing performance. The greater level of de-oxygenation in elite climbers may be due a greater oxidative capacity, influence of the metaboreflex or an increased perfusion pressure. Further research investigation into the underlying mechanisms and trainability of such responses is warranted.

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