Abstract
Currently it is unclear whether blood flow (BF) or muscle oxidative capacity best governs performance during intermittent contractions to failure. The aim of this study was to determine oxygenation kinetics and BF responses during intermittent (10s contraction: 3s release) contractions at 40% of MVC in different ability rock climbers (N=38). Total forearm BF, as well as de-oxygenation and re-oxygenation of the flexor digitorum profundus (FDP) and the flexor carpi radialis (FCR) were assessed. Compared to the control, intermediate and advanced groups, the elite climbers had a significantly ($p < 0.05$) greater force time integral (FTI), MVC and MVC/kg. Furthermore, the elite climbers de-oxygenated the FDP significantly more during the first (7.8, 11.9, 12.4 vs. 15.7 O_2%) and middle (7.3, 8.8, 10.4 vs.15.3 O_2%) phases of contractions; and for the FCR during the first phase only (8.3, 7, 11.7 vs. 13.3 O_2%), and had a significantly higher BF upon release of the contractions (656, 701, 764 vs. 971 $mL \cdot min^{-1}$). The higher FTI seen in elite climbers may be attributable to a greater blood delivery, and an enhanced O_2 recovery during the 3s release periods, as well as a superior muscle oxidative capacity associated with the greater de-oxygenation during the 10s contractions.

Introduction

One of the least understood yet most important components of elite rock climbing performance is the unique ability of the forearm flexors to conduct intense intermittent isometric contractions for a prolonged period of time [25]. Knowledge regarding how it is possible for these athletes to use the distal parts of the fingertips to hold their body weight on what are seemly impossibly small holds for 60 – 180s during competitive ascents remains unclear. Previous studies which have attempted to understand the oxygenation kinetics during intermittent contractions, have done so in single ability groups only [18, 21]. Furthermore, only one known study has attempted to determine post-contraction blood flow (BF)

characteristics [7], unfortunately this study used handgrip dynamometry, which was later deemed to be non-climbing specific [29].

Although an understanding of forearm BF and the ability for the muscle to perfuse O_2 is of paramount importance to further increasing performance [18, 21, 24], currently no known study has attempted to assess both the combined BF and O_2 kinetics in multiple groups of athletes in order to determine the underlying physiological mechanisms. This is likely due to the difficult nature of measuring BF and O_2 kinetics during intermittent contractions, whilst ensuring ecological validity within the sport. It is therefore currently unknown whether BF or the ability for the muscle to perfuse O_2 is the limiting haemodynamic factor in forearm flexor performance. Furthermore, it is not known how these responses may differ both between the individual flexors, and the ability level of the athlete involved. Therefore, the aims of this study were to 1) determine the degree of de-oxygenation during intermittent contractions, and the subsequent re-oxygenation during intermittent rests, 2) assess forearm BF responses both during intermittent contractions and the subsequent rest periods, and 3) assess the sport-specific strength and endurance characteristics of multiple ability groups of rock climbers.

We hypothesis that elite climbers would be able to 1) de-oxygenate both the flexor digitorum profundus (FDP) and the flexor carpi radialis (FCR) significantly more than all other groups, 2) have a significantly greater BF during both the contractions and subsequent release periods, and 3) these previously mentioned physiological mechanisms would in part contribute to a significantly greater force time integral (FTI).

Method

Participants

A total of 44 young active male participants were recruited. After data screening, a total of six participants were removed due to technical errors with the near infrared spectroscopy (NIRS) equipment and ultrasound image analysis. Therefore, a total of 38 participants were categorised into four groups: intermediate (n=9), advanced (n=10) and elite (n=10) climbers as well as a control (n=9) group (aerobically trained but not forearm trained). Rock climbing participants were placed into the ability groups defined by Draper et al., [4], using the self-report methods described and validated by Draper et al., [5] (see Table 1). The groups were matched for age, height, mass and non-climbing physical activity level (IPAQ [2]). Ethical approval which met the standards of the journal [11] was granted by the institutional review board. Informed consent was obtained from the participants after they were given a detailed written and verbal description of the procedures.

Procedures

Participants were excluded from the study if they were prescribed any medications which were known to have any vascular actions. All participants were asked not to consume caffeine or heavy meals at least two hours prior to testing. All testing sessions were conducted between the hours of 7am and 11am and were conducted in a climate controlled exercise physiology laboratory.

Fingerboard apparatus

The fingerboard was designed based on the specifications described by [18] and [21]. For comparability reasons, modifications consisted of removing the wooden ledge in exchange for a climbing hold (55mm wide and 12mm deep), enhancing the sport specificity of the fingerboard (to an open crimp, described by Schweizer et al., [25]. For schematics and

diagrams of the device see Macleod et al., [18] and Philippe et al., [21]. In order to determine the reliability of the fingerboard, 15 male participants not involved in the study performed three maximal voluntary contraction (MVC) trials on two separate days. The between-day coefficient of variation was 0.5%.

Warm-up, familiarisation and MVC

The warm-up and familiarisation comprised of four main exercises. The first part consisted of six sustained sub-maximal contractions (5kg loads on the hold) on the apparatus. Each sustained contraction was held for a 10s period. A series of stretches and mobilisation exercises were then carried out. A series of intermittent contractions with the same 5kg load were then completed. In order to work as a warm-up and a familiarisation activity, the intermittent contractions were the same duration and frequency as the main test (10s contraction: 3s rest). This was followed by a further set of stretches and mobilisation exercises all based around the hand and forearm flexors on the dominant side. Following this, the MVC trials were conducted. Each participant had three MVC trials each separated by a 30s active rest period. If the highest MVC occurred on the third attempt, then a fourth attempt was allowed. Participants were verbally encouraged throughout each contraction.

Exercise protocol

Following the warm-up and familiarisation, participants were given 5 minutes to mobilise and stretch before beginning the intermittent protocol. Each contraction was sustained at 40% of MVC for a 10s period, this was followed by a rest of 3s before the following 10s contraction. The 10:3s contraction/rest cycle continued until volitional fatigue, or the

participants 10s contraction fell more than 5% below 40% of MVC for more than a 2s period. Participants were verbally encouraged to contract for as long as possible.

Near infrared spectroscopy

Near infrared spectroscopy works by measuring the relative changes (absorption) within the wavelength range 650-1000nm; these wavelengths are influenced by the presence of haemoglobin [22]. More specifically, one wavelength is sensitive to oxygenated haemoglobin and another to de-oxygenated haemoglobin. The current study used A NONIN 7600 (Plymouth, Minnesota, USA) which has previously been validated to assess muscle tissue oxygenation [17, 19], as well as having been previously used specifically to assess forearm oxygenation kinetics [23]. In this case, the device measured oxygenated and de-oxygenated haemoglobin kinetics within the FDP and the FCR. The effectiveness of the optodes is affected by the presence of excessive adipose tissue in the body. However, mean body fat percentages (assessed using bio-impedance, **InBody 230, BioSpace**) shown in Table 1 are low, and 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.

Near infrared spectroscopy outcome measures

Based on previous work MacLeod at al., and Philippe et al., [18, 21], the amount of de-oxygenation that occurred during the contractions was defined and reported as the mean of the first, middle and last three contraction phases. However, the current study aimed to determine not only absolute de-oxygenation and re-oxygenation during the contraction-rest phases, but as a novel measure, determine the relative re-oxygenation. Relative rest phase re-oxygenation (shown in Figures 1 and 2) considers the re-oxygenation during the 3s rest

phases, with respect to the amount of de-oxygenation which took place during the preceding 10s contraction.

Flexor locations

In accordance with Philippe at al., [21] a line was drawn on the anterior side of the forearm from the carpus to the medial epicondyle of the humerous to locate the FDP. Furthermore, each participant performed a contraction whilst wearing a NIRS optode to locate the area of greatest contraction. The FCR was located using the same technique as the FDP; however, the line was drawn on the posterior side of the forearm between the crease of the elbow and the carpus.

Blood flow

Brachial artery diameter and blood velocity measurements were made using a SonoSite Micromax duplex Doppler unit (FujiFilm, Washnigton, USA), equipped with a 13-6 MHz linear array transducer (HFL38e). Standard operating procedures in accordance with Stoner & Sabatier [27] were followed. To measure change in vessel diameter, at each stage three 10s MPEG-2 clips (30 frames ·s) were collected using a video capture device (ADS technologies, Cerritos, California). Changes in diameter across the cardiac cycle were claculated using semi-automated edge-detection software custom written to interface with the LabVIEW data acquisition platform (version 8.1, National Instruments, Austin, TX) [26]. In accordance with Stoner & Sabatier [27] mean diameters were used for analysis. To measure blood velocities, spectral waveforms were continuously captured using a video capture device. Sonication angle was kept constant (between 45-60^{o}) and the sample volume included most of the vessel. Offline, semi-automated software was custom written to interface with MatLab (R2013a, MathWorks, Natick, MA) and used to calculate time averaged maximum blood velocities

across the cardiac cycle as suggested by Stoner & Sabatier [27]. Blood flow was calculated as the product of brachial artery cross-sectional area and the time averaged maximum blood velocity.

Statistical analysis

All analysis was performed using Statistical Package for Social Sciences (SPSS, Version 20.0), R-Project, and Microsoft Excel (2007). For all analysis the critical α-level was set at 0.05. Before data analysis was conducted, 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 variance could not be assumed then data was log transformed to maintain the robust nature of ANOVA. For every independent variable a series of ANCOVA's were performed, the covariates were: height, mass, age, skeletal muscle mass and body fat percentage. None of the covariates were found to significantly affect any of the participant's scores. A series of one-way ANOVA's were used to determine if there were differences present between ability groups for each independent variable. Where significant between-group differences were found, subsequent post-hoc analyses (LSD) were conducted to determine where the difference may lay. Bonferroni correction was applied to multiple testing to prevent type I error.

Results

Strength and endurance characteristics

A series of one-way ANOVAs (Table 1) found that the elite climbers has a significantly greater MVC compared to the control (mean difference 167, CI 82 – 252), intermediate

(mean difference 139, CI 54 – 224) and advanced (mean difference 113, CI 31 – 196) groups. Furthermore, the differences were exacerbated when MVC was normalised to mass and consequently the elite climbers had a significantly higher MVC/kg compared to the control (mean difference 2.68, CI 1.62 – 3.75), intermediate (mean difference 2.47, CI 1.41 – 3.54), and advanced (mean difference 1.73, CI 0.7 – 2.77) groups. There was also a significant difference between ability groups for the independent variable force time integral (FTI). In accordance with MacLeod et al., [18] and Philippe et al., [21] the FTI was used as a measure of climbing specific endurance. The FTI was determined using the equation FTI = 0.4 x length of contraction (s) x force (N). Post-hoc LSD revealed that the elite group had a significantly higher FTI compared to the advanced (mean difference = 21261, CI 4249 – 38273), intermediate (mean difference = 19535, CI 2957 – 37012) and control (mean difference = 27727, CI 9684 – 457710) groups. There were no significant differences in the length of contraction between the ability groups.

Insert Table 1 near here

Blood flow

As shown in Table 2, BF upon the release of contraction increased as ability level increased, with the elite group having a significantly higher BF than the control group (mean difference 317, CI 103 – 531), but not the intermediate (mean difference 271, CI 38 – 504) or advanced (173, CI 41 – 386) groups. Furthermore, there was no between-group significant differences or meaningful effects for Δ BF.

Insert Table 2 near here

De-oxygenation

Mean (SD) data in Table 2 presents the mean de-oxygenation that occurred in the FDP and FCR during the first, middle and last three contractions during the intermittent test. A one-way ANOVA revealed that de-oxygenation in the FDP was significantly greater in elite group compared to the control groups during the first (mean difference 7.9, CI 2.8 – 13.1) and middle (mean difference 8, CI 2.1 – 13.9) contraction phases. In the FCR the elite group de-oxygenated significantly more than the intermediate group during the first phase only (mean difference 6.3, CI 2.1 – 10.6).

Relative re-oxygenation

Flexor digitorum profundus

Insert Figure 1 near here

A series of one-way ANOVAs revealed no between-group differences during the first ($F_{(3,36)} = 1.306$, $p = 0.289$), middle ($F_{(3,36)} = 0.546$, $p = 0.654$), or last ($F_{(3,36)} = 1.295$, $p = 0.292$) three rest phases and the estimated percentage variances were only 11, 5 and 11%, respectively.

Flexor carpi radialis

Insert Figure 2 near here

A series of one-way ANOVAs found no significant between-group differences during the first ($F_{(3,36)} = 0.232$, $p = 0.873$) and middle ($F_{(3,36)} = 0.990$, $p = 0.409$) phases, and the estimated percentage variances were only 2% and 8% respectively. However, there was a significant difference during the last ($F_{(3,36)} = 4.532$, $p = 0.009$) rest phase, the estimated percentage of variance was 29%. The elite group re-oxygenated significantly more than the control (mean difference 4.1, CI 1.3 – 6.9) and intermediate (mean difference 4.3, CI 1.4 – 7.1) groups.

Discussion

To our knowledge this is the first study to investigate muscle oxygenation kinetics and total forearm BF with respect to climbing performance in multiple ability groups of rock climbers. The main findings of the study were 1) the significantly greater FTI in elite climbers is likely due to the significantly greater de-oxygenation during contractions, as well as the re-oxygenation during subsequent recovery periods, 2) the FTI may be increased due to a significantly greater BF upon the release of contractions, 3) rock climbers with a best on-sight of 25+ (Ewbank) appear to have a significantly greater FTI and 4) both MVC and MVC/kg appear to be accurate tools for determining rock climbing performance.

As expected Table 1 shows that both MVC and MVC/kg were significantly greater in elite climbers compared to all other groups. However, MVC/kg explained a greater amount of the difference between groups (40% vs 36%). Similar to MacLeod et al., [18], Table 1 suggests the elite group had a significantly higher FTI compared to all other groups. Although MacLeod et al., [18] previously showed that climbers who had a best on-sight grade of 24 (Ewbank) had a significantly greater FTI than non-climbers, a novel finding of the current

study is that the FTI was only significantly different when climbers had a best on-sight grade of 25 or greater (Ewbank). Although MacLeod et al., [18] suggested the higher FTI was due to climbers being more accustomed to producing maximal efforts, and consequently having exhibited a larger central command-mediated pressor response, we propose that it would be unlikely to be a consequence of just being accustomed to working maximally. A more likely explanation may be the significantly greater release BF after the 10s contractions and greater re-oxygenation during the intermittent rest periods (3s) between elite climbers and non-climbers. Furthermore, mean difference and CI in Table 1 suggest the FTI had an increasing trend (although not significant) across all climbing groups compared to the control, suggesting a trainable effect (the FTI explained 26% of the variance between groups).

MacLeod et al., [18] and Philippe et al., [21] defined rest phase re-oxygenation as the difference in O_2% between the start of the rest phase and the end of the rest phase. However, this only accounts for the absolute change and not one that is relative to the amount of de-oxygenation that occurred during the preceding contraction. The significantly greater FTI in the elite group may be explained in part by this significantly greater de-oxygenation observed during the contraction phases (Table 2), as well as the corresponding re-oxygenation (Figures 1 and 2) and significantly increased BF upon release of the contraction (Table 2). Table 2 shows the elite group had a significantly greater de-oxygenation during the first and middle phases within the FDP, and during the first phase within the FCR. Further emphasing the importance of the de-oxygenation data, when results are presented as relative re-oxygenation (Figures 1 and 2) there were no significant differences in the FDP, and only the elites were higher than the control and intermediate during the last phase in the FCR. This suggests that the extent of de-oxygenation may be an important determinant of the significantly greater FTI. The amount of relative re-oxygenation, i.e. which is normalised to the previous

contractions de-oxygenation profile is particularly important and should not be overlooked. This is of particular interest as muscle oxidative rate measured using NIRS has been significantly correlated to PCr re-synthesis (measured by 31-magnetic resonance spectroscopy after exercise) [10, 22]. This relative re-oxygenation may provide a better representation of the PCr re-synthesis during the intermittent contractions within the current study, and is suggestive of a denser capillary bed within the muscle.

Between-group differences in FTI may be in part due to the larger amount of intramuscular O_2 used during the contraction phases (10s), and consequently ATP may be produced from different metabolic processes. It is possible that climbers in the current study, who had a higher on-sight grade, were able to de-oxygenate the FDP more as they were able to recruit more muscle fibres, and rely to a greater extent on localised aerobic capacity. Furthermore, the larger amount of O_2 which is paid back during the 3s rest phase may have been derived from an increased aerobic contribution, as a consequence of the significantly increased BF upon release of the contraction seen in the elite group (Table 2), or an increase in the ability of elite climbers to more efficiently off-load O_2 from HbO_2. An increase in aerobic contribution has been seen previously in other sports. Previously, Gaitanos et al., [8] investigated muscle metabolism during and after intermittent running sprints to failure. The authors reported that during the latter sprints there was a considerable reduction in ATP being generated through anaerobic processes and a 10-fold decrease in the rate that glycogen was degraded to lactic acid. The increase in ATP being generated from aerobic processes was matched by a decrease in muscular power output when attempting to run maximally. Therefore, it seems plausible that elite level climbers in the current study had a significantly greater FTI as they may have been more reliant on slow rate glycolysis, whilst non-climbers

and lower level climbers may rely more heavily on fast rate. However, further investigation into energy system contributions is required to determine the extent of each mechanism.

Despite the significantly greater MVC, a potential increase in type I muscle fibre density due to the significantly greater training frequency (hours per week) in the elite group could also help to explain the greater FTI. An increase in type I fibre has been suggested to allow a muscle to be more active with lower tissue oxygenation levels during contraction [20]. Furthermore, previous studies have shown that lower level rock climbers have higher levels of blood lactate compared to more advanced climbers, even after pre-practising a route and becoming more accustomed to the moves [1]. However, as we did not directly measure the metabolic products within the muscle, or fibre type distribution, this theory is merely speculation. The greater FTI seen in the elite climbers could be due to a number of factors which are associated with trained athletes: a faster metabolic clearance [15, 28], a greater energy contribution from oxidative-phosphorylation [14, 16], an increased presence of the metaboreflex [3] or neurological adaptations [6]. The potential for intramuscular adaptation in elite climbers was previously highlighted by the work of España-Romero & Watts [6]. The authors showed that although climbers had significantly greater finger flexor strength compared to non-climbers, there was no hypertrophy in the forearms. In addition, Ferguson & Brown [7] suggested that a reduced pressor response seen in trained climbers during intermittent contractions could be brought on by a reduction in metabolic by-products causing less stimulation of chemosensitive afferent nerve endings. It is well known that the peripheral effects of endurance performance on metabolic products have been shown to reduce many metabolites which stimulate chemosensitive nerve endings [9, 12-14].

Conclusion

The main findings of the current study were: 1) the higher FTI seen in elite climbers may be attributable to the significantly greater de-oxygenation during contractions, as well as the re-oxygenation and increased BF during the subsequent 3s recovery periods, 2) both MVC and MVC/kg appear to be accurate tools for determining rock climbing performance, and 3) only rock climbers with a best on-sight of 25+ (Ewbank) appear to have a significantly greater FTI. It would also appear that elite level rock climbers may have a greater localised aerobic capacity within the forearm flexors, shedding light on the current discordant findings regarding energy system contribution in the literature. However, further investigation into the aerobic/anaerobic contribution, capillary density, presence of the metarboreflex, and the potential trainability of the FDP and FCR in rock climbing is warranted.

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Table 1 Mean (SD), F and P values for anthropometric and demographic characteristics, as well as forearm strength and endurance in all ability groups.

Table 2 Mean (SD), F and P values for de-oxygenation (%) of the flexor digitorum profundus and flexor carpi radialis during the first, middle and last three intermittent contractions, as well as total forearm blood flow and heart rate responses during contraction and release periods.

Figure 1 Mean (SD) relative rest phase re-oxygenation (Δ) that occurred in the flexor digitorum profundus during the first, middle and last three rest phases of the intermittent test.

Figure 2 Mean (SD) relative rest phase re-oxygenation (Δ) that occurred in the flexor carpi radialis during the first, middle and last three rest phases of the intermittent test.