Oxygen recovery kinetics in the forearm flexors of multiple ability groups of rock climbers

ABSTRACT

The purpose of this study was to determine muscle tissue oxidative capacity in intermediate, advanced and elite rock-climbers. Forty-four male participants performed i) a sustained and ii) intermittent contractions at 40% of MVC on a sport-specific finger board until volitional fatigue. Near infrared spectroscopy was used to assess muscle tissue oxygenation during both the exercise and the 5 minute passive recovery period, in the flexor digitorum profundus (FDP) and flexor carpi radialis (FCR). During the sustained contraction only, muscle tissue de-oxygenation (O_2 debt) in the FDP and FCR was significantly greater in elite climbers compared to the control, intermediate and advanced groups (FDP 32 vs. 15, 19, 22% O_2; FCR 19 vs. 11, 8, 15% O_2 respectively). However, elite climbers had a significantly quicker time to half recovery ($T_{1/2}$) than the control and intermediate groups in the FDP (8 vs. 95 and 47s respectively) and the FCR (7 vs. 30 and 97s respectively), as the O_2% recovered per second was significantly greater (FDP 4.2 vs. 0.7 and 0.3; FCR 4.8 vs. 0.1 and 0.2 $O_2\%\cdot s^{-1}$ respectively). Furthermore, during the intermittent contraction $T_{1/2}$ in elite climbers was significantly quicker compared to the control and intermediate groups in the FDP (8 vs. 93 and 83s respectively) and FCR (16 vs. 76 and 50s respectively). Consequently, lower level climbers should focus training on specific intermittent fatigue protocols. Competition/elite climbers should make use of appropriate rests on route to aid recovery and increase the chances of reaching the next hold.

Key words: Oxidative capacity, haemodynamic kinetics, oxygen recovery, rock climbing, hand grip exercise

INTRODUCTION

Despite an exponential global growth in competitive rock climbing over the last two decades, to date there remains a dearth in the research available regarding training for climbing (13). One of the major reasons for this lack of information for practitioners has been due to the conflicting findings of the multifaceted mechanisms which underpin the sport. Rock climbing encompasses a multitude of physiological, psychological and bio-mechanical aspects, and as such some previous laboratory assessments have had limited ecological validity (Watts, Philippe & MacLeod). As an example Watts et al., used electromyography to show that handgrip dynamometry, although commonly used in previous studies (REFS), was not representative of finger flexor strength in rock climbers. Furthermore, MacLeod and Philippe et al., (REF number) assessed forearm finger flexor oxygenation as well as strength and endurance using a 22mm metal force plate with grip tape attached, and not an actual climbing hold. Therefore, major determinants of performance such as the aerobic/anaerobic contributions during an ascent (1), and the potential benefits/hindrances to forearm muscles caused by pausing to rest on a route (11, 17) remain discordant.

Rock climbing has been shown to involve large periods of time spent cycling between sustained and intermittent isometric forearm contractions (9), and so oxidative capacity in the highly stressed local muscle groups is important, and has become a prominent area of interest (10, 11, 14, 17). Previous studies have used near infra-red spectroscopy (NIRS) to assess de-oxygenation (the offloading of oxygen from haemoglobin in the muscle tissue) during both sustained and intermittent contractions to failure, but have not been used to assess oxidative capacity per se (10, 11, 14, 17). Tissue oxygen (O_2) recovery assessed using NIRS has been shown to have a similar time constant to phosphocreatine (PCr) re-synthesis assessed using magnetic resonance spectroscopy (15), and so the application of NIRS may provide useful information on muscle tissue oxidative capacity in climbers. Therefore, the aim of this study was to compare muscle tissue oxidative capacity in multiple ability groups of rock climbers. Specifically, the aims were to assess: i), muscle tissue oxidative capacity, ii) O_2% recovery per second in the flexor digitorum profundus (FDP) and the flexor carpi radialis (FCR), and iii) maximal de-oxygenation and the force time integral (FTI).

METHODS

Experimental Approach to the Problem

Rock climbing groups (control, intermediate, advanced and elite) were categorized based on the validated (REF), self-reported indoor lead on-sight and red point grades using the guidelines suggested by Draper et al. All participants undertook the testing at the end of the indoor season (late spring) to help minimize seasonal variation in training programmes. NIRS was used to assess oxygenation kinetics as it has recently been shown to be an effective for assessment of muscle tissue oxygenation kinetics in the forearms of rock climbers (Mac, Fryer, Philippe). To ensure sound practical implications for climbers could the drawn from the study, the FDP and FCR were used. The FDP has been suggested (17) to be the most important flexor muscle for climbing as it bends the last (distal) joints of fingers two, three, four and five (used in the open crimp position). The FCR is the second most important finger flexor as it attaches to the second and third fingers. All testing was performed using an open crimp, one of the most common grip techniques in the sport.

Subjects

Forty-four male subjects were recruited and subsequently divided into four ability groups: control, intermediate, advanced and elite. Before any testing took place, all subjects gave informed written consent after a verbal and written explanation of the procedures was conducted. The institutional Human Ethics Review Board granted ethical approval prior to data collection. Due to difficulties with the NIRS signals during testing, a total of 6 subjects and all their data were excluded from the study and all analyses. The control group was matched for age, height, body mass and general physical activity level (IPAQ (2)). All control subjects conducted lower limb exercises such as running and cycling 1-2 times a week, but did not partake in any upper limb training. Climbing groups were subsequently checked for balance across age, gender, height and mass (Table 1).

******* INSERT TABE 1 NEAR HERE*****************

Procedures

Each subject completed all testing during a single visit to an environmentally controlled exercise physiology laboratory. Figure 1 shows a schematic depicting the protocol used during the study. A rock climbing specific fingerboard designed by MacLeod et al., (14) and modified (addition of climbing holds instead of wooden force plate) by Fryer et al., (10, 11) was used to conduct all strength and endurance tests (fingerboard the between-day coefficient of variation was 0.5 %). A schematic and picture of the fingerboard and climbing hold is shown in Figure 2. All subjects completed a standardized warm-up and a set of familiarization trials based on the protocol suggested by MacLeod et al., (14), Philippe et al., (17) and Fryer et al., (10, 11). All testing was conducted using the subject's dominant arm with the elbow flexed to 90^o and the shoulder externally rotated to 90^o. After the warm-up and familiarization, participants conducted three MVCs; if the highest value was attained on the third attempt, a fourth was permitted. For the fatigue protocol all subjects performed two contractions until volitional fatigue; a sustained contraction and an intermittent contraction (10s contraction with 3s rest) both at 40% of MVC (randomized order). During both protocols, subjects were verbally encouraged to contract for as long as possible. Following exhaustion all subjects remained still (passive recovery) with their hand remaining on the climbing hold (which was head height, see Figure 2 for schematic) for a total of five minutes. Exhaustion was defined as; not being able to maintain ± 5% of the 40% MVC for a 2second period. Active recovery between the sustained and intermittent test consisted of 20 minutes light cycle ergometry at 40W and 30W for males and females respectively. Twenty minutes low intensity cycle ergometry was used as Heyman et al., (2009) found this to preserve performance during repeated bouts of exhaustive climbing.

********************Insert Figures 1 and 2 near here************************

Near infrared spectroscopy and forearm flexors

A 2-channel NONIN 7600 (Plymouth, Minnesota, USA) was used to assess oxygenation changes in the FDP and the FCR throughout the entire protocol. Optodes were fitted and used in accordance with manufacturer guidelines. Optodes were held in place over the FDP and FCR with medical tape and covered with a crepe bandage to ensure there was no light interference with the signals. To locate the FDP and FCR muscles, a line was drawn on the flexor aspect of the forearm from the carpus to the medial epicondyle of the humerus. As suggested by Philippe et al., (17), each participant performed a contraction on the fingerboard to locate the area of greatest muscular contraction.

Muscle oxidative capacity measures

Time to half recovery ($T_{1/2}$) was calculated by subtracting the maximal de-oxygenation reached (e.g. de-oxygenated down to 48%) from the baseline oxygenation (e.g. 100%). The difference (52%) was then halved (26.5%) to determine the half recovery percentage. Therefore, the time (s) taken for the muscle re-oxygenation to recover to this amount (26.5%) was considered the $T_{1/2}$. Oxygen debt represents the O_2% which was needed to return tissue saturation back to those seen at baseline. Oxygen recovery per second represents the O_2% which is paid back per second during $T_{1/2}$.

Statistical Analyses

Analysis was performed using Statistical Package for Social Sciences (SPSS, IBM, Version 20.0). Before 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 using the Levene's test. All data was shown to be normally distributed and equal variance was assumed. 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 two-way (ability x contraction) repeated measures ANOVAs were used to determine if there were significant effects. If a significant interaction effect was found then follow-up one-way ANOVAs were performed for each contraction type followed by post-hoc bonferroni corrected paired *t*-tests. All data is presented as mean (SD) unless otherwise stated. Mean difference and confidence intervals (CI) at 95% were used to highlight meaningfulness. For all statistical analysis the critical α-level was set at 0.05

RESULTS

Strength and endurance characteristics

There was a significant interaction effect ($P = 0.034$) for FTI (contraction X ability). Follow up analyses revealed no significant between group differences during the sustained contraction ($P = 0.106$). However, for the intermittent contraction there were significant between ability group differences ($P = 0.018$). Post hoc bonferroni suggested that the elite group had a higher FTI compared to the control group (mean difference = 27727, CI 2835 – 52620 (FTI)). There were no significant interactions or main effects for the length of contraction during sustained or intermittent contractions.

********************** Insert Table 2 near here***********************

Muscle tissue oxygenation kinetics

Oxygen debt

For the FDP and FCR there was a significant (P= 0.019, P= 0.010 respectively) interaction (ability group x contraction type). For the FDP a follow up analyses revealed no ability group differences during the intermittent contraction. However, there were significant between group differences during the sustained contraction (P< 0.001). Post hoc bonferroni suggested that during the sustained contraction the elite group had to repay a significantly greater O_2% than the control (mean difference = 17, CI 9 – 26 (O_2%)), intermediate (mean difference = 14, CI 5 – 22 (O_2%)) and advanced groups (mean difference = 10, CI 2 – 19 (O_2%)). For the FCR a follow up analyses suggested there were no between group differences during the intermittent contraction (P> 0.05). However, for the sustained contraction there was a significant between group difference (P= 0.005). Post hoc bonferroni suggested the elite group had to repay a significantly greater O_2% than the control (mean difference = 8, CI 1 – 16 (O_2%)) and intermediate (mean difference = 11, CI 3 – 19 (O_2%)) groups only.

Time to half recovery

In the FDP and FCR no significant interaction effects (*P*= 0.522, *P*= 0.097 respectively) or main effects 'contraction type' (*P*= 0.415, *P*= 0.636 respectively) were found. However, there was a significant main effect 'ability group' in both the FDP (*P*< 0.001) and FCR (*P*= 0.005). In the FDP post hoc bonferroni suggested that the elite group had a significantly quicker $T_{1/2}$ than the control (mean difference = 85, CI 49 – 122 (s)) and intermediate (mean difference = 56, CI 20 – 92 (s)) groups. Furthermore, the advanced climbers had a significantly quicker $T_{1/2}$ than the intermediate (mean difference = 80, CI 44 – 117 (s)) and control (mean difference = 51, CI 15 – 87 (s)) groups. In the FCR post hoc bonferroni suggested the elite group had a significantly quicker $T_{1/2}$ compared to the intermediate (mean difference = 63, CI 16 – 109 (s)) and control (mean difference = 44, CI 4 – 91 (s)) groups only.

********************** Insert Table 3 near here**********************

Oxygen recovery per second

There was a significant interaction effect for both the FDP and FCR (*P*= 0.018, *P*= 0.012 respectively). In the FDP a follow up analyses revealed a significant between ability group difference after both the intermittent (*P*= 0.001,) and sustained (*P*< 0.001) contractions. Post hoc bonferroni suggested that post intermittent contraction the elite group recovered a significantly greater O_2% per second than the control (mean difference = 1.4, CI 0.33 – 2.47 (O_2%)) and intermediate (mean difference = 1.4, CI 0.35 – 2.38 (O_2%)) groups only. After the sustained contraction the elite and advanced group recovered a significantly greater O_2% per second than the control (mean difference = 4.3, CI 0.7 – 2.31 and, mean difference 2.62, CI 0.67 – 4.57

(O_2%) respectively) and intermediate (mean difference = 3.83, CI 1.88 – 5.78 and mean difference = 2.19, CI 0.24 – 4.14 (O_2%) respectively) groups.

In the FCR, follow up analyses revealed no significant between ability group differences following the intermittent contraction. However, there was a significant difference (*P*= 0.001) following the sustained contraction. Post hoc bonferroni suggested that the elite group had a significantly greater O_2% per second compared to the control (mean difference = 4.29, CI 1.24 – 7.34 (O_2%)) and intermediate (mean difference = 4.56, CI 1.51 – 7.61 (O_2%)) groups only.

********************** Insert Figure 3 near here***********************

DISCUSSION

Unlike previous studies (MaC and Philippe), the current study incorporated a climbing hold (Figure 1) into the assessments of oxidative capacity and so findings are more applicable to the application of rock climbing. Furthermore, this was the first study to assess oxidative recovery after contractions to failure in rock climbers. The main findings of the current study were 1) during a sustained contraction to failure elite climbers use a significantly greater amount of muscle tissue O_2 in both the FDP and FCR compared to their lower counterparts, 2) oxidative capacity is significantly greater in elite climbers compared to non-elite climbers in both the FDP and FCR, and this is not affected by contraction type, and 3) the O_2% which is paid back per second during recovery is significantly greater in elite climbers compared to non-elite climbers in both the FDP and FCR, and this is significantly greater post sustained contraction compared to an intermittent contraction.

It would appear that during sustained and intermittent contractions, elite rock climbers are able to utilize a greater portion of their muscle tissue oxidative capacity (Table 3) in both the FDP and the FCR compared to their lower level counterparts. Previous research has shown that with an increased MVC there is i) no hypertrophy with training in high-level climbers (7), and ii) no significant between ability group differences in conduit flow during a sustained contraction in climbers (11). Therefore, this increased muscle O_2 consumption in elite climbers may be due to either a greater capillary density, an increased ability to off-load more O_2 within the muscle fibers, and/or have greater mitochondrial respiratory capacity than lower level and non-climbers. Consequently, training the FDP in non-elite rock climbers is likely to increase forearm strength and endurance (FTI, as seen in Table 2).

Similar to previous findings (Philippe et al., (17), Fryer et al., (10) and Fryer et al., (11)), elite climbers elicited a significantly greater FTI throughout the intermittent contractions compared to their lower-ability counter parts (Table 2). As PCr re-synthesis, a proxy for oxidative capacity, has been positively correlated to re-oxygenation using NIRS (12, 20), it seems probable that the short intermittent breaks (3s) allow for sufficient recovery, thereby enabling a greater FTI. This would appear to be a response which is trainable, considering the FTI appears to be related to ability group in the current study (Table 2). This evidence builds upon previous literature which suggests that more advanced climbers may have a greater aerobic capacity than their lower counter parts (1, 4, 8, 9, 18). Furthermore, it suggests that elite climbers may benefit from short breaks which allow the recovery of PCr stores in the forearms. These breaks would be particularly useful before attempting crux sections on a route (the most difficult/technical section of an ascent).

Although the sustained O_2 debt was significantly greater when compared to the intermittent contraction, the $T_{1/2}$ was not significantly greater as the O_2% paid back per second was significantly greater during the sustained recovery. As $T_{1/2}$ and O_2 % per second were significantly quicker/greater post sustained and intermittent contractions in the elite climbers (compared to non-elite), it would appear that these athletes have an improved oxidative capacity which is not hindered by a contraction type. This increased $T_{1/2}$ in elite climbers may be a consequence of an increased arterial diameter and consequently greater blood flow post ischemia. Fryer et al., (10) suggested that elite climbers have a significantly greater blood flow during intermittent rest periods (10s contraction, 3s rest) compared to lower level climbers (10). Furthermore, Thompson et al., reported that climbers had a larger arterial diameter post venous occlusion compared to non-climbers. Therefore, post contraction blood flow and microvascular adaptation may explain the significantly faster $T_{1/2,}$ and the significantly greater amount of O_2 paid back per second in elite level climbers. These factors suggest that the muscle tissue recovery of climber's forearms is likely to be a multifactorial one. However, it is now clear that one of these responses is that elite climbers are able to uncouple and utilize oxygen (mitochondrial capacity) to a greater extent than their lower counter parts. As a consequence these elite climbers should make use of appropriate rests during an ascent in order to be able to recover muscle tissue oxygen and PCr stores. As an example, elite level climbers should consider resting before a crux section is attempted.

PRACTICAL APPLICATIONS

Competitive rock climbing performance is linked to the ability to sustain and perform repeated contractions whilst pulling and holding the body position during an ascent. The ability to repeatedly perform adequate grip performance is in part limited by the muscle's ability to recover (i.e., oxidative capacity) from its previous contraction. The performance related parameters of the current study's intermittent protocol clearly discriminate better the elite climbers from the control group. These results should encourage improving and optimizing sport-specific intermittent fatigue protocols as part of a competitive climbers training regime. Furthermore, elite level climbers should make use of appropriate rests, such as those seen before a crux section, in order to re-oxygenate the muscles (a proxy for PCr re-synthesis) thus increasing the chance of success. For climbers who are non-elite (have a best on-sight lead of < 25 Ewbank), training to increase forearm performance should focus on the FDP.

REFERENCES

1. Bertuzzi, RCM, Franchini, E, Kokubun, E, and Kiss, MAPDM. Energy system contributions in indoor rock climbing. Eur J Appl Physiol 101: 293-300, 2007.
2. Booth, ML, Ainsworth, BE, Pratt, M, Ekelund, U, Yngve, A, Sallis, JF, and Oja, P. International physical activity questionnaire: 12-country reliability and validity. Med Sci Sports Exerc 195: 3508-1381, 2003.
3. Chance, B, Dait, MT, Zhang, C, Hamaoka, T, and Hagerman, F. Recovery from exercise-induced desaturation in the quadriceps muscles of elite competitive rowers. Am J Physiol-Cell Physiol 262: C766-C775, 1992.
4. Dickson, T, Fryer, S, Blackwell, G, Draper, N, and Stoner, L. Effect of style of ascent on the psychophysiological demands of rock climbing in elite level climbers. Sports Technol 5: 1-9, 2012.
5. Draper, N, Couceiro, J, Fryer, S, Dickson, T, Winter, D, Ellis, G, Hamlin, M, Shearman, J, and North, C. Reporting climbing grades and grouping categories for rock climbng. Isokinet Exer Sci 19: 273-280, 2011.
6. Draper, N, Dickson, T, Blackwell, G, Fryer, S, Priestley, S, Winter, D, and Ellis, G. Self-reported ability assessment in rock climbing. J Sports Sci 29: 851-858, 2011.

7. España-Romero, V, andWatts, P. *Strength:Volume ratio for the forearm in climbers and non-climbers*. in *American College of Sports Medicine* 2012. San Francisco.
8. Fryer, S, Dickson, T, Draper, N, Blackwell, G, and Hillier, S. A psychophysiological comparison of on-sight lead and top rope ascents in advanced rock climbers. Scand J Med Sci Sports 23: 645-650, 2012.
9. Fryer, S, Dickson, T, Draper, N, Eltom, M, Stoner, L, and Blackwell, G. The effect of technique and ability on the VO_2 – heart rate relationship in rock climbing. Sports Technol 5: 143-150, 2012.
10. Fryer, S, Stoner, L, Lucero, A, Witter, T, Scarrott, C, Dickson, T, Cole, M, and Draper, N. Haemodynamic kinetics and intermittent finger flexor performance in rock climbers. Int J Sports Med2014.
11. Fryer, S, Stoner, L, Scarrott, C, Lucero, A, Witter, T, Love, R, Dickson, T, and Draper, N. Forearm oxygenation and blood flow kinetics during a sustained contraction in multiple ability groups of rock climbers. J Sport Sci 2014.
12. Hamaoka, T, Iwane, H, Shimomitsu, T, Katsumura, T, Murase, N, Nishio, S, Osada, T, Kurosawa, Y, and Chance, B. Noninvasive measures of oxidative metabolism on working human muscles by near-infrared spectroscopy. J Appl Physiol 81: 1410-1417, 1996.
13. López-Rivera, E, andGonzález-Badillo, JJ. The effects of two maximum grip strength training methods using the same effort duration and different edge depth on grip endurance in elite climbers. Sports Technol 5: 100-110, 2012.
14. MacLeod, D, Sutherland, DL, Buntin, L, Whitaker, A, Aitchison, T, Watt, I, Bradley, J, and Grant, S. Physiological determinants of climbing-specific finger endurance and sport rock climbing performance. J Sports Sci 25: 1433-1443, 2007.
15. McCully, K, Iotti, S, Kendrick, K, Wang, Z, Posner, J, Leigh, J, and Chance, B. Simultaneous in vivo measurements of HbO2 saturation and PCr kinetics after exercise in normal humans. J Appl Physiol 77: 5-10, 1994.
16. Osada, T, Katsumura, T, Murase, N, Sako, T, Higuchi, H, Kime, R, Hamaoka, T, and Shimomitsu, T. Post-exercise hyperemia after ischemic and non-ischemic isometric handgrip exercise. J Physiol Anthropol Appl Human Sci 22: 299-309, 2003.
17. Philippe, M, Wegst, D, Müller, T, Raschner, C, and Burtscher, M. Climbing-specific finger flexor performance and forearm muscle oxygenation in elite male and female sport climbers. Eur J Appl Physiol 112: 2839-2847, 2011.
18. Pires, FO, Hammond, J, Lima-Silva, AE, Bertuzzi, R, and Kiss, MAPDM. Ventilation behavior during upper-body incremental exercise. J Strength Cond Res 25: 225, 2011.
19. Pires, FO, Lima-Silva, AE, Hammond, J, Franchini, E, Dal'Molin, KMA, and Bertuzzi, R. Aerobic profile of climbers during maximal arm test. Int J Sports Med 32: 122, 2011.
20. Sako, T, Hamaoka, T, Higuchi, H, Kurosawa, Y, and Katsumura, T. Validity of NIR spectroscopy for quantitatively measuring muscle oxidative metabolic rate in exercise. J Appl Physiol 90: 338-344, 2001.

Figure 1 A schematic of the testing protocol used to assess muscle tissue re-oxygenation of the flexor digitorum profundus and flexor carpi radialis after sustained and intermittent contractions to failure.

Figure 2 A schematic and photograph showing the body and arm position (A) as well as the climbing hold (B) used during the tests.

Figure 3 O_2% recovered per second in the flexor digitorum profundus (FDP) [A] and flexor carpi radialis (FCR) [B] during sustained and intermittent contractions in climbers of different ability levels and control subjects. Values are means and SD.

NB: O_2% recovered ·second (%) describes the O_2% paid back per second during the time to half recovery. * Shows the group is significantly different ($p < 0.05$) from the elite group. ** Shows the group is significantly different ($p < 0.05$) from the advanced group