Oxygen Recovery Kinetics in the Forearm Flexors of Multiple Ability Groups of Rock Climbers

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Abstract

Fryer, SM, Stoner, L, Dickson, TG, Draper, SB, McCluskey, MJ, Hughes, JD, How, SC, and Draper, N. Oxygen recovery kinetics in the forearm flexors of multiple ability groups of rock climbers. *J Strength Cond Res* 29(6): 1633–1639, 2015—The purpose of this study was to determine muscle tissue oxidative capacity and recovery in intermediate, advanced, and elite rock climbers. Forty-four male participants performed (a) sustained and (b) intermittent contractions at 40% of maximal volitional contraction (MVC) on a sport-specific fingerboard until volitional fatigue. Near-infrared spectroscopy was used to assess muscle tissue oxygenation during both the exercise and the 5-minutes passive recovery period, in the flexor digitorum profundus (FDP) and flexor carpi radialis (FCR). During the sustained contraction only, muscle tissue deoxygenation (O_2 debt) in the FDP and FCR was significantly greater in elite climbers compared with the control, intermediate, and advanced groups (FDP: 32 vs. 15, 19, 22%; FCR: 19 vs. 11, 8, 15%, 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 47 seconds, respectively) and the FCR (7 vs. 30 and 97 seconds, respectively) because the O_2% recovered per second being significantly greater (FDP: 4.2 vs. 0.7 and 0.3; FCR: 4.8 vs. 0.1 and 0.2, respectively). Furthermore, during the intermittent contraction, $T_{1/2}$ in elite climbers was significantly quicker compared with the control and intermediate groups in the FDP (8 vs. 93 and 83 seconds, respectively) and FCR (16 vs. 76 and 50 seconds, respectively). Consequently, lower-level climbers should focus training on specific intermittent fatigue protocols. Competition or 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, hemodynamic kinetics, oxygen recovery, rock climbing, handgrip exercise

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29(6)/1633–1639

Journal of Strength and Conditioning Research

Introduction

Despite an exponential global growth in competitive rock climbing over the past 2 decades, to date, there remains a dearth in the research available regarding training for climbing (14). One of the major reasons for this lack of information for practitioners has been the conflicting findings of the multifaceted mechanisms, which underpin the sport. Rock climbing encompasses a multitude of physiological, psychological, and biomechanical aspects, and as such, some previous laboratory assessments have had limited ecological validity (15,17,21). As an example, Watts et al. (21) used electromyography to show that handgrip dynamometry, although commonly used in previous studies (11), was not representative of finger flexor strength in rock climbers. Furthermore, MacLeod et al. (15) and Philippe et al. (17) assessed forearm finger flexor oxygenation and also strength and endurance using a 22-mm metal force plate with grip tape attached and not an actual climbing hold. Therefore, major determinants of performance such as the aerobic and anaerobic contributions during an ascent (1) and the potential benefits and hindrances to forearm muscles caused by pausing to rest on a route (10) remain discordant.

Rock climbing has been shown to involve large periods spent cycling between sustained and intermittent isometric forearm contractions (8), and so oxidative capacity in the highly stressed local muscle groups is important and has become a prominent area of interest (9,14,17). Previous studies have used near-infrared spectroscopy (NIRS) to assess deoxygenation (the off-loading of oxygen from hemoglobin in the muscle tissue) during both sustained and intermittent contractions to failure, but have not been used to assess oxidative capacity per se (9,10,15,17). Oxygen (O_2) recovery

Table 1. Mean (*SD*) and 1-way ANOVA results for subject demographic and anthropometric characteristics.*

	Control, mean (*SD*)	Intermediate, mean (*SD*)	Advanced, mean (*SD*)	Elite, mean (*SD*)	*p* (ANOVA)
Age (y)	26 (2)	29 (4)	27 (5)	30 (9)	0.665
Height (m)	1.78 (0.07)	1.78 (0.09)	1.79 (0.07)	1.75 (0.09)	0.624
Body mass (kg)	79 (11)	80 (13)	72 (10)	69 (5)	0.090
Body fat %	19 (11)†	20 (4)†	13 (4)	12 (3)	0.015
Years climbing	NA	6 (5)†	7 (4)†	14 (7)	0.019
Climbs per week	NA	1 (0.2)†‡	3 (0.7)	3 (0.3)	0.001
Hours per week	NA	3 (0.6)†‡	6 (2)	8 (2)	<0.001
Years leading	NA	6 (2)†	7 (4)†	13 (8)	0.018
Best on-sight lead (Ewbank)	NA	18 (0.5)	22 (1)	25 (1)	NA
Best red point lead (Ewbank)	NA	19 (1)	23 (2)	28 (2)	NA

*ANOVA = analysis of variance; NA = not applicable (as groups are defined on grading categories suggested by Draper et al. (4)
†Shows the group is significantly different ($p \leq 0.05$) from the elite group.
‡Shows the group is significantly different ($p \leq 0.05$) from the advanced group.

in muscle tissue assessed using NIRS has been shown to have a similar time constant to phosphocreatine (PCr) resynthesis assessed using magnetic resonance spectroscopy (16), 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: (a) muscle tissue oxidative capacity, (b) O_2% recovery per second in the flexor digitorum profundus (FDP) and the flexor carpi radialis (FCR), and (c) 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 (5), self-reported indoor lead on-sight and red point grades according to the guidelines suggested by Draper et al. (4). All participants undertook the testing at the end of the indoor season (late spring) to help minimize seasonal variation in training programmes. Near-infrared spectroscopy was used to assess oxygenation kinetics because it has recently been shown to be effective for the assessment of muscle tissue oxygenation kinetics in the forearms of rock climbers (9,10,15,17). To ensure valid practical implications for climbers could be 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 because it bends the last (distal) joints of fingers 2, 3, 4, and 5 (used in the open crimp position). The FCR is the second most important finger flexor because 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 4 ability groups: control, intermediate, advanced, and elite. Before any testing took place, all subjects gave

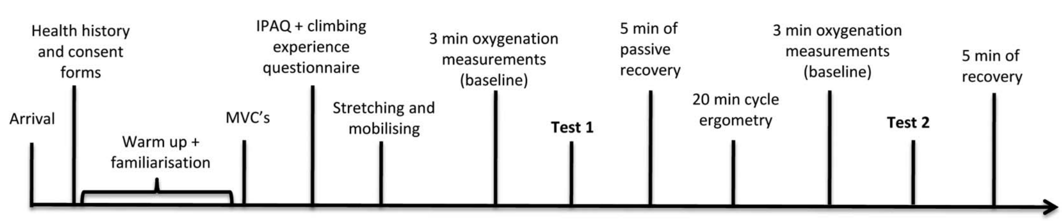

Figure 1. A schematic of the testing protocol used to assess muscle tissue reoxygenation of the flexor digitorum profundus and flexor carpi radialis after sustained and intermittent contractions to failure.

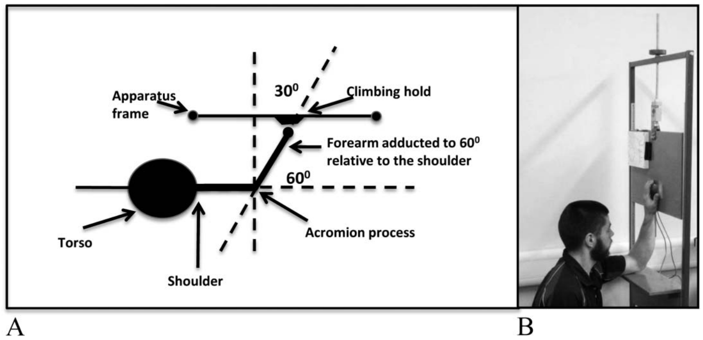

Figure 2. A schematic and photograph showing the body and arm position (A) and the climbing hold and the open crimp finger grip used during all tests (B).

informed written consent after a verbal and written explanation of the procedures was conducted. The Institutional Human Ethics Review Board at the University of Canterbury, New Zealand granted ethical approval before data collection. Because of 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 (International Physical Activity Questionnaire (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 body mass (Table 1).

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. (15) and modified to improve ecological validity (addition of climbing holds instead of wooden force plate) by Fryer et al. (9,10) was used to conduct all strength and endurance tests (for 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. (15), Philippe et al. (17), and Fryer et al. (9,10). All testing was conducted using the subject's dominant arm with the elbow flexed to 90° and the shoulder externally rotated to 90°. After the warm-up and familiarization, participants conducted 3 maximal volitional contractions (MVC); if the highest value was attained on the third attempt, a fourth was permitted. For the fatigue protocol, all subjects performed 2 contractions (randomized order) until volitional fatigue: a sustained contraction and an intermittent contraction (10 seconds contraction with 3 seconds rest) both at 40% of MVC. During both protocols, subjects were verbally encouraged to contract for as long as possible. After exhaustion, all subjects remained still (passive recovery) with their hand remaining on the climbing hold (which was head height, Figure 2 for schematic) for a total of 5 minutes. Exhaustion was defined as not being able to maintain −5% of the 40% MVC for a 2-second period. Active recovery between the sustained and intermittent test consisted of

Table 2. Mean (*SD*) and 1-way ANOVA results for forearm strength and endurance characteristics in all ability groups.*†

	Control, mean (*SD*)	Intermediate, mean (*SD*)	Advanced, mean (*SD*)	Elite, mean (*SD*)	One-way ANOVA	
					p	% Variance
Sustained FTI	10,799 (5,882)	17,319 (5,933)	16,826 (7,435)	15,605 (4,830)	0.106	16
Intermittent force time integral	25,524 (16,000)	33,717 (7646)	31,990 (11,463)	53,252 (29,981)‡	0.018	26
MVC (N)/body mass (kg)	3.2 (1)	3.4 (0.6)	4.2 (0.6)	5.9 (1.8)‡§‖	<0.001	49

*ANOVA = analysis of variance; FTI = force time integral.
†% variance is the estimated variance explained by the mean effects within each group for the named variable.
‡The group is significantly different ($p \leq 0.05$) from the control group.
§The group is significantly different ($p \leq 0.05$) from the intermediate group.
‖The group is significantly different ($p \leq 0.05$) from the advanced group.

Table 3. Mean (*SD*) and 2-way ANOVA results for muscle tissue reoxygenation characteristics in the FDP and FCR after sustained and intermittent contractions to failure in multiple ability groups of climbers.*†

	Control, mean (*SD*)		Intermediate, mean (*SD*)		Advanced, mean (*SD*)		Elite, mean (*SD*)		ANOVA results *p*		
									Main effects		Interaction
	Sustained ($n = 9$)	Intermittent ($n = 9$)	Sustained ($n = 9$)	Intermittent ($n = 9$)	Sustained ($n = 10$)	Intermittent ($n = 10$)	Sustained ($n = 10$)	Intermittent ($n = 10$)	Ability	Contraction	Ability × contraction
FDP											
O_2 debt (%)	15 (7)	12 (6)	19 (4)	13 (5)	22 (6)	18 (6)	32 (9)	20 (9)	<0.001	<0.001	0.019
Time to 1/2 recovery (s)	95 (63)	93 (58)	47 (32)	82 (72)	12 (9)	14 (15)	8 (3)	8 (4)	<0.001	0.415	0.522
FCR											
O_2 debt (%)	11 (9)	13 (8)	8 (4)	6 (2)	15 (7)	9 (9)	19 (5)	10 (9)	0.025	0.041	0.010
Time to 1/2 recovery (s)	30 (25)	76 (49)	97 (65)	50 (64)	15 (18)	46 (84)	7 (5)	16 (13)	0.004	0.636	0.097

*ANOVA = analysis of variance; FDP = flexor digitorum profundus; FCR = flexor carpi radialis.
†O_2 debt (%) describes the O_2% that had to be paid back to the muscle during the time it took to achieve half recovery. It is determined from the O_2% at the point of release (handgrip failure).

20-minute low-intensity cycle ergometry at 40 W and 30 W for male and female subjects, respectively. Twenty minutes of low-intensity cycle ergometry was used because Heyman et al. (13) found this to preserve performance during repeated bouts of exhaustive climbing.

Near-Infrared Spectroscopy and Forearm Flexors

A 2-channel NONIN 7600 (Plymouth, MN, 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 that 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 deoxygenation reached (e.g., deoxygenated 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 (seconds) taken for the muscle reoxygenation to recover to this amount (26.5%) was considered the $T_{1/2}$. Oxygen debt represents the O_2% that was needed to return tissue saturation back to those seen at baseline. Oxygen recovery per second represents the O_2% that is paid back per second during $T_{1/2}$.

Statistical Analyses

Analysis was performed using Statistical Package for Social Sciences (version 20.0; SPSS, IBM, Armonk, NY). 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 were shown to be normally distributed, and equal variance was assumed. For every independent variable, a series of analyses of covariance were performed, the covariates were as follows: 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 2-way (ability × contraction) repeated-measures analyses of variances (ANOVAs) were used to determine if there were significant effects. If a significant interaction effect was found, then follow-up 1-way ANOVAs were performed for each contraction type followed by post hoc Bonferroni corrected paired *t*-tests. All data are 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 × 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 with the control group (mean difference = 27,727; CI, 2835–52,620). There were no significant interactions or main effects for the length of contraction during sustained or intermittent contractions (Table 2).

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 × contraction type). For the FDP, 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), intermediate (mean difference = 14; CI, 5–22), and advanced (mean difference = 10; CI, 2–19) groups. For the FCR, follow-up analyses suggested that 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 that the elite group had to repay a significantly greater O_2% than the control (mean difference = 8; CI, 1–16) and intermediate (mean difference = 11; CI, 3–19) groups.

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 $T_{1/2}$ (in seconds) than the control (mean difference = 85; CI, 49–122) and intermediate (mean difference = 56; CI, 20–92) groups. Furthermore, the advanced climbers had a significantly quicker $T_{1/2}$ (in seconds) than the intermediate (mean difference = 80; CI, 44–117) and control (mean difference = 51; CI, 15–87) groups. In the FCR, post hoc Bonferroni suggested that the elite group had a significantly quicker $T_{1/2}$ (in seconds) compared with the intermediate (mean difference = 63; CI, 16–109) and control (mean difference = 44; CI, 4–91) groups (Table 3).

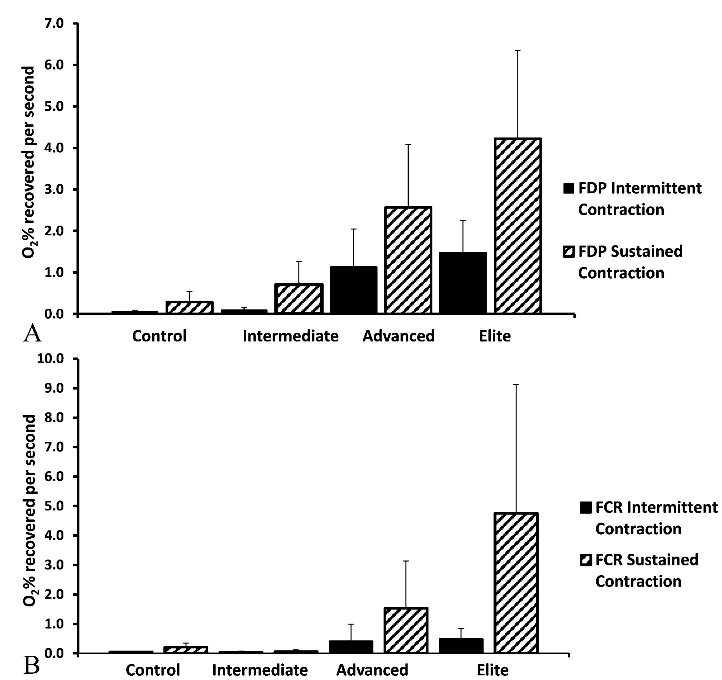

Figure 3. O_2% recovered per second in the flexor digitorum profundus (A) and flexor carpi radialis (B) during sustained and intermittent contractions in climbers of different ability levels and control subjects. Values are means and *SD*. O_2% recovered ·second (%) describes the O_2% paid back per second during the time to half recovery. *The group is significantly different ($p \le 0.05$) from the elite group. **The group is significantly different ($p \le 0.05$) from the advanced group.

Oxygen Recovery per Second. Figure 3 shows a significant interaction effect for both the FDP and FCR ($p = 0.018$; $p = 0.012$, respectively). In the FDP, 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 after 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) and intermediate (mean difference = 1.4; CI, 0.35–2.38) groups. After the sustained contraction, the elite and advanced groups 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, respectively) and intermediate (mean difference = 3.83; CI, 1.88–5.78 and mean difference = 2.19; CI, 0.24–4.14, respectively) groups.

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

Discussion

Unlike previous studies (15,17), the current study incorporated a climbing hold (Figure 2) 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 as follows: (a) 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 with their lower counterparts; (b) oxidative capacity is significantly greater in elite climbers compared with nonelite climbers in both the FDP and FCR, and this is not affected by contraction type; and (c) the O_2% that is paid back per second during recovery is significantly greater in elite climbers compared with nonelite climbers in both the FDP and FCR, and this is significantly greater after sustained contraction compared with an intermittent contraction.

It would appear that during sustained and intermittent contractions, elite rock climbers are able to use a greater portion of their muscle tissue oxidative capacity (Table 3) in both the FDP and the FCR compared with their lower-level counterparts. Previous research has shown that with an increased MVC, there is (a) no hypertrophy with training in high-level climbers (6) and (b) no significant between-ability group differences in the conduit flow during a sustained contraction in climbers (10). Therefore, this increased muscle O_2 consumption in elite climbers may be the result of a greater capillary density, an increased ability to off-load more O_2 within the muscle fibers, or have greater mitochondrial respiratory capacity than lower-level climbers and nonclimbers. Consequently, training the FDP in nonelite rock climbers is likely to increase forearm strength and endurance (FTI, as seen in Table 2).

Similar to previous findings (9,10,17), elite climbers elicited a significantly greater FTI throughout the intermittent contractions compared with their lower-ability counterparts (Table 2). Because PCr resynthesis, a proxy for oxidative capacity, has been positively correlated to reoxygenation using NIRS (12,19), it seems probable that the short intermittent breaks (3 seconds) allow for sufficient recovery, thereby enabling a greater FTI. This would appear to be a response, which is trainable, considering that the FTI appears to be related to ability group in the current study (Table 2). This evidence builds upon the previous literature which suggests that more advanced climbers may have a greater aerobic capacity than their lower counterparts (1,3,7,8,18). Furthermore, it suggests that elite climbers may benefit from short breaks, which allow PCr stores in the forearms to recover. These breaks would be particularly useful before attempting crux sections on a route (the most difficult or technical section of an ascent).

Although the sustained O_2 debt was significantly more when compared with the intermittent contraction, the $T_{1/2}$ was not significantly quicker because the percentage of O_2 paid back per second was significantly greater during the sustained recovery (Figure 3). Because $T_{1/2}$ and O_2% per second were significantly quicker and greater after sustained and intermittent contractions in the elite climbers (compared with nonelite), it would appear that these athletes have an improved oxidative capacity, which is not hindered by contraction type. This increased $T_{1/2}$ in elite climbers may be a consequence of an increased arterial diameter and consequently greater blood flow after ischemia. Fryer et al. (9) suggested that elite climbers have a significantly greater blood flow during intermittent rest periods (10-second contraction, 3-second rest) compared with lower-level climbers. Furthermore, Thompson et al. (20) reported that climbers had a larger arterial diameter after venous occlusion compared with nonclimbers. Therefore, postcontraction blood flow and microvascular adaptation may in part 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 multifactorial. However, it is now clear that one response is related to elite climbers being able to uncouple and use oxygen (mitochondrial capacity) to a greater extent than their lower counterparts. As a consequence these elite climbers should make use of appropriate rests during an ascent to be able to recover muscle tissue oxygen and PCr stores.

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, to re-oxygenate the muscles (a proxy for PCr re-synthesis) thus increasing the chance of success. For climbers who are nonelite (have a best on-sight lead of <25 Ewbank), training to increase forearm performance should focus on the FDP.

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