RELATIVE IMPORTANCE OF FOUR MUSCLE GROUPS FOR INDOOR ROCK CLIMBING PERFORMANCE

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ABSTRACT

Deyhle, MR, Hsu, H-S, Fairfield, TJ, Cadez-Schmidt, TL, Gurney, BA, and Mermier, CM. Relative importance of four muscle groups for indoor rock climbing performance. *J Strength Cond Res* 29(7): 2006–2014, 2015—Little research is available to guide training programs for rock climbers. To help meet this need, we sought to determine the relative importance of 4 muscle groups for rock climbing performance. Eleven male climbers were familiarized with an indoor climbing route before 5 separate days of testing. On testing days, subjects were randomly assigned to climb with no prefatiguing exercise (control climb) or after a prefatiguing exercise designed to specifically target the digit flexors (DF), shoulder adductors (SA), elbow flexors (EF), or lumbar flexors (LF). Immediately after the prefatiguing exercise, the subject climbed the route as far as possible without rest until failure. The number of climbing moves was recorded for each climb. Surface electromyography of the target muscles was recorded during the prefatigue. Fewer climbing moves were completed after prefatigue of the DF (50 ± 18%) and EF (78 ± 22%) ($p \leq 0.05$) compared with the control climb. The number of moves completed after prefatigue of the LF and SA were not statistically significant compared with the control climb ($p > 0.05$). The short time lapse between the end of prefatiguing exercise and the start of climbing (transit time), which may have allowed for some recovery, was not different among trials ($p > 0.05$). Electromyography median frequency was reduced from beginning to end of each prefatiguing exercise. These results suggest that among the muscle groups studied in men, muscular endurance of DF and EF muscle groups is especially important for rock climbing on 40° overhanging terrain.

KEY WORDS prefatigue, electromyography, median frequency, forearm, muscle fatigue, sport climbing

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INTRODUCTION

Rock climbing as a competitive sport draws contestants from around the world (25) of both sexes (25) and various age groups (24). Rock climbing competitions usually take place in indoor climbing gymnasiums (24,25). The number of indoor rock climbing gyms and the number of people getting involved in rock climbing both recreationally and competitively are increasing (22).

Climbing competitions typically take place in indoor gymnasiums with plastic hand and foot holds bolted into the modular walls to create climbing routes of various difficulties. Most climbing competitions are judged on completion of routes while taking into account the difficulty of the route. Competition rules vary depending on the format, but in general, the climber who can complete or make the most progress on the hardest routes wins. There is a small subspecialty of climbing competitions that are based on speed.

The goal among competitive climbers and climbing enthusiasts alike is often to increase one's rock climbing prowess, so she or he may be able to climb more challenging rock climbs. Training is crucial to help climbers maximize their potential and ability to successfully complete harder rock climbs. Reportedly, climbers spend up to 20 hours per week training (18) and use a variety of resistance, endurance, and coordination exercises (16). Despite training being a common practice among climbers, little research is available on the topic. Research aimed at further elucidating the physiological demands of rock climbing could lead to more research-informed training programs for rock climbing.

Difficult rock climbing is likely limited in large part by local muscular fatigue. In a study by Watts et al. (26), participants reported that inability to generate sufficient gripping force on the holds was the reason for falling during a rock climb to failure. Furthermore, grip strength and endurance remained reduced for 20 minutes after the climbing bout suggesting that climbing is taxing on the gripping muscles (26). Muscle groups that become fatigued during rock climbing can be thought of as the most important for rock climbing because climbing performance may be limited by endurance of these muscles. Understanding which muscles are essential, especially in high-level rock climbing, is needed to help individuals interested in designing training programs to improve rock climbing performance.

The available literature shows that variables related to muscular strength, power, and endurance of the upper body are among the most useful in explaining variance in rock climbing ability (17,18). Muscles involved in gripping and digit flexion (DF) are likely to be highly important in rock climbing because climbing itself has been shown to result in fatigue of these muscles (26). Also, electromyography (EMG) of the flexor digitorum superficialis (FDS) (a digit flexor) shows that this muscle is highly active during simulated rock climbing moves (15). Several studies have also positively correlated grip strength and endurance with climbing ability and performance (11,12,17,22,25). Strength and endurance of elbow flexors (EF) and shoulder adductors (SA) may also be of importance in rock climbing. The maximum number of pull-ups (12), bent arm hang time (12,18), and single arm pulling strength (22) have been correlated with climbing performance and ability. In theory, abdominals or lumbar flexors (LF) may be important for climbing, given the apparent need to stabilize the spine during climbing locomotion; however, studies have failed to show a correlation with climbing ability and abdominal muscular endurance (11,12).

Although several studies have found positive correlations between performance characteristics of muscle groups and climbing ability, to date, no study has looked at multiple muscle groups of the upper body individually in relation to climbing performance. The purpose of this study was to determine the relative importance of the DF, EF, SA, and LF muscle groups to rock climbing performance. It was hypothesized that the DF muscle group will show the greatest importance followed by the EF, SA, and LF muscle groups, respectively.

METHODS

Experimental Approach to the Problem

This study was designed to equally and individually reduce each muscle group's ability to do work by imposing an isolated prefatiguing exercise at 25% of maximal voluntary isometric contraction (MVIC) immediately before 1 bout of rock climbing to failure. This percentage of MVIC was chosen because research shows that recovery time after fatiguing contractions is inversely related to the relative intensity of the contraction used (20). This approach was expected to answer the research question because each prefatiguing exercise was expected to reduce climbing performance to a degree inversely proportional to that muscle group's importance to rock climbing. Subjects visited the gym on 6 separate days. Baseline testing and climbing route familiarization was performed on the first day. Each prefatiguing exercise was randomly assigned over the course of the following 5 separate days. A control, with no prefatiguing exercise, was also randomly assigned. Each visit was separated by at least 24 hours, but no more than 7 days. Climbing performance, as measured by the number of hand moves completed, was recorded for each trial. All trials were performed on the same wall using the same moves (Figure 4). The climbing sequence (hand movement strategy) and climbing rate was the same for each subject and every trial.

Subjects

Eleven male rock climbers (age = 27.7 ± 3.8 years, weight = 68.1 ± 6 kg, height = 175.4 ± 7.4 cm, body fat = 7.66 ± 2.2%) with an average of 3.9 ± 2.5 years climbing experience and an average self-reported climbing ability of 5.12b on the Yosemite Decimal System (YDS) volunteered to participate in this study. The YDS is a grading system used to qualify the difficulty of climbing routes. Technical climbing routes currently extend from easiest to hardest on a scale ranging from 5.0 to 5.15c on the YDS. Climbs harder than 5.9 are further divided with suffix letters "a"–"d." The subjects in this study are considered to be advanced climbers, given that their average ability is high on the range of the current YDS. A priori power analysis was conducted (G*Power 3.1) using data from a previously published climbing study (18). Results from the power analysis indicated that 11 subjects would allow acceptable power of 0.85 (5). The study protocol was approved by the University's Institutional Review Board. Before testing, subjects signed informed consent and HIPAA forms and filled out climbing and health history questionnaires. To be eligible to participate in this study, volunteers were required to be able to red point rock climbs rated at least 5.12a difficulty on the YDS, which means that they could complete the rock climb after having prior practice climbing that specific rock climb. Climbing ability was self-reported. Potential subjects were also required to be able to climb the specific route used in the study from start to finish without rest. They were excluded if they were not between the ages of 18 and 44 years, had been diagnosed with cardiovascular, metabolic, or neurological diseases, or had any injury or limitation that would be aggravated by the study protocol or hinder performance of rock climbing.

Baseline Testing and Climbing Familiarization

All baseline testing and climbing familiarization took place in 1 day on the subject's first visit in the order that is presented in this section. Height and weight were measured using a calibrated mechanical balance scale and stadiometer. A t-shirt, shorts, and no shoes were worn during weight and height measurements. The same experienced technician measured skinfold thickness using a Lange caliper (Cambridge Scientific Industries, Columbia, MD, USA) at the chest, abdomen, and thigh for body composition estimation. Two measurements within 2 mm of 1 another for each site were averaged. The sum of the averaged measurements was taken and used to estimate body density (13). Body fat percentage was estimated using the equation described by Brozek et al. (4). Anthropometric data were collected to provide descriptive information of the subject sample.

Maximal voluntary isometric contractions were performed for digit flexion, shoulder adduction, elbow flexion, and trunk flexion (on dominant side where applicable). Peak force during MVIC was measured using a hydraulic hand dynamometer (Rolyan, Germantown, WI, USA) for digit flexion and a back strength dynamometer (Takei Scientific Instruments Co., Ltd., Tokyo, Japan) for all other MVICs. Each MVIC lasted 3 seconds and was performed in triplicate with a 60-second rest between attempts. A 60-second rest was chosen based on pilot data that showed this rest interval allowed for sufficient recovery as to not reduce subsequent attempts. The greatest of the attempts was recorded (Table 1). Each MVIC protocol was designed to isolate the muscle group of interest. The following points describe the protocol used for each MVIC test:

- Digit flexion MVIC: The handgrip dynamometer was adjusted for each subject so that the middle phalanx lined up with the handle (18). The subject was instructed to hold the dynamometer with a straight arm with arm hanging at his side.
- Shoulder adduction MVIC: Subjects sat in a chair with shoulder abducted at 90° on the frontal plain. This joint angle was chosen for ease of joint angular measurement. A padded Velcro strap was wrapped around the upper arm just proximal of the elbow joint. A rope was attached to the Velcro strap at 1 end and to the dynamometer at the other end that was hanging directly over the subject's elbow. The subject was instructed to slowly pull downward on the rope against the dynamometer (Figure 1).
- Elbow flexion MVIC: Subjects were seated in a chair with elbows resting on a padded bench in front of the subject's chest. A rope was attached to the subject's wrist with a Velcro strap. The other end of the rope was attached to the back strength dynamometer that was fixed at ground level in front of the subject. With a pronated wrist and elbow at 90°, the subject performed the MVIC against the dynamometer (Figure 2). The joint angle was chosen for ease of joint angular measurement.
- Lumbar flexion MVIC: Subjects started resting supinated on a mat. A nylon sling was placed around the shoulders of the subject that were configured like backpack straps. Attached to the sling was a rope that was attached to the back strength dynamometer. Subjects then did a half sit-up as described in the Young Men's Christian Association's (YMCA) fitness assessment protocol (12). Enough slack was in the sling to allow the subject to reach the prescribed half sit-up range of motion (8.9 cm horizontal displacement). From this body position, the subject did the MVIC against the dynamometer (Figure 3).

After completing all MVIC testing, the subject was given 1 hour to learn the climbing route used in this study. During this time, the same expert climber who set the route gave verbal and visual demonstrations on how to climb the route most efficiently. The subjects were allowed and encouraged to climb the route as many times as they wanted to get as familiar with it as possible. Each subject used exactly the same hand sequencing to climb the route. Minor differences in foothold sequencing were permitted based on individual preference. Toward the end of the climbing familiarization hour, each subject climbed the route twice, keeping pace with a metronome. The metronome was set to 71 $\text{b}\cdot\text{min}^{-1}$. Every third beat was accented. The climber was instructed to make a hand move on every accented beat. When keeping with the metronome, the climbers made about 24 moves per minute.

The climbing route used for this study was set on an indoor climbing wall. The angle of the wall was 40° overhanging (from vertical). A highly experienced professional rock climber and route setter set the route by bolting plastic hand and footholds on the modular climbing wall. The difficulty of the climbing route was rated 5.11b on the YDS. Every effort was made to maintain homogeneity of difficulty in each section and for each move on the route. Each hold used to make up the route was the same color plastic and was marked with white tape. The uniform hold color and the use of marking tape made the route easy to follow for the climbers. The route consisted of a total of 24 moves (hand holds) from start to finish. The route started at the 6-o'clock position on the climbing wall and traveled in a clockwise circular manner up and around the perimeter of the climbing wall. The route finished on the same holds from which the route started. This circular design allowed for continuous climbing so that climbers were not limited by an end point on the route. They could climb around as many times as they were able until they reached task failure and could not

Table 1. Dynamometry values for GD, SAD, EFD, and LFD.*†

	GD (kg_f)	$GD\cdot kg^{-1}$	SAD (kg_f)	$SAD\cdot kg^{-1}$	EFD (kg_f)	$EFD\cdot kg^{-1}$	LFD (kg_f)	$LFD\cdot kg^{-1}$
Mean (*SD*)	55.3 (13.0)	0.8 (0.1)	47.5 (5.3)	0.7 (0.5)	29.3 (2.7)	0.4 (0.04)	30.6 (9.3)	0.5 (0.1)

*GD = handgrip; SAD = shoulder adduction; EFD = elbow flexion; LFD = lumbar flexion.
†Values are presented as absolute force in kilograms (kg_f) and in relative force per kilogram of body mass (kg^{-1}).

Figure 1. Shoulder adduction dynamometry. With an isometric contraction of the shoulder adductors, the participant pulls downward against the dynamometer as hard as possible for 3 seconds.

complete another move. The low height of the climbing wall and the large (0.25-m thick) mats covering the floor did not warrant the use of ropes or harnesses. Figure 4 shows the climbing wall and route.

Figure 2. Elbow flexion dynamometry (forearm pronated). With an isometric contraction of the elbow flexors, the participant pulls backward against the dynamometer as hard possible for 3 seconds.

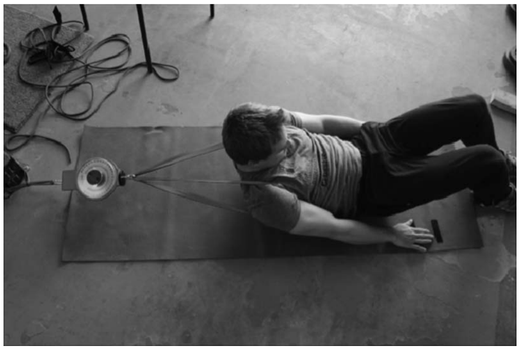

Figure 3. Lumbar flexion dynamometry. With an isometric contraction of the lumbar flexors, the participant pulls forward against the dynamometer as hard as possible for 3 seconds.

Prefatiguing Exercises and Climbing Tests

Each prefatiguing exercise was designed to target 1 of the 4 muscle groups of interest. Each prefatiguing exercise was performed bilaterally where applicable. The exercises were implemented using systems of pulleys and weights (Figure 5). A Velcro strap was used to anchor the pulling rope to the subject's elbow and wrist for the SA and EF exercises, respectively. The use of the Velcro strap allowed for better isolation of the targeted muscle groups. A wooden dowel was held lightly in the hands of the subject during EF exercise to maintain a pronated forearm position. A padded board was used to hold down the subject's upper arm and isolate the DFs. The resistance of all exercises was set at 25% of MVIC. To set the resistance, a researcher measured the minimum force required to hold the weight still at the pulling end of the rope (where the subject would be attached) with the dynamometer. Weights were added or removed until the target force was reached. During each exercise, the subject was required to hold the weights isometrically at a predetermined joint angle, body position, or task. The predetermined joint angle was 90° at the elbow and shoulder for the EF and SA exercises, respectively. The predetermined body position for the LF exercise was holding the top of the half sit-up position of the YMCA half sit-up test (12). The required task of the DF exercise was that the subject could maintain a grip without slipping on the handhold. A researcher continuously monitored the subjects' performance in maintaining the aforementioned requirements of the exercises. When the subject failed to meet the requirement of the exercise (joint angle, body position, or grip), the researcher would lift the weight momentarily to allow the subject to reestablish the required position. Fatigue was reached when the subject required adjustments more frequently than every 5 seconds. At the point of fatigue, the exercise was terminated and the subject then hurried over to the climbing route. Recall of maximal rating of perceived

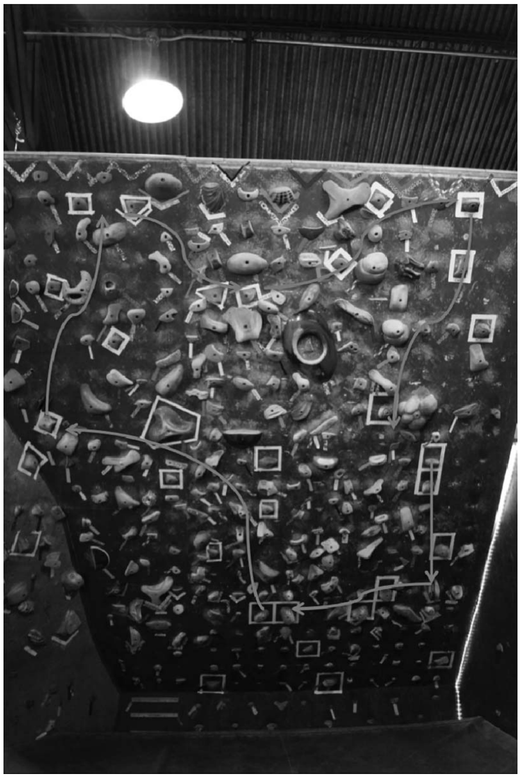

Figure 4. This shows the rock climbing route used for the study. The hand and foot holds are marked inside boxes of white tape. Arrows show the general path of the route and its continuous nature.

exertion (RPE) using the Borg's 15-grade scale (3) was taken after each prefatiguing exercise. Figure 5 shows each prefatiguing apparatus.

Surface EMG was recorded (Noraxon TeleMyo 2400T G2; Noraxon, Scottsdale, AZ, USA) on the subject's dominant side continuously from start to finish of each prefatiguing exercise at 3,000 Hz. We recorded EMG mean frequency to verify that the prefatiguing exercises resulted in muscular fatigue of the targeted muscles. Because of technical difficulties, EMG data were lost for 2 subjects during the DF exercise and for 1 subject during the SA exercise. Electrodes were placed over the FDS for prefatiguing exercise of the DF. Electrode placement was performed according to the technique of Blackwell et al. (2). Using Noraxon's guidelines for lead placement (14), electrodes were placed over the latissimus dorsi, pectoralis major, and infraspinatus for prefatiguing exercise of the SA muscle group. Also, using Noraxon's guidelines (14), electrodes were placed over the brachioradialis (BR) for the prefatiguing exercise of the EF muscle group. For the prefatiguing exercise of the LF muscle group, electrodes were placed over the rectus abdominis 1 cm above the umbilicus and 2 cm from the midline (19).

Figure 5. This shows the weighted rope and pulley systems for each prefatiguing exercise. Clockwise from top left: digit flexion apparatus, shoulder adduction apparatus, elbow flexion apparatus, and lumbar flexion apparatus.

Extensive pilot testing was performed to ensure that prefatiguing exercises effectively fatigued the targeted muscle groups. We verified that each prefatiguing exercise was successful as they resulted in reduced strength, endurance, and EMG median frequency of the targeted muscle group.

Immediately after termination of prefatiguing exercise, the subject quickly walked or jogged to the climbing wall (15 m away) and began climbing as quickly as possible. The subject was allowed to apply chalk (magnesium carbonate) to his hands just before climbing but not after the start of the climb. The subject climbed continuously for as long as possible until he could not complete another move. No resting was allowed during the climb, and this was enforced by the use of a metronome that helped climbers stay on pace. The number of moves completed was recorded as the primary dependent variable. A complete move (1 move) was made when the subject grasped the next handhold in sequence. Partial moves (0.5 move) were made if the subject unsuccessfully attempted to move to the next handhold. Unsuccessful attempts included letting go of a hold and moving toward the next hold or touching the next hold but not having control of it. For each trial, subjects climbed with the metronome amplified on the climbing gym sound system speaker. Climbers climbed in rhythm with the metronome at the same rate that they had been familiarized (~24 moves

Table 2. Climbing rate in moves per minute for C, DF, SA, EF, and LF trials.*†

	C	DF	SA	EF	LF
Climbing rate (moves per minute)	27 (3)	27 (4)	27 (5)	26.5 (4.5)	25.5 (2.5)
Time to fatigue (s)	NA	386 (159)	317 (140)	259.5 (195)	349 (136)
Transit times (s)	NA	18.73 (3.0)	20.36 (3.1)	21.78 (6.0)	23.65 (4.4)

*C = control; DF = digit flexor; SA = shoulder adductor; EF = elbow flexor; LF = lumbar flexor; NA = not applicable.

†Values are presented as mean (*SD*). No significant differences were found ($p > 0.05$) in climbing rates. Time to fatigue in seconds during prefatiguing exercise of the DF, SA, EF, and LF. No significant differences in fatigue times were observed ($p > 0.05$). Transit times in seconds from the end of prefatiguing exercise to the start of rock climbing for DF, SA, EF, and LF trials. No significant differences were found among transit times ($p > 0.05$).

per minute). The researchers loosely enforced the climbing pace. The primary purpose of the metronome was to keep the subjects from resting.

Time was measured from the start of the prefatiguing exercise to the end of the climbing bout. Time at the end of prefatigue, start of route, and end of route was also recorded. For each control trial, subjects briskly walked or jogged from where the prefatiguing exercise took place and started climbing as quickly as possible. For the control climb, the transit time and climbing time were recorded. Transit time data are not presented. The reason for measuring transit time for the control climb was to maintain the same feeling of urgency to start climbing the subjects may have felt during the other trials.

Maximal RPE recall was recorded after each prefatiguing exercise and each climbing trial.

Electromyography Data Processing

Median frequency data were collected and used to verify that fatigue was taking place in the targeted muscles as it decreases during fatiguing isometric contractions (20,21). Median frequency was chosen over other EMG methods because it is not impacted by relative contraction intensity (20). Electromyography data were processed using fast Fourier transformation. For each muscle measured, 12 one-second time points were selected evenly from start to end of the raw EMG data. Median frequency of each 1-second time point was plotted and fitted with a regression. We used a technique used by others (20,21) by analyzing the slope of the line, start and end frequency, and percent decrease in frequency.

Statistical Analyses

Repeated-measures analysis of variance was used to test for significant differences in the means of prefatiguing times, RPE, transit times between prefatiguing exercise and climbing, climbing rate, and moves completed during each trial. Tukey's multiple comparison test was used when significant differences were found. Alpha level of $p \leq 0.05$ was used for statistical significance. Effect size was calculated to determine the strength of the primary independent variables (each prefatiguing exercise) on climbing performance (5). Effect sizes of >0.80, 0.79–0.50, 0.49–0.10, and <0.09 were considered large, moderate, small, and trivial, respectively (5). Prism GraphPad 5.04 (San Diego, CA, USA) was used for statistical analyses. Unless otherwise noted, data are presented as mean ± *SD*.

Table 3. Slope and percent decrease in median frequency from start to finish of exercise.

	Slope (mean ± *SD*)	Percent change in median frequency (mean ± *SD*)
Flexor digitorum superficialis*	−1.8 ± 0.7	−23.0 ± 11.5
Latissimus dorsi†	−1.1 ± 1.0	−10.4 ± 15.3
Infraspinatus†	−3.4 ± 2.4	−33.5 ± 16.8
Pectoralis major†	−0.4 ± 0.6	−6.5 ± 10.6
Brachioradialis‡	−1.6 ± 1.0	−16.5 ± 15.2
Rectus abdominis§	−3.0 ± 2.1	−31.9 ± 17.5

*Measured during digit flexion.
†Measured during shoulder adduction.
‡Measured during elbow flexion.
§Measured during lumbar flexion.

RESULTS

No significant differences were found among times to fatigue during prefatiguing exercise, transit times, or climbing rate ($p > 0.05$). These data are presented in Table 2. All RPE values were 18 or greater (at or near maximal exertion) for each prefatiguing exercise and climbing bout. No significant differences in RPE were found among trials ($p > 0.05$). Table 3 shows the negative EMG

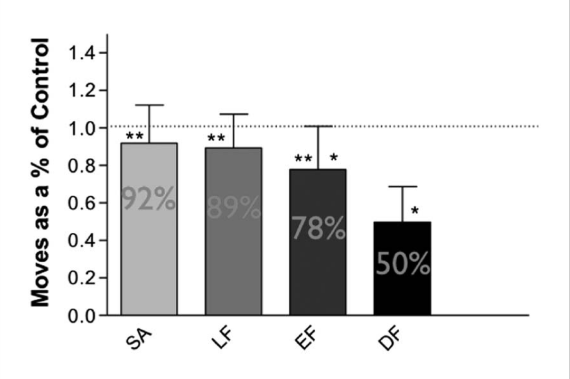

Figure 6. Climbing hand moves completed after prefatiguing exercise of the shoulder adductors (SA), lumbar flexors (LF), elbow flexors (EF), and digit flexors DF. Control is equal to 1.0 on the y-axis (dotted line). *Significant difference from control. **Significant difference from DF ($p \le 0.05$).

median frequency slope and percent change in median frequency from start to end of the prefatiguing exercise for each muscle measured. Absolute number of moves completed for control, DF, EF, LF, and SA trials were 56 ± 13, 28 ± 12.5, 43.5 ± 16.5, 49.5 ± 13.5, and 51 ± 14.5, respectively. Climbing moves were expressed as a percentage of moves completed during the control climb for statistical analysis. Compared with the control climb, significantly fewer moves were completed after DF prefatigue (50 ± 18% of control, $p < 0.0001$) and EF prefatigue (78 ± 22% of control, $p = 0.02$). Moves completed after LF prefatigue (89 ± 17% of control, $p = 0.57$) and SA prefatigue (92 ± 19% of control, $p = 0.77$) were not significantly different from control climb. Significant differences were also found between the number of moves completed after DF prefatigue and all other conditions ($p \le 0.05$). Figure 6 shows these data graphically. Effect size for DF, EF, LF, and SA interventions were large (0.89), moderate (0.58), small (0.42), and small (0.29), respectively.

DISCUSSION

Most studies examining muscle strength, power, endurance, or fatigue in rock climbing have done so indirectly by correlating muscle performance characteristics with climbing performance (18,25), ability (12,17,21,22), or by a model of rock climbing (1,7,15,21). A few studies have directly measured reduced strength and endurance of the forearm muscles using grip dynamometry after indoor climbing (23,26). To our knowledge, this study is the first to directly and individually look at fatigue of the muscles of the forearm and other muscle groups with respect to the impact on climbing performance. The results of this study may be especially relevant to the sport because actual climbing performance on a designated route is the dependent variable in this study.

The most significant finding of this study, consistent with our hypothesis, is that climbing performance is reduced the most after prefatigue of the DF followed by the EF (Figure 6). Additionally, effect size was large and moderate for the DF and EF trials, respectively. Climbing performance after prefatigue of LF and SA was not significantly reduced relative to the control climb. Prefatiguing the LF and SA both resulted in a small effect size.

The lack of a significant difference after LF prefatigue is not surprising, given that, to date, no study has shown that strength or endurance of the abdominal muscles is related to climbing ability (11,12). It is possible that a different climbing route that is more overhanging or with smaller foot holds may have required more abdominal muscle activation. It is also possible that the apparatus used for prefatiguing LF, which exerted force primarily through the sagittal plane, lacked adequate climbing specificity.

The lack of a significant reduction in climbing performance after SA fatigue is puzzling, given the anecdotal (25) and correlative (12,18,22) support for shoulder girdle muscle function in climbing. However, the studies that correlated shoulder girdle function to climbing performance used some version of a pull-up or pulling action to measure strength and endurance of the shoulder and arm (12,18,22). These exercises are coupled with both elbow flexion and gripping, and therefore, do not specifically isolate the shoulder girdle muscles. The present results suggest that the elbow flexion and gripping component, rather than the shoulder adduction component of the pull-up action, may be the limiting factor. Perhaps, the higher strength and endurance in the pulling motion exhibited by high-performing climbers (12,18,22) could be attributed in large part to the strength and endurance of the EF or DF, which are also involved in those exercises.

It has been suggested that as the difficulty of the rock climb increases, more work is distributed from the lower body to the arm and shoulders (9). The difficulty of the climbing route used in this study (5.11b) was 1 full grade below the average subject's reported ability (5.12b). Perhaps, the low relative intensity of the route used in this study did not require as much use of the SA.

Frontal plane shoulder adduction was used because pulling endurance of the shoulders adductors operating on the frontal plane has been shown to be positively correlated with climbing performance (12,18). It is possible that prefatiguing exercise with isometric shoulder extension may have had a greater impact on climbing performance. By moving the forces to the sagittal plane with shoulder extension, many of the same muscles would be challenged, but perhaps in a more climbing-specific way.

A final observation possibly related to the lack of reduction in climbing performance with fatigued SA is speculative regarding postocclusive reactive hyperemia (PORH). A Velcro strap was used to anchor the rope to the subject's elbow during the SA prefatiguing exercise. The purpose of this arrangement was to isolate the SA muscle group and keep the EF and DF muscle groups from contracting. Despite keeping the Velcro strap loose around the subject's arm, the nature of this arrangement likely resulted in some occluded blood flow to the forearm. Research shows that after occlusion, robust vasodilation results in excessive blood flow distal to the occluded site for several minutes (7). This phenomenon is called PORH. Climbers have been shown to have a greater PORH response and vascular conductance in the forearm compared with sedentary nonclimbers (7). It seems possible that after removal of the arm straps on the SA prefatiguing apparatus, the subjects could have experienced PORH to the forearm. The preemptive hyperemia to the forearm before the start of the climb may have delayed fatigue at the level of the forearm during climbing and offset the negative impact of SA fatigue to climbing performance.

No significant differences were observed in time to fatigue among the 4 muscle groups studied (Table 2). The EF muscle group, however, seemed to show a shorter time to fatigue compared with the other muscles groups. Because the present results suggest that the EF muscle group is very important for climbing and that the EF seem to have a shorter duration to fatigue, training strategies aimed at improving the fatigue resistance of the EF muscle group (especially the BR) may be beneficial for climbing performance.

Electromyography of all muscles showed decreases in median frequency from beginning to end of each prefatiguing exercise (Table 3). The percent difference from beginning to end frequency in the FDS muscle in this study was very similar to results from Petrofsky (−23 vs. −24%) (20). However, the slope of median frequency over time in this study was greater than reported previously (−1.8 vs. −0.87) (21).

The nature of the climbing wall and the repeated climbing of the same route could pose potential limitations. The looping nature of the route used for this study makes for a combination of positive vertical displacement climbing (climbing up), horizontal displacement climbing (traversing), and negative vertical displacement (downclimbing). Positive vertical displacement increases the physiological demands of climbing compared with traverse climbing (8) or downclimbing. Therefore, although we tried to make the technical difficulty of the climb used in this study uniform, the physiological demands of the route may have varied with climbing direction. The use of a climbing ergometer (Treadwall; Brewers Ledge, Randolph, MA, USA) would be a suitable approach to control for this variable. Climbers have been shown to adapt to a specific rock climb after repeated practice over several weeks (6). In an effort to control for the learned effect on this route, pretesting familiarization and a randomized design were used.

In conclusion, the main findings of this study show that after prefatiguing of the DF, climbing performance is significantly reduced to the greatest degree followed by the EF muscle group. These results suggest that among the muscle groups studied, DF and EF muscle groups show primary and secondary importance, respectively. Under the study conditions, prefatiguing exercise of the LF and SA had no significant impact on climbing performance.

Practical Applications

The results of this study suggest that the endurance of the DF and EF muscle groups may be especially important in rock climbing. Therefore, strength and conditioning strategies that improve fatigue resistance of the DF and EF muscle groups may be particularly effective in the improvement of rock climbing performance. The results from this study can also be used to help climbers chose better climbing strategies that reduce reliance on the DF and EF muscle groups. Developing such climbing movement strategies may delay the onset of fatigue in these muscle groups and may allow the climber to make further progress on a rock climb and improve their chances of completing the climb. Similarly, the results from this study may help coaches and climbers choose more effective rest positions during climbing. Resting is a strategy that climbers use by temporarily stopping forward progress during a rock climb to allow for some recovery before continuing. Choosing resting positions that reduce reliance on the DF and EF muscle groups may allow for more complete recovery of these muscles during rest, and in turn, allow further progress and greater likelihood of completing the climb.

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