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Physiology of difficult rock climbing

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Abstract The purpose of this review is to explore existing research on the physiological aspects of difficult rock climbing. Findings will be categorized into the areas of an athlete profile and an activity model. An objective here is to describe high-level climbing performance; thus the focus will primarily be on studies that involve performances at the 5.11/6c (YDS/French) level of difficulty or higher. Studies have found climbers to be small in stature with low body mass and low body fat. Although absolute strength values are not unusual, strength to body mass ratio is high in accomplished climbers. There is evidence that muscular endurance and high upper body power are important. Climbers do not typically possess extremely high aerobic power, typically averaging between 52–55 ml·kg⁻¹·min⁻¹ for maximum oxygen uptake. Performance time for a typical ascent ranges from 2 to 7 min and oxygen uptake ($\dot{V}O_2$) averages around 20–25 ml·kg⁻¹·min⁻¹ over this period. Peaks of over 30 ml·kg⁻¹·min⁻¹ for $\dot{V}O_2$ have been reported. $\dot{V}O_2$ tends to plateau during sustained climbing yet remains elevated into the post-climb recovery period. Blood lactate accumulates during ascent and remains elevated for over 20 min post-climbing. Handgrip endurance decreases to a greater degree than handgrip strength with severe climbing. On the basis of this review, it appears that a specific training program for high-level climbing would include components for developing high, though not elite-level, aerobic power; specific muscular strength and endurance; ATP-PC and anaerobic glycolysis system power and capacity; and some minimum range of motion for leg and arm movements.

Keywords Rock climbing · Performance · Endurance · Strength

Introduction

As a defined activity, rock climbing has developed from a mere training mode for alpine mountaineering into a specific recreational activity and leisure pursuit. Advances in safety techniques and, in particular, the use of permanently installed anchors, has enabled climbers to explore more difficult terrain and concentrate on the necessary physical and technical movement requirements. Through dedicated practice and preparation, modern rock climbers have achieved ascents of extremely difficult terrain. Competitive venues for climbing now exist around the world on natural rock and artificial structures.

Climbers have developed various subjective systems for rating the difficulty of individual climbing route pitches or rope lengths. The most common system employed in North America is the Yosemite Decimal System (YDS). The YDS system uses the numeral 5 to indicate “free” climbing, where no artificial means are employed to aid progress, followed by a “decimal point” and a second numeral to indicate the overall difficulty of the route. This scale currently extends from 5.0 (easiest) to 5.15 (most difficult). Letter subdivisions of a, b, c and d are used from the 5.10 level upward to indicate further gradients of difficulty. Thus, a route rated 5.11b would be more difficult than a route rated 5.11a for most climbers. A common rating system in Europe is the French system which uses integers from 5 upward with letter subdivisions of a, b and c. Where possible, this article will present difficulty ratings in the YDS system and the French system as YDS/French.

Figure 1 presents a plot of the “most difficult” rock route in the United States by year between 1965 and 2000. It is evident that the rate of increase in difficulty has slowed somewhat since the early 1980s; however, the

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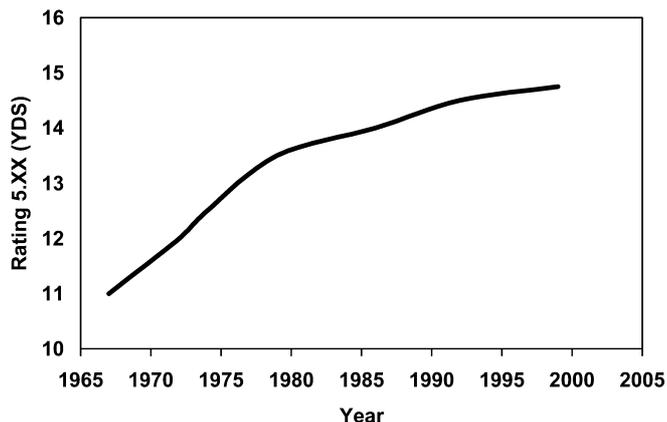


Fig. 1 Plot of the “most difficult” outdoor rock routes in the United States by year from 1965 to 2000

overall slope is still upward. Further increases in performance levels are possible, but these will likely come more slowly. This places more emphasis on understanding the multiple factors of climbing performance and the interactions among these factors. Although this review will focus on physiological aspects, it is important to keep in mind other factors of influence in climbing.

Serious climbers may employ a multi-factor strategy in order to achieve and maintain performance at the highest levels. Goddard and Neumann (1993) have described a six-component model for climbing performance which includes: (1) background conditions—talent, time and resources; (2) external conditions—available rock types, the nature of routes and equipment; (3) tactical aspects—experience, knowledge and planned goals; (4) psychological aspects—arousal, fear and ability to concentrate; (5) technique—motor skill, coordination and awareness of specific techniques, and (6) physiological aspects or physical abilities—strength, power, endurance and flexibility. Any proposed model for difficult rock climbing performance will be complex and the relative importance of a single component may vary among climbing styles and from route to route. This review will be limited to the base of published scientific literature related to the physiological aspects of climbing performance.

The exercise physiologist views optimal physical performance as a matching of an appropriate athlete type with a specific and individualized physical training program. Decisions regarding the profile for the athlete type are made from descriptive studies of proven elite performers to determine anthropometric characteristics, muscular strength and endurance capabilities, flexibility, anaerobic power/capacity and aerobic attributes. The specific training program design involves a comprehensive activity analysis to determine the primary bioenergetic systems (ATP-PC, anaerobic glycolysis, oxidative metabolism), energy expenditure rate and volume, oxygen uptake requirements, muscular strength and endurance requirements, and neuromuscular recruitment patterns. The activity analysis is matched with

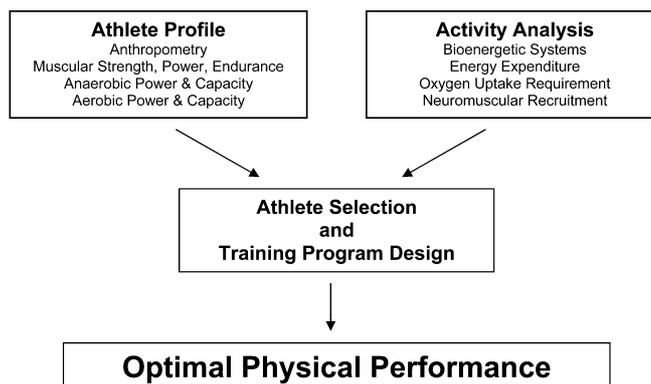


Fig. 2 Schematic for optimizing physical performance of a given task through the integration of athlete profile characteristics and the nature of work for the specific activity

known principles of physical training to provide an initial model for development of the important characteristics identified in the athlete profile (Fig. 2).

This review will categorize the existing research into the areas of the Athlete Profile and the Activity Model. Since the objective here is to describe high-level rock climbing performance, the focus will primarily be on studies that involve *difficult* climbing, defined here as performances at the 5.11/6c level of difficulty or higher. It should be noted that most published research papers in this area have concentrated on sport style climbing, where the climber clips the rope into permanent protection anchors along the route. This style maximizes safety and enables the climber to focus on difficulties of a more physical nature. Thus, the reader may perceive a bias toward sport style climbing, though much of the reported data will have carryover value to traditional style rock climbing, where the climber must establish anchors along the route during the ascent.

Athlete profile

Anthropometry

The traditional image of an elite rock climber, as depicted in the popular media, tends to be one of a large and very mesomorphic individual. Controlled observations and studies of contemporary climbers dispel this image. The modern elite rock climber tends to be a relatively small individual with a low percentage of body fat. Table 1 presents a summary of reported anthropometrical data for high-level rock climbers. While estimated percentage body fat values are presented in this table, and within the text, it should be pointed out that estimation methods and equations vary among the studies. Differences in percentage fat values are to be expected with different estimation equations. Thus, the focus should be primarily on the sum of skinfold measurements data.

Table 1 Summary of reported anthropometrical data for high-level rock climbers

Reference	No. of subjects (male/female), ability	Height (m)	Mass (kg)	Body mass index	Fat (%)	$\sum 7$ SF ^a (mm)
Watts et al. 1993	21 (M), 5.13c/8b (mean)	1.778 (0.065)	66.6 (5.5)		4.7 (1.3)	37.8 (6.8)
Watts et al. 1993	7 (M), 5.14a/8c (mean)	1.793 (0.052)	62.4 (4.5)		4.8 (2.3)	36.3 (6.4)
Grant et al. 1996	10 (M) > 5.10a/6a	1.789 (0.085)	74.5 (9.6)		14.0 (3.7)	
Watts et al. 1996	11 (M), 5.13b/8a (mean)	1.756 (0.089)	65.9 (8.6)		5.4 (1.5)	40.8 (7.3)
Mermier et al. 1997	9 (M), > 5.11/7a	1.757 (0.056)	66.3 (6.4)		6.8 (2.6)	
Booth et al. 1999	6 (M), 5.12a–5.13b/7b–8a (onsight)	1.757 (0.027)	62.6 (3.3)	20.3 (2.1)		
Zapf et al. 2001	20 (M), > 5.13a/8a	1.771 (0.044)	65.6 (4.9)	20.9 (1.1)		
Watts et al. 2003b	52 youth (M), 5.11d/7a (mean)	44.8 (26.0)%-ile ^b	51.5 (13.6)%-ile ^b	19.1 (2.2)	4.4 (2.2)	45.3 (13.0)
Watts et al. 1993	18 (F), 5.12c/7c (mean)	1.654 (0.040)	51.5 (5.1)		10.7 (1.7)	42.5 (8.9)
Watts et al. 1993	6 (F), 5.13b/8a (mean)	1.623 (0.046)	46.8 (4.9)		9.6 (1.9)	36.7 (10.5)
Mermier et al. 1997	5 (F), > 5.11/7a	1.647 (0.056)	54.5 (3.9)		14.6 (2.3)	
Watts et al. 2003b	38 youth (F), 5.11b/6c (mean)	54.4 (31.3)%-ile ^b	40.6 (9.6)%-ile ^b	17.5 (2.1)	12.2 (2.6)	56.0 (14.5)

^a $\sum 7$ SF is sum of seven skinfold measurements (chest, subscapula, midaxilla, suprailiac, abdomen, tricep, thigh).

^b %-ile is sex and age adjusted percentile norms obtained from the U.S. Department of Health and Human Services Centers for Disease Control and Prevention (CDC).

In the only large-scale study to date, Watts et al. (1993) reported data for 39 competitive sport rock climbers who were semifinalists at an international competition. These elite climbers were found to be relatively small in stature with males ($n=21$) averaging 1.778 (0.065) m in height and 66.6 (5.5) kg in body mass, while females ($n=18$) averaged 1.654 (0.040) m and 51.1 (5.1) kg. Ponderal Indices ($\text{height}/\sqrt{[3]\text{mass}}$) were 43.8 (4.8) and 44.4 (0.9) for males and females, respectively, and similar to reported values for distance runners and ballet dancers. Skinfold thicknesses, expressed as the sum of measurements from seven anatomical sites, were 37.8 (6.8) mm for males and 42.5 (8.9) mm for females. Calculated percentage body fat values were very low at 4.7 (1.3)% and 10.7 (1.7)% for males and females, respectively. Competition finalists, who reported best-ascent abilities of 5.14a/8c for males and 5.13b/8a for females, tended to be lighter than the semifinalist group in both men ($n=7$) and women ($n=6$), with little difference in height. The mean percentage fat value for female finalists was extremely low at 9.6 (1.9)% and the sums of skinfolds were nearly identical for males [36.3 (6.4) mm] and females [36.7(10.5) mm].

In a different study, Watts et al. (1996) reported data for a group of 11 male rock climbers with an ability range of 5.12a/7b to 5.13d/8b. This group supported the earlier data of Watts et al. (1993) with the climbers averaging 1.756(0.089) m in height and 65.9 (8.6) kg in body mass, with a mean sum of seven skinfolds of 40.8 (7.3) mm. Body fat was calculated at 5.4 (1.5)%, with a range of 3.5–7.7%.

Grant et al. (1996) published anthropometrical data for ten elite (ability > 5.10a/6a) male rock climbers. This group had a mean height, mass and percentage body fat of 1.789(0.085) m, 74.5 (9.6) kg and 14.0 (3.7)%; however, mean values were not significantly different from a group of non-climbers tested by the same researchers.

Arm lengths of 0.738 (0.039) m and leg lengths of 1.146 (0.046) m were also reported, but these values were not significantly different from non-climbers who, generally, had longer arms and legs. Whether this group of climbers was truly representative of *elite* is questionable since an ability level of 5.10a/6a would be considered *intermediate* by modern competition standards.

A study by Booth et al. (1999) reported a mean height of 1.757 (2.7) m and body mass of 62.6 (3.3) kg in seven climbers (six male, one female) who ranged in on-sight ability between 5.10c/6b and 5.11c/7a. The mean sum of nine skinfolds for this group was 61.3 (3.3) mm (range of 52.6–78.9 mm). These values would calculate out slightly higher than the average single skinfold thickness for the elite climbers in the study by Watts et al. (1993).

Fifteen male climbers of very high ability (5.12c/7c to 5.14b/8c) were found to present data similar to that of the early study of Watts et al. (1993), with a mean height of 175.1 (6.6) cm and mean body mass of 67.2 (6.3) kg (Watts et al. 2000). The sum of seven skinfolds and percentage body fat means were 37.9 (9.1) mm and 5.2 (1.5)% in this sample.

Watts et al. (2003b) have recently presented data for a large group ($n=90$) of young competitive climbers with a mean age of 13.5 (3.0) years and an average of 3.2 (1.9) years of climbing experience. These athletes were near the mid-range of percentile scores for sex- and age-matched North American norms for height and body mass (see Table 1). These percentile scores were significantly lower than for a sex- and age-matched control group of physically active young people ($n=45$) who were not climbers. Body mass index, whether expressed as an absolute or as a percentile score, did not differ between the two groups. Means for the sum of seven skinfolds did differ between the groups: 50.4 (14.5) versus 76.7 (33.4) mm for climbers versus controls, respectively. The authors indicated that

the climbers were proportionately smaller and had a higher proportion of fat-free mass than the non-climber athletes.

Although the outer limits of the ranges for stature and mass can include larger individuals, for the most part, the best climbers tend to be small. Greater height may enable longer reaches between moves; however, there may be biomechanical disadvantages associated with longer moment arms relative to resistance forces. Taller climbers would also tend to be heavier. Higher body mass would increase the muscular strength requirement for maintaining contact with holds and increase the workload of moving along the climbing route. Reduction of body fat, or maintenance of an existing low body fat level, would be advantageous since this would further reduce body mass that does not contribute to support and movement. Some concern has been expressed relating to the potential adverse effects of extremely low body fat and the potential for disordered eating and weight loss practices in climbers. (Downing 1994; Steuart 1996) To date, there have been no published studies to document such practices or subsequent effects on health in climbers.

Muscular strength and endurance

Most studies that have reported muscular strength and endurance data for rock climbers have focused on the forearm and hand and have employed some type of handgrip dynamometry, with values expressed as maximum handgrip force. Handgrip dynamometry typically involves an isometric contraction of the fingers in opposition to the thumb and the base of the hand. The results of studies that have measured hand and finger strength in climbers are summarized in Table 2. Reported values in these studies are not particularly high in comparison to recreational climbers or active non-climbers. However, when handgrip force is expressed relative to body mass, as a strength-to-mass ratio, scores for climbers are very high in comparison with age- and sex-matched norms. (Watts et al. 1993)

For the most part, with the exception of the study of Ferguson and Brown (1997), handgrip force values are similar across studies. Absolute handgrip strength in elite competitive climbers has been found to rank at the 50th and 75th percentiles of North American age-matched norms for males and females, respectively (Watts et al. 1993). Grant et al. (1996) found no significant differences in handgrip strength among elite climbers, recreational climbers or non-climbers for the right hand. This group did find elite climbers to have significantly higher values than the other groups with the left hand. This may be due to a greater symmetry of strength between right and left arms in elite climbers, with non-dominant arm strength close to that of the dominant side.

Expression of handgrip strength relative to body mass improves the normative percentile rankings for both males and females to >80th and >90th, respectively, in the study of Watts et al. (1993). As noted in Table 2, handgrip force:mass ratios have been found to range between 0.75 and 0.78 for males and around 0.65 (0.06) for females. Watts et al. (1993) found that climbing ability could be predicted from a regression equation that included strength:body mass ratio and percentage body fat as independent variables; however, the r^2 value was low at 0.33.

The weak association of measured handgrip strength to rock climbing performance may be supported by observation of the nature of the basic hand positions employed during climbing. Figure 3 illustrates four basic "grips" commonly used in rock climbing along with a typical handgrip dynamometer. Except for the pinch grip, none of these involve opposition of the thumb and/or palm against the fingers in a manner similar to that employed during handgrip dynamometry. Thus, measurement of hand strength via grip dynamometry may lack specificity with most hand positions required during actual rock climbing.

Works by Grant et al. (1996, 2001) have attempted to quantify hand and finger strength in climbers via a more specific methodology. In these studies, forces applied by the fingers were measured for two hand positions via a

Table 2 Summary of forearm and hand strength data in high-level rock climbers

Reference	No. of subjects (male/female), ability	Test mode	Strength (N)	Strength:weight ratio
Watts et al. 1993	21 (M), (mean) 5.13c/8b	Handgrip dynamometer	506.0 (62.8)	0.78 (0.06)
Cutts & Bollen 1993	13 (M), 5.8/5b–5.12a/7b (mean)	Handgrip dynamometer	519.8 (56.9)	0.75 (0.10)
Grant et al. 1996	10 (M), > 5.10a/6a	Handgrip dynamometer	532.5 (22.6)	
Grant et al. 1996	10 (M), > 5.10a/6a	"Open" grip with 4 fingers	446.2 (30.4)	
Watts et al. 1996	11 (M), 5.13b/8a (mean)	Handgrip dynamometer	581.6 (69.6)	
Ferguson & Brown 1997	5 (M), 5.11c–5.13b/7a–8a	Modified handgrip dynamometer	713.9 (34.3)	
Watts et al. 2000	5.12c–5.14b/7c–8c	Handgrip dynamometer	507.0 (73.6)	0.77 (0.07)
Watts et al. 2003b	52 youth (M), 5.11d/7a (mean)	Handgrip dynamometer	357.9 (126.5)	0.70 (0.13)
Watts et al. 1993	18 (F), 5.12c/7c (mean)	Handgrip dynamometer	335.4 (60.0)	0.65 (0.06)
Grant et al. 2001	10 (F), ~5.9/5c	Handgrip dynamometer	337.4 (11.8)	
Grant et al. 2001	10 (F), ~5.9/5c	"Open" grip with 4 fingers	320.7 (11.8)	
Watts et al. 2003b	38 youth (F), 5.11b/6c (mean)	Handgrip dynamometer	246.1 (66.7)	0.62 (0.08)

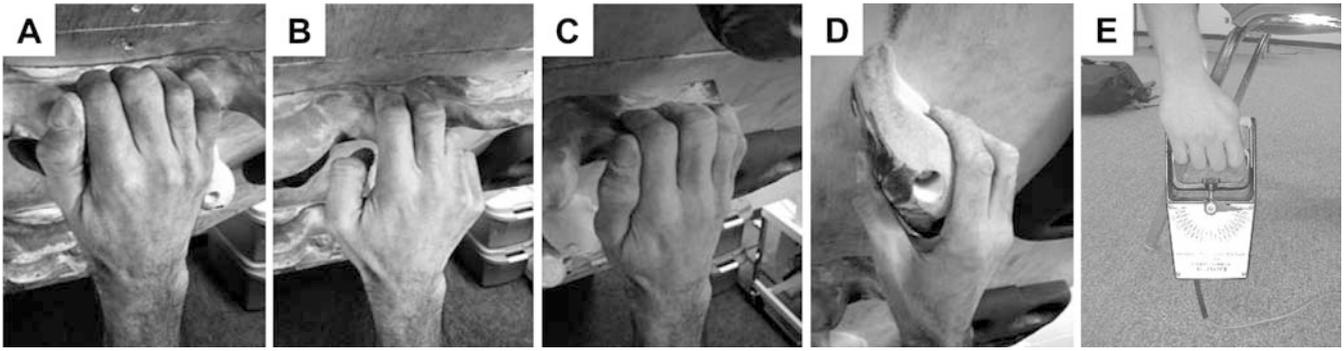


Fig. 3 Four common hand positions used in rock climbing: **A** open, **B** pocket, **C** crimp, **D** pinch, and **E** a typical handgrip dynamometer

plate and strain gauge apparatus. The apparatus positioned and fixed the arm such that only the fingers would apply direct force. Data for males and females are included in Table 2, along with measured handgrip force for the subjects in each study. Strength values for the climbing-specific tests were slightly below values for handgrip dynamometry. Although climbers achieved higher forces than non-climbers, there were no significant differences between elite and recreational climbers. Grant et al. (1996) compared force values for right and left hands and suggested that hand forces exhibit more symmetry in climbers than in non-climbers.

A recent study by Schweizer (2001) reported maximum single-finger forces of 96.1 (20.6) N and 115.7 (30.4) N for “crimp” and “open” positions, respectively, in a climbing specific test. An interesting finding of this study was that the individual force of a single finger (middle) was higher when applied with the finger isolated versus when the finger worked parallel to the other three fingers.

Since many hand configurations employed in difficult climbing do not involve an actual squeezing-type grip, it seems likely that the primary force for contact has a genesis in the effect of gravity on body mass. The climber seeks a position such that the force resulting from gravity pulls the hand and/or fingers into the rock. As long as the specific hand configuration is maintained, the climber is able to sustain contact. The progression of fatigue may ultimately lead to an inability to maintain the required hand position, with the result that contact is lost. If it is true that this ability to maintain a specific hand configuration against resistance force is important, then muscular endurance, and isometric endurance in particular, should be well developed in climbers.

Very few studies have reported muscular endurance data for climbers, and the mode of testing has varied. Cutts and Bollen (1993) have measured integrals of the force–time curve at 80% of maximal handgrip and at 50% of maximal pinch. Climbers scored higher than non-climbers for left handgrip and right and left pinch. Watts et al. (1996) reported isometric endurance times at 70% maximal handgrip force to be 34.5 (10.2) s for

expert (5.12a–5.13d/7b–8b+) climbers. No comparisons with non-climbers were made in that study. In one study by Grant et al. (1996), elite (>5.10a/>6a) climbers scored higher than recreational climbers for bent arm hang [53.1 (13.2) vs 31.4 (9.0) s] and pull-ups [16.2 (7.2) vs 3.0 (9.0)].

In a study on blood pressure and forearm conductance, Ferguson and Brown (1997) employed a specially designed forearm ergometer to test handgrip measurements in sedentary individuals and five climbers with abilities ranging from 5.11d/7a to 5.13c/8a. Endurance was measured in both sustained isometric and rhythmic isometric (5-s contraction with 2-s relaxation) modes with the resistance load at 40% of maximal for each mode. Maximal handgrip force and sustained isometric endurance time were not significantly different between climbers and non-climbers; however, the mean rhythmic isometric time for climbers was nearly double that for non-climbers [853 (76) vs 420 (69) s]. The results also indicated a significantly enhanced forearm vasodilator capacity in trained climbers. This could enable an increased oxygen supply and a greater degree of recovery between contractions.

Flexibility

Flexibility, or range of motion, is often mentioned in rock climbing instructional texts as an important component of the physical fitness model for climbing. Certain common positions and movements seem to require a significant range of motion in specific articulations. Stemming and turnout positions, where the body must be kept close to the rock surface while the feet are in opposition wide to either side, require extreme abduction and external rotation at the hip. High-step moves, where one foot must be brought up and placed on a high rock feature while the opposite foot must maintain a low position for support, requires a great deal of posterior leg and hip flexibility. In spite of these qualitative observations, very little actual data for flexibility in climbers has been published.

Grant et al. (1996) published data for a sit-and-reach test (hip, back, and posterior thigh), a foot-raise test (similar to a high-step move), and a leg-span test (hip abduction) in male climbers. Scores for the sit-and-reach test were reported to be “average” with no differences

among elite, recreational, and non-climbers. Values in the foot-raise test were higher for climbers than non-climbers, although not significantly. For the leg-span test, it was reported that elite climbers scored higher than the other two groups; however, numerical data were not provided in the manuscript. Similar results for females climbers have been reported by Grant et al. (2001).

Mermier et al. (2000) reported hip and shoulder range of motion data for male and female climbers of varying abilities. This group found that hip flexion and hip abduction were weakly predictive of climbing performance in comparison with other anthropometric and strength variables.

Aerobic power

Aerobic power is typically measured as the maximum oxygen uptake ($\dot{V}O_{2\max}$) attainable during a rapidly progressive work test to exhaustion. Such tests usually involve measurement and analysis of expired air during treadmill exercise or stationary cycle ergometry. Four studies have reported $\dot{V}O_{2\max}$ values in rock climbers. These data are summarized in Table 3. It should be noted that traditional $\dot{V}O_{2\max}$ test modes, treadmill, and cycle ergometry are not specific to rock climbing, particularly with regards to work requirements of the upper body. Thus, interpretation of such data is limited when used to determine relative intensities of climbing.

In the studies that have employed treadmill running, $\dot{V}O_{2\max}$ scores for climbers are similar to values reported for team sport athletes and gymnasts. When compared with age-range norms, a $\dot{V}O_{2\max}$ value of $55 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ would be rated as “excellent” relative to general aerobic fitness. However, this level would be considered low in comparison to averages for endurance athletes, which usually fall within a range of 65 to $80+ \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$.

Booth et al. (1999) employed a special climbing ergometer to assess $\dot{V}O_2$ during speed-controlled climbing and found a peak $\dot{V}O_2$ mean of $43.8 (2.2) \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ during fast climbing. These values for $\dot{V}O_{2\max}$ in climbers are similar to those seen for gymnasts and team sports athletes and are consistent with an aerobic fitness level required for quick recovery from high intensity effort. Whether high aerobic power is predictive of climbing performance or whether increasing aerobic power improves climbing performance are questions that have not been studied.

Athlete profile summary

Mermier et al. (2000) employed a principle components analysis in an attempt to identify important physiological and anthropometrical determinants of climbing performance. The study involved 44 subjects (24 male, 20 female) of varying climbing abilities (5.6–5.13c/5a–8b). Climbing performance was scored by having the subjects attempt ascents of two climbing routes where difficulty increased with height. The analysis procedure extracted three components identified as: training (strength, anaerobic power, percentage body fat and self-reported climbing skill), anthropometrics (height, mass, arm span, leg length and ratio of arm span to height), and flexibility (hip flexibility and years of climbing experience). Percentages of variance in climbing performance explained by the training, anthropometrics, and flexibility components were 58.9%, 0.3%, and 1.8%, respectively. These results provide insights; however, the wide range of climbing abilities among the subjects could limit application of the results. It is unknown whether such a model will hold for a more homogenous group of high ability. In the elite competition climbers studied by Watts et al., only percentage body fat and handgrip strength:body mass ratio were significant predictors of ability (Watts et al. 1993).

Figure 4 presents a hypothetical Athlete Profile for high-level sport rock climbers. This model is suggested based upon limited existing data and theoretical concepts. Some components of the model await investigation in high-level climbers. There is an absence of controlled training studies to test whether changes in a component will result in a change in climbing performance.

Athlete Profile for Rock Climbing	
•	Small stature and low body mass
•	Low percent body fat ($\Sigma\text{skinfolds}$)
•	High upper-body strength to body weight ratio
•	High dynamic and isometric muscular endurance
•	High upper body power
•	Moderate to high aerobic power ($\dot{V}O_{2\max}$)

Fig. 4 Theoretical athlete model of high-level rock climbing ability

Table 3 Summary of studies that have reported maximum oxygen uptake values ($\dot{V}O_{2\max}$) in rock climbers

Reference	Ability of subjects	Test mode	$\dot{V}O_{2\max}$ ($\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$)
Billat et al. 1995	> 5.12a/7b	Running	54.8 (5.0)
Billat et al. 1995	> 5.12a/7b	Arm pulling	22.3 (2.6)
Wilkins et al. 1996	> 5.12a/7b	Running	55.2 (3.6)
Watts & Drobish 1998	5.8–5.11b/5b–7a	Running	50.5 (7.0)
Booth et al. 1999	5.10d–5.12d/6b–7a	Fast climbing	43.8 (2.2)

Activity analysis

The nature of rock climbing presents difficulties for controlled analyses of the physiological responses to performance of the activity. Even with the advent of indoor modular climbing facilities, progression of the climber upward along a route limits data collection via traditional methodologies. Fortunately, recent advances in portable instrumentation have opened investigation into this area.

Oxygen uptake and energy expenditure

Table 4 presents a summary of studies that have measured $\dot{V}O_2$ during rock climbing movements. From these studies, it appears that $\dot{V}O_2$ averages between 20 and 30 ml·kg⁻¹·min⁻¹ during climbing, with peaks that can exceed 30 ml·kg⁻¹·min⁻¹. These levels of $\dot{V}O_2$ are equivalent to energy expenditure rates close to 10 kcal·min⁻¹.

Billat et al. (1995) were the first to publish data for $\dot{V}O_2$ during rock climbing. Four expert climbers were tested on two routes, both rated 5.12a/7b, using a Douglas bag system to collect expired air each 30 s during the last half of each route. Heart rate (HR), $\dot{V}O_2$, and blood lactate (BL) means were 176 (14) beats·min⁻¹, 24.9 (1.2) ml·kg⁻¹·min⁻¹, and 5.75 (0.95) mmol·l⁻¹, respectively, for the route with more technically complex moves. The second route was steeper and more physically difficult and produced HR, $\dot{V}O_2$, and BL means of 159 (15) beats·min⁻¹, 20.5 ml·kg⁻¹·min⁻¹, and 4.30 (0.77) mmol·l⁻¹. It is also notable that an analysis of movement time during each route revealed that the climbers were dynamic (moving) 63 (9)% of the time and maintaining static positions for 37 (9)% of the time.

Watts and Drobish (1998) first reported data for energy expenditure during continuous climbing over a range of terrain angles. These researchers utilized a non-motorized climbing treadmill or Treadwall (Brewer's Ledge, Inc., Jamaica Plain, Mass., USA) to enable continuous analysis of expired air and heart rate during climbing. The Treadwall was adjustable to several

angles, from 80 to 102° from the horizontal. A route was set on the Treadwall surface with modular holds with a difficulty level of approximately 5.7/5a at the lowest angle and approximately 5.11a/6c at the steepest angle. Sixteen subjects (nine male and seven female) climbed 4-min bouts at angles of 80, 86, 91, 96, and 102° with 6 min of rest imposed between each bout. Mean distances climbed per 4-min bout decreased from 27.4 (6.6) m at 80° to 8.2 (4.0) m at 102°. Although HR increased with increasing angle, $\dot{V}O_2$ remained relatively unchanged at approximately 30 ml·kg⁻¹·min⁻¹. For the subjects in this study, $\dot{V}O_{2max}$ averaged 52 ml·kg⁻¹·min⁻¹, thus sustained climbing required less than 60% of the aerobic power measured during running. Since $\dot{V}O_2$ did not vary with different climbing angles, energy expenditure remained within a narrow range of 10.4–11.2 kcal·min⁻¹. However, since climbing distance decreased with increasing angle, the energy expenditure per 1-m climbing segment was significantly increased at the 96 and 102° angles (from between 1.5 and 2.0 kcal·m⁻¹ at 80–90° to 5 kcal·m⁻¹ at 102°). It is interesting to note that calculated estimates of the mechanical efficiency for climbing ranged from 11.0% at 180° to 8.2% at 91° and 3.3% at 102°, assuming a body mass of 70.6 kg (mean for these subjects). BL began to increase significantly at 91°, with a mean of 5.9(1.2) mmol·l⁻¹ at 102°. The increase in BL was significantly correlated with a decrease in handgrip force ($r = 0.96$).

Portable battery-powered instrumentation for metabolic analysis was first employed by Wilkins et al. (1996). This group used an AeroSport TEEM 100 (Aerosport, Ann Arbor, Mich., USA) to continuously collect and analyze expired air during a 27-move boulder route (5.12a/7b) of 2:15 (0:15) min:s duration. $\dot{V}O_2$ averaged 20.9 (0.8) ml·kg⁻¹·min⁻¹ with mean peaks of 27.4(1.0) ml·kg⁻¹·min⁻¹. The average and peak $\dot{V}O_2$ values per subject represented 33–38% and 43–50% of $\dot{V}O_{2max}$ (determined via treadmill running).

Mermier et al. (1997) measured HR, $\dot{V}O_2$, and BL during ascents of three routes of different difficulties (easy = 5.6/<5a, moderate = 5.9/5c, and difficult = 5.11+/7a) by 14 experienced climbers. Expired air was collected via Douglas bags during the last minute of each ascent. HR increased with difficulty, with means of 142

Table 4 Summary data for studies that have measured $\dot{V}O_2$ during climbing

Reference	Condition	Duration (min:s)	Avg. $\dot{V}O_2$ (ml·kg ⁻¹ ·min ⁻¹)	Peak $\dot{V}O_2$ (ml·kg ⁻¹ ·min ⁻¹)
Billat et al. 1995	5.12a/7b route indoor	3:30–4:15	NR ^a	24.9 (1.2)
Wilkins et al. 1996	5.12a/7b 27-moves indoor bouldering	2:15 (0:15)	20.9 (0.8)	27.4 (1.0)
Mermier et al. 1997	5.11+/7a route indoor	~5:00	NR ^a	24.9 (4.9)
Watts & Drobish 1998	Treadwall, various angles to 102°	4:00	29.5 (5.2) to 31.7 (4.6)	NR ^a
Booth et al. 1999	5.10d/6b route outdoor	7:36 (0:33)	NR ^a	32.8 (2.0)
Watts et al. 2000	5.12b/7b route indoor	2:34 (0:25)	24.7 (4.3)	31.9 (5.3)
Doran & Grace 2000	5.9/5c traverse	2:26 (0:33)	18.6	NR ^a

^aNR indicates data not reported

(19), 155 (15), and 163 (15) beats·min⁻¹ for the easy, moderate, and difficult routes, respectively. Mean $\dot{V}O_2$ values were 20.7 (8.1), 21.9 (5.3), and 24.9 (4.9) ml·kg⁻¹·min⁻¹ for the three routes.

Watts et al. (2000) used a very lightweight portable metabolic analysis system (AeroSport KB1-C) to record data throughout a sport lead ascent and 10 min of recovery. Fifteen male climbers (range of ability 5.12c/7c to 5.14b/8c) led a 27-move route, rated 5.12b/7b, on an indoor wall with a mean climbing time of 2.57 (0.41) min. Expired air was analyzed continuously with data averaged over 20-s intervals. Oxygen uptake means were similar to those from earlier studies, with $\dot{V}O_2$ at 24.7 (4.3) ml·kg⁻¹·min⁻¹ and $\dot{V}O_{2\text{peak}}$ at 31.9 (5.3) ml·kg⁻¹·min⁻¹. Eight subjects followed climbing with a 30-min passive recovery period, which involved quiet sitting in a recumbent position. The remaining seven subjects exercised by pedaling a recumbent cycle ergometer at 25 W throughout the 30-min recovery period. Expired air was analyzed throughout 10 min of recovery in both subgroups. Total net $\dot{V}O_2$ during the first 10 min of resting recovery was 2.809 (0.518) l. BL increased by 3.2 (0.8) mmol·l⁻¹ from pre-climb to 1 min post-climb. Lactate had returned to the pre-climb level within 20 min in the active recovery group, but remained elevated throughout the 30 min post-climb in the resting recovery. An interesting observation by these authors was the occurrence of an apparent plateau in $\dot{V}O_2$ after approximately 80–100 s of climbing. Unfortunately, $\dot{V}O_{2\text{max}}$ was not measured in the subjects; thus, whether this plateau represented a metabolic steady state or attainment of a climbing-specific $\dot{V}O_{2\text{max}}$ could not be determined. The elevated post-exercise $\dot{V}O_2$ and BL suggest some anaerobic contribution to the energy requirement of climbing.

Booth et al. (1999) has also observed a plateau of $\dot{V}O_2$ during climbing of an outdoor route rated 5.10 and requiring 7:36 (0:33) min:s to complete. This group recorded a mean peak $\dot{V}O_2$ of 32.8 ml·kg⁻¹·min⁻¹ during the ascent. Of particular interest in this study was the possible measurement of climbing-specific $\dot{V}O_{2\text{max}}$. Oxygen uptake was recorded during climbing at different speeds on a vertical climbing ergometer (Crestville Holdings, Sydney, NSW, Australia) set with modular climbing holds. HR and $\dot{V}O_2$ increased linearly with increasing climbing speed and attained maximum values of 190 (4) beats·min⁻¹ and 43.8 (2.2) ml·kg⁻¹·min⁻¹ at a speed of 16 m·min⁻¹. The mean peak $\dot{V}O_2$ during the outdoor route ascent was 75 (4)% of the subjects' climbing-specific $\dot{V}O_{2\text{max}}$ values. This percentage of $\dot{V}O_{2\text{max}}$ for climbing is higher than values previously reported (Billat et al. 1995; Wilkins et al. 1996). However, the climbing-specific $\dot{V}O_{2\text{max}}$ of Booth et al. (1999) was probably lower than what would have been observed in these subjects with a treadmill running protocol, as used in the earlier studies.

Booth et al. (1999) used regression analysis to determine the relationship between climbing velocity in m·min⁻¹ and $\dot{V}O_2$ in ml·kg⁻¹·min⁻¹. All subjects were

able to complete 5-min climbing bouts at 8, 10 and 12 m·min⁻¹. The resulting equation was: $\dot{V}O_2 = 11.8 + (2.36 \times \text{velocity})$ with $r^2 = 0.98$. When this equation was applied to the average climbing pace for the outdoor route in this study, a $\dot{V}O_2$ of 19.4 ml·kg⁻¹·min⁻¹ or 44% of the climbing-specific $\dot{V}O_{2\text{max}}$ was predicted. This value was considerably lower than the measured $\dot{V}O_2$ of 32.8 ml·kg⁻¹·min⁻¹ (75% of $\dot{V}O_{2\text{max}}$) during ascent of the outdoor route. Booth et al. suggested that the higher route $\dot{V}O_2$ may be due to increased isometric contraction time during static positions and a greater loading of the arms due to steeper terrain.

Watts et al. (1995) have also observed responses of $\dot{V}O_2$ to three different climbing paces on the Treadwall. No attempt to exhaust the subjects was made in this study, thus, the $\dot{V}O_2$ at the faster pace cannot be assumed to represent a climbing-specific maximum. The measured mean $\dot{V}O_2$ values of Watts et al. match up well with the $\dot{V}O_2$ values predicted for the three paces using the equation of Booth et al. (1999): 33.1 versus 32.8 at 8.9 m·min⁻¹, 37.2 versus 35.2 at 9.9 m·min⁻¹, and 43.3 versus 41.1 at 12.4 m·min⁻¹.

The combined results of the studies by Booth et al. (1999) and Watts et al. (1995) suggest that climbing-specific $\dot{V}O_{2\text{max}}$ values can exceed 40 ml·kg⁻¹·min⁻¹ and are higher than values reported during actual route ascents in rock climbing. Whether these paced climbing tests may be considered climbing-specific remains unclear since the pace- $\dot{V}O_2$ relationship appears to differ between climbing ergometer work and ascents on actual rock.

Blood lactate

BL increases during climbing, but not to the levels observed during maximum treadmill running or cycling (Table 5). The relatively low lactate accumulations observed with climbing are assumed to be due to the lower active muscle mass of the upper body in comparison with the large lower body muscle mass activated during running or cycling. Increases in BL with climbing have been found to correlate with decreases in handgrip endurance ($r = 0.76$) but not with decreases in handgrip strength ($r = 0.56$) (Watts et al. 1996). Lactate levels can remain elevated beyond 20 min of resting recovery (Watts et al. 1996, 2000); however low-intensity active recovery can shorten removal time (Watts et al. 2000). Although BL level has been correlated with a decrease in handgrip strength with climbing, the impact of elevated BL upon subsequent climbing performance has not been assessed.

Werner and Gebert (2000) have published data for BL responses to actual route ascents during World Championship competition. They analyzed ear-lobe blood samples taken within 1 min of climbing from 46 competitors (28 male, 18 female). BL concentration means were 6.7 (1.1) mmol·l⁻¹ for ascents with a mean climbing height of 13.2 (4.9) m and time

Table 5 Summary of reported blood lactate responses to climbing

Reference	Condition	Blood lactate (mmol·l ⁻¹)
Billat et al. 1995	3 min post route, 5.12a/7b	5.8 (1.0)
Watts et al. 1996	1 min post climbing to a fall, 5.12a/7b	6.1 (1.4)
Mermier et al. 1997	1–2 min post indoor route, 5.11 + /7a	3.2 (0.9)
Watts & Drobish 1998	1 min post 4-min bout at 102 degrees	5.9 (1.2)
Booth et al. 1999	Post outdoor route, 5.10d/6b	4.5 (0.5)
Watts et al. 2000	1 min post indoor route, 5.12b/7b	6.8 (1.9)
Werner & Gebert 2000	1 min post UIAA World Championship competition	3.8–8.9

of 4.2 (1.8) min. BL level was significantly correlated with attained height on the competition route ($r=0.41$, $P<0.05$).

Muscular strength and endurance

The impact of sustained climbing on muscular strength and endurance has been studied by Watts et al. (1996) In this study, 11 expert climbers (ability = 5.12a/7b to 5.13d/8b) lead continuous laps on an indoor arching-roof route until falling. Mean climbing time was 12.9 (8.5) min. The authors observed a 22% decrease in handgrip strength (maximal voluntary contraction, MVC, with dynamometry) and a 57% decrease in handgrip endurance (dynamometer holding time at 70% MVC force). Both strength and endurance remained depressed throughout 20 min of resting recovery although strength returned toward pre-climb levels at a faster rate. The duration of this climbing task was longer than reported in other studies; thus, the specific route characteristics may have placed greater stress upon endurance factors than upon strength. The decrease in strength was significantly correlated with climbing time ($r=0.70$), but not with BL accumulation ($r=0.56$). The decrease in endurance was significantly correlated with climbing time ($r=0.70$) and lactate accumulation ($r=0.76$).

In a more recent study, Watts et al. (2003a), reported that climbing to the point of failure does not affect finger curl strength when measured by a climbing-specific device. In this study the peak force applied by four fingers in an “open grip” position common in climbing was measured via a piezoelectric force sensor. The apparatus used was found to provide reliable results in repeated trials (Watts and Jensen 2003). Forearm electromyograms (EMG) recorded during the finger curl test were also unchanged after climbing to fatigue (Watts et al. 2003a).

Watts et al. (2000) found that active recovery, consisting of recumbent cycling at 25 W, facilitated the return of BL to pre-climb levels within 30 min. The impact of the observed post-climb elevation in BL on subsequent climbing performance was not investigated in either of these studies (Watts et al., 1996, 2000). Whether the faster removal of lactate with active recovery has an impact on subsequent climbing performance needs to be addressed.

Some indication of the actual force demands placed on the hands and fingers may be derived from studies conducted by Quaine et al. (1997) and Quaine and Martin (1999). This group employed a vertical climbing frame instrumented with three-dimensional strain gauges to record force at each hand and foot during support. Forces at the hand were around 5–6 kg with four-point support (both hands and both feet) and around 9–10 kg with three-limb support (release of one hand). These forces are considerably lower than the maximum finger forces recorded by Grant et al. (1996). However, the use of the feet for support could have minimized force on the hand. Applied forces during actual climbing have not been reported.

With severe climbing on terrain with small holds and features, the ability to quickly apply the required force for maintenance of contact may be important. Thus, the rate of force development within the muscle may be more important than absolute strength. Rate of force development as a factor of performance in climbing has not been studied.

Neuromuscular recruitment

Forearm EMGs have been studied during climbing movements by Koukoubis et al. (1995) and Watts et al. (submitted for publication, 2003); however, results have differed. Koukoubis et al. (1995) studied experienced climbers during performance of three consecutive fingertip pull-up movements with pronated forearms. EMGs from the interosseous, brachioradialis, flexor digitorum superficialis, and biceps brachii muscles of the dominant arm were normalized for the specific muscle MVC EMG. The flexor digitorum had the highest EMG activity during hanging (69% of MVC EMG), which was sustained throughout the pull-up task. The brachioradialis attained peaks of 67% MVC EMG at the beginning of the pull-up phase of the movement. Whether this study has an application to actual climbing may be questioned since the movement involved simple hanging, pulling up, and lowering without feet support. From observations of contemporary climbers on difficult routes, it would appear that such finger-only support, with no foot contact, is not common.

Watts et al. (submitted for publication, 2003) recorded EMG from the anterior forearm during a specific climbing movement with six different hand positions.

The movement, commonly referred to as a “twist-lock”, is used to make relatively long reaches on steep terrain. Climbers performed the movement in both ascending (UP) and descending (DN) directions on a 45° overhanging board fitted with identical commercially available training holds (Nicros HIT Strips, Nicros Inc., St Paul, Minn., USA) spaced 18 inches (~46 cm) apart. EMG data were integrated (iEMG) and normalized as percentages of the peak iEMG obtained during an MVC using a handgrip dynamometer. The specific hand positions investigated were basic “grips” used in rock climbing and included: crimp; pinch; three two-finger pocket combinations with digits V+IV (2F1), IV-III (2F2), and III+II (2F3), and an open position. For all hand positions during UP and DN movements, the climbing iEMG was greater than 100% MVC iEMG and was greatest for the crimp and 2F1 positions. The 2F3 position evidenced the lowest iEMG; however, this mean was still 126 (32)% of MVC iEMG. All DN iEMGs were significantly lower than UP iEMGs. These data appear to support earlier suggestions that handgrip dynamometry lacks specificity with actual climbing efforts.

Activity analysis summary

Figure 5 presents a summary of research findings relative to the activity of rock climbing. As for the Athlete Profile, research data on actual rock climbing is limited. Furthermore the specific nature of climbing involved in individual studies is not always reported. It is possible that the physiological responses to climbing will vary among routes which are rated at the same difficulty level yet present different steepness, texture and feature, and problem-solving characteristics.

Activity Analysis for Rock Climbing

- Route ascent times typically range from 2 to 7 minutes with approximately 38% of this spent in static positions.
- $\dot{V}O_2$ averages 20-25 $\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ with peaks to over 30 $\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$.
- $\dot{V}O_2$ can plateau with sustained climbing of >2 minutes yet remains elevated into recovery.
- Blood lactate accumulates to 4-7 times resting level with a typical climbing bout or route ascent and remains elevated for more than 20 minutes during resting recovery.
- Handgrip endurance decreases to a greater degree than handgrip strength with severe climbing and recovers at a slower rate.
- EMG evidence indicates that the forearm musculature is activated to a greater degree during steep climbing than during standard maximum handgrip dynamometry.

Fig. 5 Summary of the activity analysis for rock climbing

Most studies have focused on aerobic metabolism by measuring oxygen uptake during climbing or simulated climbing. Climbing route ascent times range from 2 to 7 min, on average, with approximately 38% of this time spent in static positions. $\dot{V}O_2$ averages 20–25 $\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$, with peaks of over 30 $\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$, and can plateau with sustained climbing of greater than 2 min duration. Whether this plateau represents a metabolic steady state is doubtful since $\dot{V}O_2$ remains elevated into recovery, and significant increases in BL are common. Higher climbing $\dot{V}O_2$ values are possible with fast climbing speeds; however, such speeds are not common in actual difficult climbing.

There is evidence that energy expenditure rate, expressed as $\text{kcal}\cdot\text{min}^{-1}$, remains constant as climbing angle changes but, since pace varies with angle, energy expenditure per distance climbed increases with steeper terrain. The total energy cost of a specific route ascent is higher than that recorded via indirect calorimetry during climbing because lactate accumulates in the blood and $\dot{V}O_2$ remains elevated into the recovery period.

BL increases to between 3 and 7 $\text{mmol}\cdot\text{l}^{-1}$ during climbing and remains elevated through 30 min of passive recovery. Active recovery may increase the removal rate of lactate; however elevations are still evident during 10–20 min of recovery. These elevations in BL are sometimes, though not always, correlated with decreased handgrip forces. The impact of climbing-induced elevation in BL upon subsequent climbing performance has not been studied.

Sustained climbing, to the point of falling, impacts muscular endurance to a relatively greater degree than muscular strength. The fatigue experienced in the forearm musculature appears to have an origin within the muscle contractile elements.

Activation of the anterior forearm musculature has been observed as constant during contact with holds and can involve greater muscle fiber recruitment than that observed during maximal handgrip dynamometry. It is likely that maintaining contact with a hold or feature in climbing requires less of a “squeezing”, or concentric, force with the fingers than a force applied eccentrically to resist changes in finger positions. The hand and fingers must maintain a critical configuration against forces that result from the effect of gravity and the body’s position as these forces tend to open the specific grip position. Existing data support the suggestion that isometric strength and endurance against an eccentric force may be of great importance in climbing.

Implications for specific training

Although a significant literature base is developing relative to the physiological aspects of rock climbing, there remains a need for much work. The athlete profile is perhaps best defined at this point, although questions remain. No published work has attempted to test the effectiveness of specific training strategies for high-level

climbers. A model for specific training remains hypothetical. Currently available texts and resources on training for climbing are based primarily on traditional systems for developing muscular strength and endurance. A few generalizations, however, may be made. Figure 6 presents a summary of training components for optimizing rock-climbing performance. Traditional models are available for training in each component; however, adaptations in workout designs must be made to ensure specificity to climbing. Although outside the scope of this review, it should be noted that overuse-type injuries are common in rock climbing at the higher difficulty levels, so any specific training plan should involve a periodized schedule, and appropriate stress management.

Future questions

There is a wealth of opportunity for future climbing research. The oxygen uptake kinetics during climbing are not well defined. The question of whether a climber attains a $\dot{V}O_2$ steady-state or encroaches on a climbing-specific $\dot{V}O_{2max}$ remains unclear. If climbers actually attain a maximum aerobic power during climbing, then further development of the aerobic system could enhance performance.

BL has been observed to increase with climbing, yet the impact on subsequent performance is unknown. Study in this area would assist in the development of specific interval training guidelines for climbing and in the structure of recovery between climbing-specific workouts.

Identification of minimum strength levels for specific muscle groups is needed; how strong is strong in climbing? It is possible that efforts to increase strength past a point of associated benefits to climbing performance could encourage increased overuse injury. From a carryover perspective, data suggest that the traditional tool of handgrip dynamometry lacks specificity with rock climbing; thus, other assessment methodologies

that are repeatable and easy to administer need to be explored. Of particular interest would be a simple methodology for quantifying isometric endurance specific to rock climbing.

Some recent work has begun to investigate muscle activation patterns during climbing. More information in this area, and from additional muscle groups, is needed. The impact of increasing strength via hypertrophic versus neural adaptations needs study in regards to climbing. Hypertrophic adaptations lead to increases in mass, which, in turn, have potential to limit performance.

The published research base in climbing appears void of any controlled investigations of training designs. While concepts may be legitimately learned via anecdote and trial-and-error, development and testing of specific exercises and workout designs is important.

Most reported studies have involved adult male subjects. Many studies could be repeated, and new studies carried out, with experienced female rock climbers. In addition, many, if not most, of the best climbers of the past decade have been relatively young. In North America, competitive junior-level climbers (19 years of age and younger) far outnumber older competition climbers. Few studies have focused specifically on younger competitive climbers.

The physical components that contribute to success in difficult climbing may also change as the predominant nature of climbing changes. Although no survey has been documented, it appears that throughout the 1980s the most difficult routes, on both natural rock and artificial walls, involved very technical movements on small holds over vertical terrain whereas, in the past decade, there has been a trend towards more severe overhangs. Climbing presents diverse challenges which place different demands on the physiological support for performance. The optimal athlete profile may vary as the nature of the terrain varies.

Finally, it should be remembered that overall climbing performance is influenced by many components, as suggested by the model of Goddard and Neumann (1993). No study has attempted to quantify or rank the relative contributions of these proposed components to a given climbing performance or to climbing in general. Whether the relative contribution of physiological factors increases or decreases at the upper end of the difficulty range is not known. It may be that certain minimum levels of a given physiological factor are required for success at the elite level, at which point other factors, physiological or non-physiological, become better discriminators of performance.

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Proposed Training Program Design

- Develop general aerobic power (increase and maintain VO_{2max} at 50-60 ml·kg⁻¹·min⁻¹).
- Develop specific strength via hypertrophic and neural adaptation strategies (specific resistance training and “plyometric” training).
- Develop rhythmic isometric endurance.
- Increase specific phosphagen (ATP-PC) system capacity via short intense interval training.
- Increase lactate tolerance via longer intervals with active recovery between repetitions.
- Develop and maintain range of motion through static and dynamic stretching.

Fig. 6 General physical training components for rock climbing performance

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