

Historical Development of a Physiological Model for Rock Climbing Performance

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Luc Schöffl bouldering in Oberngrub, Frankenjura, Germany,
Photo Michael Simon

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4.1 Background

Successful performance in rock climbing is physically demanding and involves the integration of many factors associated with production of the work required to ascend over specific terrain. Recreational climbers may find success through maintenance of a high level of general physical fitness however, performance at the highest levels likely requires physiological adaptations likened to that of high-performance athletes. This chapter will explore the more notable physiological aspects of high-level rock climbing. The objective is to provide a brief historical overview of the development of a theoretical physiological model for high-level climbing performance. The chapter is not intended as a comprehensive review of research to date. For a more complete exploration, the reader is referred to the published reviews of Watts [1] and Saul et al. [2].

Figure 4.1 presents a simplified conceptual diagram for development of a model for athletic-level performance via integration of measured characteristics of the performer and the specific stress demands of the activity performed. This model provides a basis upon which associated research results may be evaluated and integrated. In order to follow and apply this model-building concept for rock climbing, an objective measure of climber performance is necessary.

Description of the performance levels of participants in research studies has typically been

relative to the most difficult rock route a participant could currently ascend without falling, referred to as red point (RP) ability. Attempts to describe climber performance ability have also used adjectives such as “expert” and “elite.” However, these have been inconsistently applied.

Historically, climbers by nature tended toward a degree of competitiveness both internally with the self and externally with other climbers or the rock terrain. The expression of climber ability relative to a subjective rating of terrain difficulty naturally evolved. The first difficulty rating system for rock climbing was developed in the late 1800s and was a precursor to the *Union Internationale des Associations d’Alpinisme* (UIAA) scale established in the 1940s. Other localized numerical systems were developed in intervening years. The Yosemite Decimal System (YDS) for rating the difficulty of specific climbing routes appeared in the 1950s and became widely used in North America, while other systems developed in the United Kingdom, France, and other regions of the world.

Since no common difficulty scale is used worldwide and the existing scales are subjective and perhaps in constant evolution, there has been a need for a standard to use for scientific research. To provide a degree of standardization, a numerical and adjective scale for climber ability was developed by Draper et al. [3] of the International Rock Climbing Research Association (IRCRA). The IRCRA ability grouping scale is open ended and currently

Fig. 4.1 Concept for development of a theoretical physiological model for optimal performance of a physically demanding task

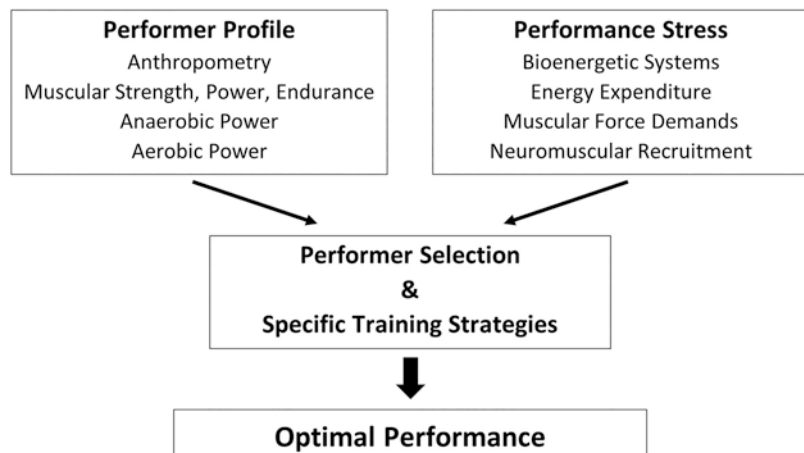


Table 4.1 IRCRA group level and scale grades compared with the Yosemite Decimal System (YDS) and French system grades. Adapted from Draper, N, D Giles, V Schoffl, F Fuss, PB Watts, et al. Comparative grading scales, statistical analyses, climber descriptors and ability grouping: International Rock Climbing Research Association position statement. Sports Tech. 2016. <https://doi.org/10.1080/19346182.2015.1107081>

IRCRA performance group level		IRCRA scale	YDS	French
Level 2 male	Level 2 female	10	5.10a	5+
		11	5.10b	6a
		12	5.10c	6a+
		13	5.10d	6b
		14	5.11a	6b+
	Level 3 female	15	5.11b	6c
		16	5.11c	6c+
		17	5.11d	7a
		18	5.12a	7a+
Level 3 male		19	5.12b	7b
		20	5.12c	7b+
		21	5.12d	7c
	Level 4 female	22	5.13a	7c+
		23	5.13b	8a
		24	5.13c	8a+
Level 4 male		25	5.13d	8b
		26	5.14a	8b+
		27	5.14b	8c
Level 5 male	Level 5 female	28	5.14c	8c+
		29	5.14d	9a
		30	5.15a	9a+
		31	5.15b	9b
		32	5.15c	9b+
		33 ^a	5.15d	9c

^aGrade currently reported as of this publication but not included in the original published IRCRA table

extends from 1 (level I ability) to 33 (level 5 ability). Grade comparisons for IRCRA “intermediate” through “higher elite” levels relative to the YDS and French rating systems are presented in Table 4.1. In this chapter, all climber ability levels and route difficulty ratings will be expressed relative to the IRCRA scale.

Early researchers were challenged by the environment and movement nature of rock climbing and by instrumentation limitations for data acquisition. More recent research has benefitted from newer measurement technology; however, the changing nature of climbing, as more difficult natural terrain is discovered and attempted, presents challenges. The increasing interest in competition climbing on artificial structures and specializations into lead, bouldering, and speed events also affects the likely physiological determinants of high-level performance. The models

upon which climber attributes, climbing stress and physical training strategies are based remain, for the most part, theoretical.

A look at how the “world’s best” performance has evolved from 1960 to more recent years is available in Fig. 4.2. The fourth-order polynomial trendline indicates a relatively steady increase in ability relative to RP ascents with a possible plateau tendency since 2010. Although the trendline indicates a plateau or, at best, only slow progression of absolute route difficulty in recent years, the number of climbers who perform at the highest level has increased. For example, in 2014, only six ascents of IRCRA level 31 were made, while in 2018, there were 21 new RP first ascents at the IRCRA level 30 or higher, and 81 different climbers had performed RP ascents at level 30 or higher [4]. The relative distribution of climber abilities within a wider range for a given year is not known.

Fig. 4.2 Plot of world's most difficult route ascent by year, 1960–2017

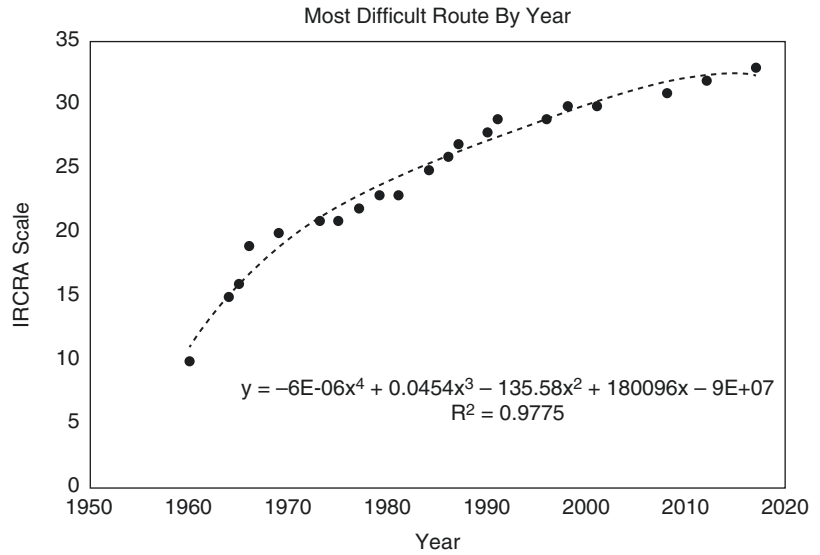
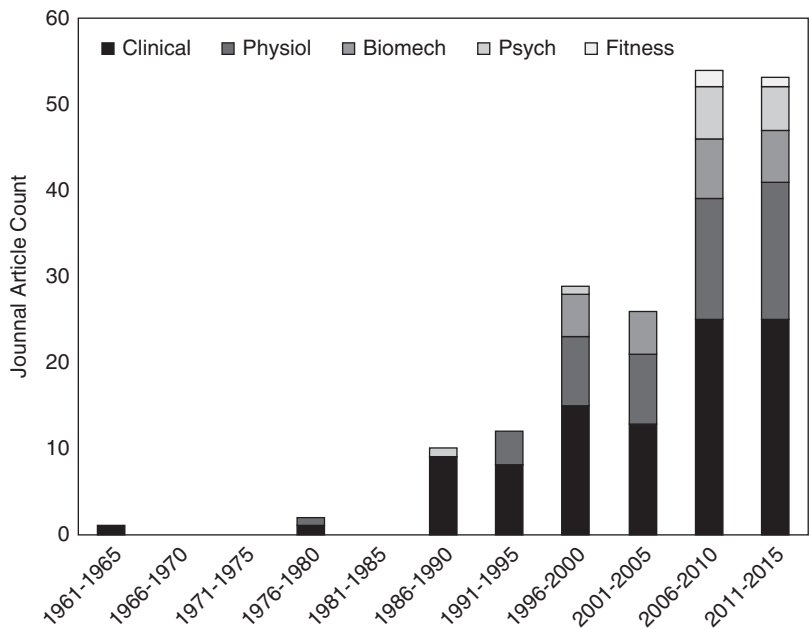


Fig. 4.3 Published research 1960–2019 via PubMed search on “rock climbing” and “rock climbers”



4.2 Physiological Study of Climbers and Climbing

Early scientific research on rock climbing was focused on the general nature of the activity and the physical aspects of climbing along with various injuries suffered by climbers. In the latter 1980s, as competition rock climbing grew in popularity, research models traditionally used for

the study of athletes were applied to climbing and climbers. The specific areas of performance physiology, biomechanics, and sport psychology have evidenced increased climbing research to date. A simple online search of the USA's National Library of Medicine site (<https://pubmed.ncbi.nlm.nih.gov/>) with the terms “rock climbing” and “rock climbers” reveals the topical trends illustrated in Fig. 4.3. A PubMed search in

Table 4.2 Selected anthropometric measures reported for high-level rock climbers

Reference	Subject characteristics	Height (cm)	Mass (kg)	%fat
Males:				
Watts et al. [5]	7 males IRCRA 26 ^a	179.3 ± 5.2	62.4 ± 4.5	4.8 ± 2.3 ^b
Watts et al. [16]	11 males IRCRA 23	175.6 ± 8.9	65.9 ± 8.6	5.4 ± 1.5 ^b
España-Romero et al. [12]	10 males IRCRA 20	172.0 ± 4.0	65.5 ± 4.5	7.6 ± 2.1 ^b 13.3 ± 3.3 ^c
Ozimek et al. [20]	6 males IRCRA 25–27	177.4 ± 5.6	66.9 ± 5.8	7.9 ± 4.8 ^b
Females:				
Watts et al. [5]	6 females IRCRA 23	162.3 ± 4.6	46.8 ± 4.9	9.6 ± 1.9 ^b
España-Romero et al. [12]	9 females IRCRA 15	162.0 ± 3.0	59.2 ± 3.6	18.0 ± 3.6 ^b 25.2 ± 3.6 ^b
Giles et al. [7]	14 females IRCRA 19.5	163.4 ± 4.7	56.5 ± 6.3	23.3 ± 4.8 ^b

^aIRCRA scale are means unless otherwise indicated

^bEstimated via skinfold measures

^cEstimated via DXA

July of 2020 found 255 studies published through 2019. Of the 255 papers, 71, or 28%, focused on physiological aspects of performance.

4.2.1 Anthropometry and Body Composition

The nature of climbing involves the work of moving the body along a relatively specific route against the negative force generated by the effect of gravity on body mass. Additionally, the force requirements for support and movement during climbing are often primarily imposed on the relatively small musculature of the upper body, in particular the muscles in control of positioning of the hands and fingers.

Anthropometry and body composition have long been of interest since body weight is a major factor for the work demand in climbing. In general, a low body mass reduces the work of climbing and reduces specific force requirements of the musculature. There is a compromise involved, however, since one positive factor of strength is muscle mass which, in turn, adds to the overall work of climbing.

Assessment of relative fat mass, expressed as percent body fat, is of particular interest, since fat mass can be a negative factor as it increases the work of climbing without directly contributing to support and movement. A summary of anthropometry results from selected research studies is presented in Table 4.2.

Watts et al. [5] published the first anthropometric study of competitive male and female sport rock climbers in 1993. Data were recorded at a 1989 international competition with 21 of 29 male and 18 of 21 female semifinalists participating. Seven of the ten male finalists and all six female finalists participated. Climbers were found to be small in stature and low in body mass with low sum of skinfold measures and estimated body fat percentage. Stature, body mass, and percent body fat averaged 179.3 ± 5.2 and 162.3 ± 4.6 cm, 62.4 ± 4.5 and 46.8 ± 4.9 kg, and 4.8 ± 2.3% and 9.6 ± 1.9% for male and female finalists, respectively. The body fat measures would be considered very low and, for both males and females, were at or below estimated essential body fat levels.

More recently, España-Romero et al. (2009) [6] reported similar height and weight means for male and female climbers of IRCRA level 3; however, percent fat means were higher when estimated via skinfold measures or via dual-energy X-ray absorptiometry (DXA). Giles et al. [7] also reported higher percent fat values when calculated from skinfold measures in 14 female climbers than the earlier study of Watts et al. [5].

Although the more recent studies have indicated higher percent fat values in some elite climbers, the best climbers still tend to be relatively small in stature with low body mass. Aside from the early study of Watts et al. [5], research has, for the most part, studied climber samples

that were convenient to the geographical location of the research. This consideration may contribute to the differences between historical and more recent data. In addition, a variety of measurement methodologies and estimation procedures have been employed. The degrees to which these factors may have influenced the specific results are not known.

Other anthropometric characteristics, such as finger length, arm length and the ratio of arm span to height, or “ape index,” have been of interest but have not consistently shown relationships with climbing ability ratings [8].

4.2.2 Bioenergetic Power

Bioenergetics involves the conversion of stored chemical energy into the mechanical energy of performing work. Generally, three primary bioenergetic systems may be described. A phosphagen-based system involves stored adenosine triphosphate (ATP) and creatine phosphate (PCr), which can provide energy rapidly, without the involvement of oxygen, for fast powerful muscle contractions. This phosphagen or ATP-PCr system is relatively limited in capacity, however, and may be nearly depleted within a few seconds, typically 5–8 s of total-body intense effort. The ATP-PCr system is limited primarily by the level of PCr stored within the muscle. Depleted PCr is restored relatively quickly between muscular contractions if blood circulation and oxygen delivery are adequate.

A carbohydrate-fueled metabolic system may also convert stored chemical energy quickly though more slowly than the phosphagen system. This system is usually termed glycolysis when the substrate is glucose and glycogenolysis when the initial substrate is stored muscle glycogen. When the rate of energy conversion is high in this pathway, the addition of oxygen is not required, and the process is considered to proceed anaerobically but with a consequent accumulation of lactate in the muscle and blood. This accumulation of lactate and a resulting dissociation of hydrogen ion (H^+) have been associated with fatigue. With the presence of oxygen, lactate may be removed as an aerobic substrate or, with adequate blood flow, shuttled to other, less active, muscle for metabolic removal. Collectively, whether the substrate is glycogen, glucose, or both, this system is typically termed anaerobic or fast glycolysis.

When the rate of energy conversion is slower and adequate blood flow and oxygen are available to the muscle, the glycolytic process may proceed through a number of additional steps aerobically, without lactate accumulation. This aerobic oxidative metabolic system may also utilize fats and protein substrates and help spare the limited stores of carbohydrate within the muscle.

Table 4.3 provides a summary of the three bioenergetic systems. Along with the rate of energy expenditure demand, a climber’s ability to take in, circulate, and utilize oxygen during a performance generally controls which bioenergetic system is primarily involved.

Table 4.3 Summary of bioenergetic system support of muscular work in climbing

Bioenergetic system	Substrate	Oxygen requirement	Power (energy/time)	Capacity (total energy available)
Phosphagen	ATP & PCr	None	Highest	Limited by muscle PCr stores. Typically enables 5–8 sec of maximal total-body exertion
Anaerobic (fast) glycolysis	Glycogen and glucose	None	High	Moderate capacity limited primarily by unbuffered H^+ ions dissociated from lactic acid. Requires adequate blood flow and oxygen for recovery
Oxidative	Glycogen, glucose, fatty acids, proteins	Required	Moderate	High capacity limited by substrate availability

Assessment of the power output capability of the aerobic, or oxidative, bioenergetic system is accomplished by measuring a climber's maximum ability to uptake and utilize oxygen (VO_2max). Since an individual's VO_2max can differ among different activities and with the degree of active muscle mass, the highest VO_2 attained during a specific activity mode, such as climbing, is usually referred to as a peak oxygen uptake or VO_2pk .

Studies have reported VO_2pk values for rock climbers of $54.8 \pm 5.0 \text{ mL kg}^{-1} \text{ min}^{-1}$ [9] and $55.2 \pm 3.6 \text{ mL kg}^{-1} \text{ min}^{-1}$ [10] for treadmill running. Billat et al. [9] reported a VO_2pk of $22.3 \pm 2.6 \text{ mL kg}^{-1} \text{ min}^{-1}$ for an arm pulling test, and Booth et al. [11] described a mean of $43.8 \pm 2.2 \text{ mL kg}^{-1} \text{ min}^{-1}$ during fast climbing in seven highly skilled climbers. España-Romero et al. [12] utilized a special climbing treadmill (treadwall) to observe climbing specific VO_2 peaks of 53.6 ± 3.7 and 49.2 ± 3.5 in male and female climbers, respectively, during fast climbing.

The VO_2pk levels observed in climbers would be considered "excellent" for general aerobic fitness but are well below the typical levels of 70–90 $\text{mL kg}^{-1} \text{ min}^{-1}$ observed in elite aerobic athletes such as distance runners and cross-country skiers. The lower values for climbers likely reflect a smaller intensely activated muscle mass during the work of climbing compared with the more total-body involvement of other endurance-type competitive activities.

Regardless of the lower total-body VO_2pk for climbers, the specific aerobic power and capacity of localized muscle groups have been found to be high. Fryer et al. [13] estimated an oxidative capacity index for forearm musculature in climbers through near-infrared spectroscopy (NIRS). This oxidative capacity index and maximal hemoglobin-myoglobin desaturation and VO_2pk during treadwall climbing were significant predictors of climbing ability and explained over 67% of the variance in RP climbing ability.

In addition to describing the maximal and peak bioenergetic characteristics of climbers, early research began to observe physiological responses and demands of actual performance

during climbing. Billat et al. [9] and Mermier et al. [14] used Douglas bags to collect expired air for VO_2 analysis during route climbing. Watts and Drobish [10] employed a nonmotorized climbing treadmill (Brewer's Ledge Treadwall®) to record the first continuous VO_2 measurements during climbing at different angles. These studies found the average climbing VO_2 to range between 24 and 32 $\text{mL kg}^{-1} \text{ min}^{-1}$ regardless of terrain angle.

As portable expired air analysis systems became available in the 1990s, researchers began to observe physiological responses continuously during actual climbing on indoor artificial walls and outdoors on real rock. Watts et al. [15] found average and peak VO_2 of 24.7 ± 4.3 and $31.9 \pm 5.3 \text{ mL kg}^{-1} \text{ min}^{-1}$, respectively, during ascents of a competition style indoor route rated IRCRA 19. Booth et al. [11] recorded a mean VO_2 of $32.8 \text{ mL kg}^{-1} \text{ min}^{-1}$ during ascents of an outdoor route. In a more recent study, España-Romero et al. [6] recorded peak VO_2 levels of $36.9 \pm 4.9 \text{ mL kg}^{-1} \text{ min}^{-1}$ during on-sight ascents of a moderate grade indoor route rated as 10 on the IRCRA scale.

In studies involving route ascents, VO_2 tends to plateau after 1.5–2.0 min of climbing, which suggests a steady-state condition is attained. A general integration of results from studies that assessed VO_2pk during maximal testing and those that measured VO_2 during typical route climbing tasks indicates the stress of actual climbing likely requires approximately 70% of VO_2pk , which would be compatible with a steady-state primarily aerobic condition.

The idea of a steady-state condition during route ascents has been challenged by results that indicated significantly elevated post-climbing VO_2 [15] and elevated blood lactate concentration [9, 15, 16]. Although blood lactate is elevated with climbing, post-ascent levels have been relatively low with observed means of 3.2–7.0 mmol L^{-1} . Furthermore, Watts et al. [15] found pre-climb values of $3.5 \pm 1.9 \text{ mmol L}^{-1}$ in climbers who felt "warmed-up" and ready to climb a competition style route.

Bertuzzi et al. [17] have attempted to rate the relative contributions of the three bioenergetic

systems for energy expenditure during routes of different difficulty levels. By their estimation, the contributions of the ATP-PC phosphagen, anaerobic glycolytic, and aerobic oxidative systems for elite climbers were $35.8 \pm 6.7\%$, $22.3 \pm 7.2\%$, and $41.9 \pm 7.4\%$ for easy (IRCRA 10), moderate (IRCRA 15), and difficult (IRCRA 19) routes, respectively. Although climbing demands the full range of bioenergetic support, the phosphagen and aerobic systems appear to be dominant.

4.2.3 Muscular Strength, Endurance, and Power

Factors of muscular performance have intuitively been of interest to climbers. These factors may be categorized into strength, the ability of muscle to generate high force; endurance, the ability of muscle to perform repeated contractions or to sustain a contraction level over time; and power, the level of force production relative to time and/or velocity of movement.

Force production by muscle is a function of the activation of motor units within a muscle. A motor unit consists of a specific neuron and the number of muscle fibers it activates. The number of motor units within a given muscle and the number of fibers within a motor unit vary across different muscles and for different individuals and are considered to be primarily determined by genetic factors. Conversely, the size of muscle fibers within a motor unit can be increased through specific training.

Relative to climbing, muscle contractions may be categorized as isotonic, where the muscle changes length either concentrically, by shortening, or eccentrically, by lengthening under load, or as isometric where muscle length remains static during force production.

Dynamic muscular force is expressed by a force-velocity relationship. On a fiber basis, the absolute contraction force declines with increasing velocity of contraction. The highest velocity of muscle fiber contraction is typically generated at 30–40% of the fiber's peak force capability, and the highest force is produced at zero velocity

during isometric or static contraction. Since establishing and maintaining contact with a specific hold in climbing is primarily a static task, isometric strength of the muscle controlling the fingers of climbers was of early interest.

The most obvious target for descriptive strength research with elite climbers has been isometric handgrip force, typically measured with a grip dynamometer, Fig. 4.4a. Watts et al. [10, 16] found absolute handgrip scores to be rather “average” in elite climbers; however, when handgrip strength was expressed as strength–body mass ratio, males placed at the 80th percentile and females placed at the 90th percentile for age and gender matched North American population norms. This finding of a high strength–mass ratio for accomplished climbers has been consistent across other studies as well.

In the 1990s, researchers began to question the specificity of handgrip dynamometry for measuring finger and hand strength in climbers. Simple observation of the hand-to-rock contact interface in climbing revealed minimal use of finger-thumb opposition during ascents of the steep edging routes popular at the time. In response to the potential limitation of handgrip dynamometry, Grant et al. [18] and Watts and Jensen [19] were among the first to construct strain gauge or force sensor devices to enable measurement of finger-curl force without thumb opposition, Fig. 4.4b, though these researchers did not measure values in elite-level climbers.

During actual pull-type movements in climbing, the finger-curl force required to maintain contact with holds is less likely to be of a concentric nature as an eccentric nature as the fingers work to resist extension. Ozimek et al. [20] measured finger force from a more eccentric contraction perspective as the total force, body weight plus added weight, a climber could support while hanging from the fingers on a 2.5 cm edge. Much higher force, 1266.3 ± 147.2 N in this study, may be generated during such hangs than during standard concentric format dynamometry.

A summary of selected research relative to hand and finger force measures is presented in Table 4.4.

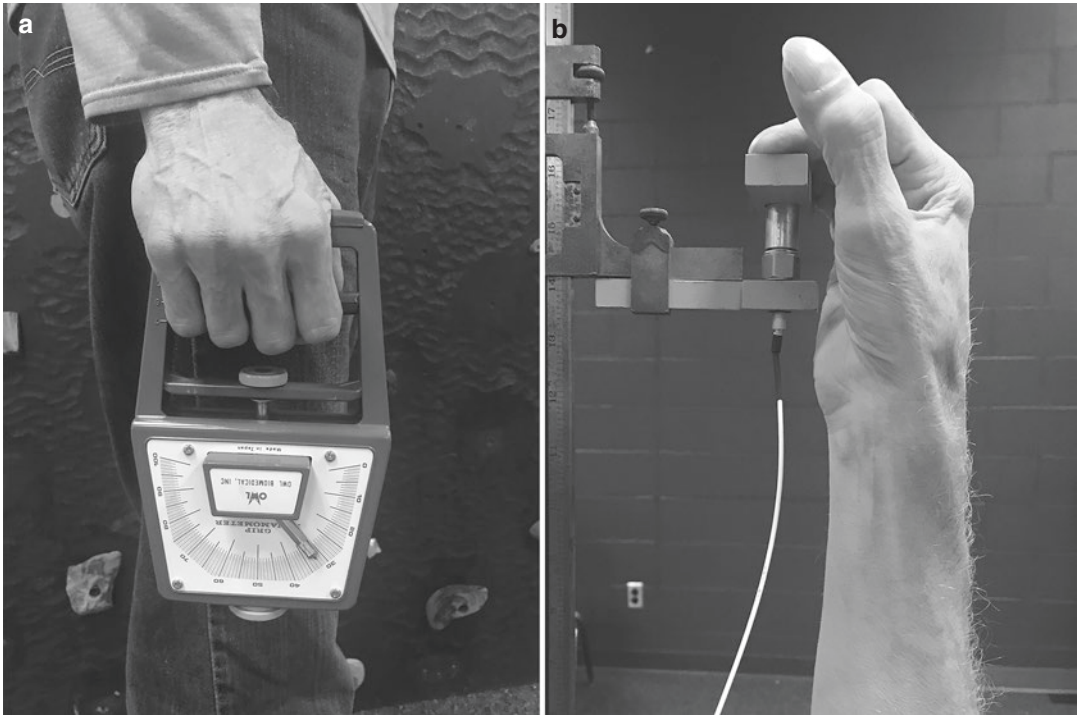


Fig. 4.4 Historical methods of measuring “grip” strength in climbers. (a) standard handgrip dynamometer and (b) plate and force sensor to measure finger curl force without opposition of the thumb

Table 4.4 Selected measures of hand and finger strength reported for high-level rock climbers

Reference	Subject characteristics	Measurement technique	Strength (N)	Strength–mass ratio
Males:				
Watts et al. [5]	7 males IRCRA 26 (mean RP ^a)	Handgrip dynamometry	477.7 ± 89.3	0.78 ± 0.13
Watts et al. [16]	11 males IRCRA 23 (mean RP)	Handgrip dynamometry	581.6 ± 69.6	Not reported
Watts et al. [15]	15 males IRCRA 20–27 (range)	Handgrip dynamometry	507.2 ± 73.6	0.77 ± 0.07
Levernier and Laffaye [26]	14 males IRCRA 25 (≥)	“Power grip” sensor—slope crimp position	476.6 ± 74.4 521.6 ± 36.2	0.72 ± 0.05 0.83 ± 0.05
Ozimek et al. [20]	6 males IRCRA 25–27 (range)	Weighted hang on 2.5 cm edge	1266.3 ± 147.2	1.93 ± 0.20
Females:				
Watts et al. [5]	6 females IRCRA 23 (mean RP)	Handgrip dynamometry	297.2 ± 30.4	0.65 ± 0.04
Giles et al. [7]	14 females IRCRA 19.5 (mean RP)	Finger force on 20 mm edge	408.4 ± 62.3	Not reported

^aRP is redpoint ascent

The high strength values in climbers may also be significant due to the relationship of strength to submaximal muscular contraction endurance. As specific maximum voluntary contraction force increases, a given absolute contraction force will be at a lower percentage of the new maximum voluntary contraction force, and an increase in endurance measures would be expected. The noted cardiovascular factors previously discussed would also contribute to increased muscular endurance, particularly for repeated contractions.

Most research has assessed muscular endurance as isometric contraction holding time at a given submaximal percentage of maximum force or as the time to maintain repeated timed contractions at a given percentage of maximum force. Limited early studies consistently found hand and upper body muscular endurance to be higher in accomplished climbers than recreational climbers or non-climbers [18, 21].

Watts et al. [16] found handgrip endurance to be impacted greater than handgrip strength with climbing to the point of failure. This group studied grip strength and endurance before and after climbers performed continuous climbing on difficult terrain, rated 18 on the IRCRA scale, to the point of a fall. In this study, maximum voluntary contraction (MVC) force decreased by 22% and holding time at 70% of the pre-climb MVC force decreased by 57%.

Ferguson and Brown [22] found experienced climbers to have double the endurance time for 40% maximum handgrip during rhythmic maximum contractions than sedentary non-climbers. Furthermore, a significantly enhanced forearm vasodilator capacity was found in the climbers in this study, which would enhance the ability to recover between contractions via aerobic metabolism.

Muscular power has also been of interest, and most assessments in climbers have looked at high velocity explosive power with body weight load during dynamic moves. Laffaye et al. [23] used accelerometers to assess upper body power in boulderers and lead climbers during an explosive pull and release vertical dynamic move off large “jug” holds. Relative power, in Watts per kilogram

body mass, was 28.4 ± 7.55 and 23.4 ± 3.7 W/kg in boulderers and lead climbers, respectively.

Giles et al. [7] have recently described muscular power characteristics in high-level female climbers. This group measured lower body power via a counter movement vertical jump test and upper body power via a power slap test, a type of explosive pull-up movement to a one-hand slap of a high point. The mean power slap score was significantly higher for an elite group ($n = 14$, ability = IRCRA 19.5 ± 3.1) than for an advanced lower ability group ($n = 13$, ability = IRCRA 15.9 ± 1.4). Lower body power was not significantly different between the ability groups.

4.3 Prediction of Climber Performance Via Physiological Characteristics

Often, research on rock climbers has associated various anthropometric and physiological measures with self-reported RP climbing ability of the research participants. Significant predictors of performance have been described; however, many studies have involved participants of a wide range of abilities. General physical fitness characteristics can be very predictive within groups with a range of abilities from novice to expert. As the ability range becomes more homogeneous, such as with a group of elite level climbers, the physiological predictors of performance likely become more narrow and specific. This phenomenon has been observed for other athlete groups. In a classic study of marathon runners, Sjödin and Svedenhag [24] found VO_2max to significantly correlate with marathon race pace with a correlation of $r = 0.78$ in 75 runners with marathon paces between 3.0 and 5.4 m/s (42 km race times of 4:00 and 2:16 h:min); however, the correlation was reduced to a nonsignificant $r = 0.01$ for fast runners with paces between 4.7 and 5.4 m/s (race times between 2:30 and 2:16).

In the study of elite competition climbers of Watts et al. [5], stepwise regression analysis was employed with stature, body mass, stature to mass ratio, sum of seven skinfolds, estimated body fat percentage, grip strength, strength to

mass ratio, and arm volume as independent variables and self-reported red point ability as the dependent variable. Ability in 39 climbers with an ability range of approximately IRCRA 21–27 was significantly predictable with strength to mass ratio and percent body fat accounting for 33% of the variance in ability.

Baláš et al. [25] studied 205 sport climbers, 136 males and 69 females, within an ability range of IRCRA 5–29, with an array of anthropometric and strength measures along with experience and training volume. Across this broad ability range, grip strength to weight ratio and hand/arm endurance along with estimated percent body fat were good predictors of performance.

Mermier et al. [14] published the first attempt at associating climber characteristics with actual measured climbing performance. Forty-four climbers attempted two artificial routes as on-sight top-roped climbing. Handhold contacts, or *moves*, on each route progressively increased in difficulty and maintenance of contact with successive handholds scored points. Together, the routes involved 63 *moves* up to IRCRA 22 level. A principal components analysis reduced the large number of measured variables to three components: training, anthropometry, and flexibility. Subsequent regression analysis found 39% of performance variance to be explained by the trainable factors, 15% by anthropometry, and 10% by flexibility. This study also involved climbers of a broad range of abilities, IRCRA 6–24, and did not look at a more homogeneous sample at an elite ability level.

In a more recent study, MacKinzie et al. [8] assessed 47 variable scores for 44 males (IRCRA 9–23) and 33 females (IRCRA 9–20). Test areas included were anthropometry; balance; muscular strength, endurance, and power; aerobic power (as running VO_2max and arm-cranking VO_2peak); and hand-eye and foot-eye spatial coordination. For this broad range of climbing ability levels, shoulder power and endurance assessed as maximum pull-ups, arm-crank power, and timed bent-arm hang were the best predictors of performance.

Based on the integration schematic of Fig. 4.1, Watts [1] (2004) proposed an initial performance

model for difficult climbing performance with the following components:

- Small stature and high strength–mass ratio. This would be especially important for strength of the musculature that controls hand and finger positions. A low body fat percentage may also contribute to strength–mass ratio, although extreme reductions in body fat can have negative consequences for health.
- High level of isometric muscle contraction endurance, particularly for repeated contractions in the musculature that controls hand and finger positions.
- Moderately high total-body aerobic power ($\text{VO}_2\text{max} \approx 50\text{--}55 \text{ mL kg}^{-1} \text{ min}^{-1}$ for males).

Subsequent research has suggested additional components for the model:

- High capacity of phosphagen, ATP and PCr, energy yield.
- High vasodilator capacity and high oxidative power and capacity of the forearm musculature.
- High upper body explosive power.

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