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Determinants for success in climbing: A systematic review

Dominik Saul [a,*], Gino Steinmetz [b], Wolfgang Lehmann [a], Arndt F. Schilling [a]

[a] *Clinic of Trauma, Orthopaedics and Reconstructive Surgery, Georg-August-University of Goettingen, Goettingen, Germany*
[b] *Department of Psychosomatic Medicine and Psychotherapy, Georg-August-University of Goettingen, Goettingen, Germany*

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ABSTRACT

Background: The number of athletes engaged in climbing sports has risen. Specific physical and psychological skills are required. The objective of this review was to determine factors for high climbing performance. We evaluated physiological, biomechanical and psychological characteristics that simplify the ascent. We also assessed training and recovery strategies.
Methods: Medline (Pubmed), Cochrane Library and Google scholar up to September 2018.
Results: A low skinfold thickness, body fat and large forearm volume were anthropometric traits in successful climbers. Well-trained forearm flexors with high aerobic capacities lead to an efficient style. Hand grip strength and endurance, postural stability and optimized kinematic motions were favourable. Elite climbers had long finger and bent-arm hang times. Psychologically, an “iceberg profile” was typical. Constant training with fingerboard and dynamic eccentric-concentric training helped to push the “red-point grade”.
Conclusion: Hand, forearm strength and endurance are highly important elements in elite climbers. An efficient climbing style with perpetual focus and accuracy, high speed and low exhaustion due to adaption to repeated isometric exercise is helpful in the ascent, while low body fat and a large bone-to-tip pulp make it easier. Constant training is essential, e.g. eccentric-concentric training of finger flexors, which should be followed by active recovery.

Introduction

With increasing popularity over the last few decades, rock climbing as a competitive as well as recreational sport has gained broad awareness.[3] Its evolution began in the 19th century in northern England and Italy, predominantly with alpine mountaineering, and continued until the 1950s when the general public began to increase their interest in climbing as a sport. The climbing without use of any aids was born in the beginning of the 20th century in the Elbe Sandstone Area.[4] Nowadays, climbing is on the rise and the number of gyms grows constantly.[5] With 1000 people trying to climb for the first time every single day in the U.S., 25 million people are climbing regularly worldwide according to the International Federation of Sport Climbing (IFSC).[6] To underline the importance of this particular athletic challenge, sport climbing will make its Olympic debut at Tokyo 2020, where speed climbing, bouldering and lead climbing will be featured.[7] The climbing sport consists of the following different subunits: ice climbing, mountaineering, traditional climbing, sport climbing and bouldering, which in turn can be subdivided further.[8]

All of these climbing subcategories demand distinct physical and psychological conditions. While ice climbing requires specialized motor coordination with perceptual attunement and, hence, requires long-term experience,[9–11] bouldering is thought to be based on essential strength, muscle endurance and low body fat percentage.[12–14] Much research has been conducted to learn which parameters distinguish the elite from the recreational climbers in all these diverse subcategories. While Fryer et al. focused on hemodynamic and cardiorespiratory predictors in only rock climbers,[15] Giles et al. illuminated physiological and psychological factors in this cohort.[16] Sheel reviewed aerobic and anaerobic pathways and their impact on climbing performance in rock climbers but constituted the importance of additional research on how “specific climbing training impacts climbing performance”.[17]

* Corresponding author.Robert-Koch-Straße 40, 37075, Goettingen, Germany.
E-mail addresses: Dominik.Saul@med.uni-goettingen.de (D. Saul), Gino.Steinmetz@med.uni-goettingen.de (G. Steinmetz), Wolfgang.Lehmann@med.uni-goettingen.de (W. Lehmann), Arndt.Schilling@med.uni-goettingen.de (A.F. Schilling).

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Definitions

Beta	Advice on how to complete a climbing route, boulder problem or sequence
Dead hang	Arms overhead, grabbing the bar with both hands
Flash	No previous practice, but a beta and clean ascent on the first attempt
Jerk coefficient	Third time derivative of a position or the rate of change of acceleration.[1]
Lead climbing	Climbing with a belay rope that is clipped into quickdraws attached to the wall (that may be placed or are preplaced)
On-sight	No previous practice or beta of the route and clean ascent on the first attempt
Red-point	Defined as lead climbing a route without using or weighting the gear or rope (with or without clipping pre-placed draws)
Smoothness factor	Body weight divided by the mean of the absolute difference (in N) between the y-force-time graph and a parabolic curve of the same impulse.[2]
Top-rope	Climbing with a placed rope from the top; no placement of quickdraws is necessary

Referring to the latter and since these reviews do only include research on rock climbing, we sought to broaden the view on other climbing-associated activities like ice climbing, bouldering and indoor climbing. With this review, we aimed to find further specific training-associated as well as universal specifications that are necessary for climbers to be successful upon all of these climbing sport subcategories.

Methods

Grading system

To allow comparisons of the results between studies, different grading systems for graduating the routes have been suggested, out of which the French/Sport system (1-9c) and Union Internationale des Associations D'Alpinisme (UIAA) system (I-XII) are most commonly used.[18–20]

The different grading systems not only differentiate between countries but also between different styles of climbing, for example, bouldering and lead climbing (Fontainebleau and French systems). The Yosemite Decimal System (YDS) is used in the USA, and the French/Sport Scale is primarily used in mainland Europe. There is also the British technical grading scale, which is mainly referred to throughout the UK. The grading system by the UIAA is widely used in central Europe.

Generally, the grading in climbing is always subjective, i.e., the first climber to ascend a route suggests a grade. After grading, the subsequent climbers who ascend the route are able to voice an opinion, which makes the definition of route difficulty partially dynamic. Comparability between climbing scales is difficult. A major issue with the different climbing scales is that the commonly used climbing scales are often subdivided by letters or -/+ grades, which makes statistical analyses challenging. To overcome this heterogeneity, Draper et al. demonstrated that grouping by self-reported climbing grades shows an accurate and valid reflection of current climbing ability[21] and proposed a comparative grading scale aimed to match the different grading systems with a single number.[20] This was then incorporated into the International Rock Climbing Research Association (IRCRA) position statement as seen in Table 1[20] which transforms grading systems into the numerical benchmarks that allow statistical comparisons between international studies.

Search strategy

Medline, Cochrane and Google Scholar databases were searched for primary manuscripts and reviews. The following keywords were used: “performance”, “achievement”, “factors”, “recovery”, the Boolean operator “AND” combined with “climbing” or “bouldering”, and additionally “NOT” linked with “animals”. Abstracts from the earliest available record though September 2018 were considered, and reference lists of primary manuscripts and reviews were manually evaluated to retain additional relevant studies. The algorithm is demonstrated in Fig. 1.

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement and checklist were used to guide this review.[22]

Eligibility criteria

This study followed the participants, interventions, comparisons, outcomes, and study design (PICOS) framework.[23]

Population

The population of interest was climbing athletes and comparable sportsmen.

Intervention (exposure)

The exposure was climbing itself in both the study group and control groups.

Comparison

Comparators are mentioned throughout the review, i.e., finger grip strength and BMI.

Outcome

The outcome parameters were the ability to climb certain routes, to climb longer, or increase muscle force.

Study design

All studies with the exception of narrative syntheses, case studies or studies not available in the English language were eligible.

Inclusion criteria

From 1203 results and after screening all headings, 353 abstracts remained, out of which 102 primary manuscripts and 6 reviews were included.

Exclusion criteria

Excluded were manuscripts that did not have the availability of full text or articles concerning animal climbing. Biomechanical studies without human participants were also excluded.

Table 1
Different climbing scales and their comparability according to Draper et al.

Climbing Ability Group		IRCRA	Font.	Vermin	YDS	French/Sport	UIAA
Lower Grade (Level 1)		1			5.1	1	I
Male & Female		2			5.2	2	II
		3			5.3	2+	III
		4			5.4	3-	III+
							III+
		5			5.5	3	IV
		6			5.6	3+	IV+
		7			5.7	4	V-
		8			5.8	4+	V
		9	<2	VB	5.9	5	V+
							VI-
Intermediate (Level 2)	Intermediate (Level 2)	10			5.10a	5+	VI
Male	Female	11	3	V0-	5.10b	6a	VI+
		12	4	V0	5.10c	6a+	VII-
		13	4+	V0+	5.10d	6b	
		14	5	V1	5.11a	6b+	VII
	Advanced (Level 3)	15	5+		5.11b	6c	
	Female		6A	V2			
		16			5.11c	6c+	VIII-
			6A+				
		17	6B	V3	5.11d	7a	VIII
Advanced (Level 3)		18	6B+	V4	5.12a	7a+	VIII+
Male		19	6C	V5	5.12b	7b	
		20	6C+	V6	5.12c	7b+	IX-
	Elite (Level 4)	21	7A+	V7	5.12d	7c	IX
	Female	22			5.13a	7c+	IX+
		23	7B	V8	5.13b	8a	
Elite (Level 4)		24	7B+	V9	5.13c	8a+	X-
Male		25	7C		5.13d	8b	X
				V10			
		26	7C+		5.14a	8b+	X+
			8A	V11			
	Higher Elite (Level 5)	27	8A+	V12	5.14b	8c	XI-
Higher Elite (Level 5)	Female	28			5.14c	8c+	XI
Male		29	8B	V13	5.14d	9a	
		30	8B+	V14	5.15a	9a+	XI+
		31	8C	V15	5.15b	9b	XII-
		32	8C+	V16	5.15c	9b+	XII
		33			5.15d	9c	

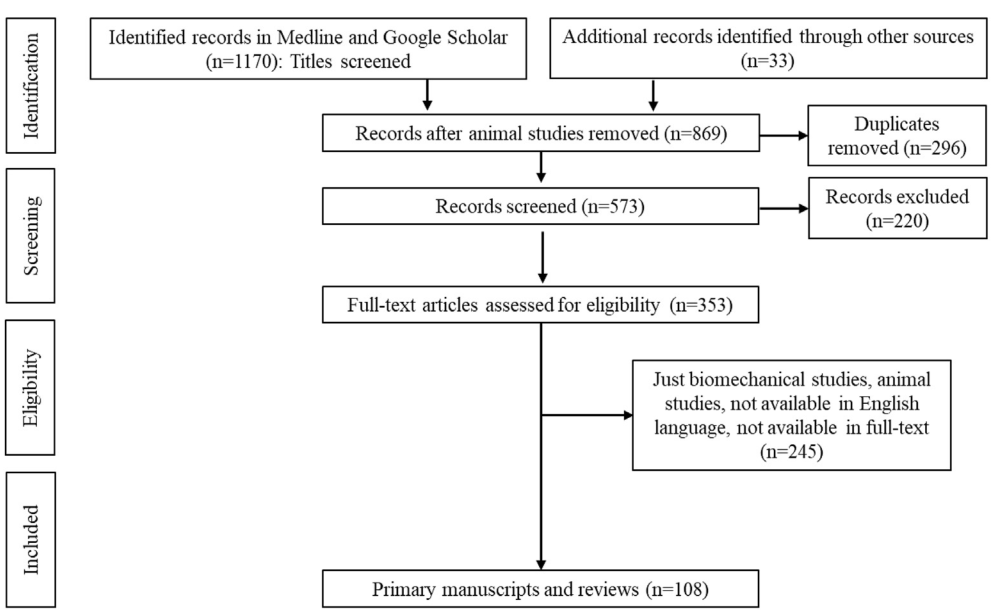

Fig. 1. PRISMA flow chart of data extraction from the literature search.

Results

Physiological requirements

Muscle

Physiological criteria for successful climbing are sometimes difficult to differentiate from biomechanical parameters because both of them are closely intertwined. Notwithstanding, we extracted 32 prospective studies consisting of 882 climbers (age 25.56 ± 4.77 years; BMI 21.84 ± 0.79 kg/m^2; years of climbing experience 7.68 ± 3.35 years). The forearm flexors have a key role in the performance of climbers. In rock climbers, the oxidative capacity index of the flexor digitorum profundus (measured with near-infrared spectroscopy) was associated with a red-point grade.[24] The maximum finger and (concentric) wrist flexor contraction, strength-to-weight-ratio and overall hand strength were significantly greater in climbers compared to that in non-climbers; re-oxygenation was faster in the former and mostly important for use in overhanging terrain.[25–27] The measurement of grip strength (using a hand dynamometer) of the right hand differs between elite and recreational climbers, while greater differences in finger strength, especially at the tip, were noted among elite climbers, recreational climbers and non-climbers.[28–34] Next to pure force, being able to sustain climbing over a long period of time constitutes a good climber, which is why endurance measured as finger and bent-arm hang times was closely linked to performance.[29]

Forearm muscles can be analysed from a more biochemical point of view. Oxygen consumption itself could be measured (VO_2) and showed higher values for harder climbing routes, accompanied by an increase in heart rate and minute ventilation (VE) in recreational and elite climbers. Longer exercise caused increased blood lactate levels, which were lower in experienced climbers compared to that of novice climbers, indicating a better/faster recovery.[35–38] A possible reason for the increase in lactate could be the repeated isometric contraction of the forearm muscles since decrease in handgrip strength could be correlated to increased blood lactate levels.[39] These forearm muscles showed higher conductance in climbers compared to sedentary subjects, which in turn led to a two-fold higher time to fatigue in climbers compared to non-climbers. This better response to sustained isometric exercise, which is essential for the successful climber, could be rooted in the enhanced forearm vasodilatory capacity and thus favour hyperaemia among the contraction phases.[36,40,41] Underlying these facts, what differs in elite vs. expert climbers is the longer time until exhaustion.[31,42] The aerobic system and anaerobic alactic system are the main energy systems utilized in indoor climbing, and climbing economy seems to be a much more important factor.[43] Notably, self -selected speed was the best compromise between the need to reduce the time spent in isometric work and the need to avoid early muscle fatigue due to increased speed and frequency of muscle contraction.[44] Maximum voluntary contraction (MVC) in climbers was significantly higher, and the recovery of forearm oxygenation during rest phases could predict endurance performance.[45,46] These phenomena depict the following key premises for the climber on longer routes: Repetitive forearm muscle training helps recovery in isometric movements. This training leads to a reduction in the fractional utilization of oxygen uptake (VO_2) and the peak uptake in climbers. Moreover, this training leads to stronger and more efficient finger flexor muscles, and reaches 70% of max VO_2, while novice climbers reached activity levels of more than 70% max VO_2 in easy traverse and vertical tasks.[38] This demonstrates the capability of sustaining a longer effort with a steady force,[47] which makes the endurance of expert climbers (and average changes in blood pressure) comparable to rowers.[48]

Heart rate and work

Heart rate responses and rating of perceived exertion (RPE) differ between beginner and recreational climbers, probably through variations in climbing technique, efficiency and anxiety.[49] Intriguingly, anxiety appeared to be a bigger stressor in climbing sports than in other physical activities because neither adrenaline nor noradrenaline concentrations differed before and after climbing.[50] Overhanging routes represent a unique challenge. Interestingly, handgrip force was negatively correlated with increasing angle and blood lactate levels. The blood lactate level was higher when wall angle increased. A maximum steepness of 80°–102° was considered to be a “very heavy” work challenge.[51] In accordance, routes with an upward displacement caused the highest peaks in average heart rate and EMG amplitudes, while vertical displacement was physiologically most demanding.[52,53]

Physique

While body weight is negatively correlated to the red-point level, only weak (negative) correlations between height and climbing level could be found.[27,54] Whether body mass index (BMI) is associated with performance is difficult to determine; nonetheless, a lower BMI was not significantly associated with a higher UIAA level[55] (Table 2). The overall skinfold thickness and body fat percentage were less in elite vs. recreational climbers.[43,56] An important predictor of success was the strength (hand grip dynamometer) to body mass ratio (SMR), which could predict climbing ability and, next to skinfold thickness, was astonishingly similar in both sexes.[54] Another interesting physiological aspect is fingertip soft tissue. The tissue dimensions were assessed in elite climbers, where for shallow edges (2.9 mm), a large bone-to-tip pulp tended

Table 2
Accumulated factors in three different climbing cohorts show tendencies towards middle-aged climbers and light and experienced climbers with low body fat and skinfold thickness in the elite climbers.

	Control		Recreational climbers		Elite (French 7c or 8a + or above)		n
	mean	SD	mean	SD	mean	SD	
Age (years)	24.43	4.81	27.73[a]	4.44	25.64	4.53	2244
BMI (kg/m^2)	22.67	1.36	21.79	2.15	21.66	1.30	1610
Years climbing	/	/	6.09	3.21	9.45[b]	4.97	2096
Body fat (%, Jackson Pollock)	16.14	4.77	14.57	5.14	12.01	5.53	912
Sum of 7 skinfolds	57.70	26.87	45.29	25.82	44.13	6.42	271
Arm length	68.63	6.21	71.80	4.69	69.65	5.20	110
Arm span	/	/	173.20	4.68	176.30	4.07	91

[a] Differs from control.
[b] Differs from recreational.

to generate a higher lifting force.[57] The forearm volume as an indirect parameter of muscle mass could also differentiate expert from control groups.[58] Furthermore, climbers seemed to have narrow shoulders relative to the hips. Whether a high ratio of arm span to height ("ape index") is helpful for climbing could not be definitively determined because there were divergent results, but a tendency towards beneficial effects can be stated.[16,56,59,60]

Considering all manuscripts collectively, seven factors were identified that were mainly assessed in sport climbers (Table 2). Age was significantly higher in recreational climbers, while BMI was lower in athletes who could perform for long periods of time. On average, elite climbers were two years younger compared to recreational climbers and had three additional years of climbing experience, which suggests that elite climbers start this sport 5 years earlier than recreational climbers. Body fat and skinfold thickness were lowest in elite climbers but did not lead to significant differences, while arm length and span were not measured regularly.

Biomechanical requirements

Biomechanics as an "analysis of human movement" has outstanding relevance for climbers since the whole sport is about optimizing movements to ascend.[61] We enrolled 41 studies with a total number of 403 participants (mean age: 25.29 ± 4.23 years, BMI: 22.41 ± 0.52 kg/m^2, climbing experience: 6.19 ± 2.75 years). The studies dealt with the biomechanical aspects of climbing athletes.

Hand grip

When it comes to the basic tool in climbing sports, much research has been conducted on the hand. Generally, throughout the research on climbers, different forms of grip (e.g., "pinch") are described, which we depict in Fig. 2. The whole hand grip (independent from handedness) and pinch strength were higher in climbers compared to that in non-climbers. Climbers also showed greater endurance in the non-dominant hand and in pinch grip endurance.[62] The maximal vertical force increased with the hold depth, and climbers had better posture strategies with slope and crimp techniques especially in antero-posterior forces and shorter movement time for more difficult postures, perhaps due to the anticipation of disequilibrium.[63,64] These posture strategies were accompanied by a variability in grasping behaviour and limb angles, which result from learning processes. Additionally, learning could occur via observing other climbers directly or could even partially be obtained by viewing videotapes.[65–67]

Coordination

A constant part of climbing routes is a pull-up, which consists of two phases as follows: Pullups, where integrated electromyography (IEMG) showed the highest values in the flexor digitorum superficialis and brachioradialis (and not M. biceps brachii); and lowering, where the flexor digitorum again was highly activated. M. brachioradialis and M. biceps brachii showed abrupt peaks on

Fig. 2. Different grips on specific handholds. Hand position can be described as "open", "half" or "full", while multiple fingers (front: Dig. II and III; back: Dig. III and IV) or single fingers ("mono") can be involved. Special grip forms are the "pinch" and "sloper".

electromyography during both lifting and lowering, which suggests that the flexor digitorum does not contribute to elbow flexion.[68]

Regarding muscle groups, the muscles of the shoulder and forearm are of the greatest importance, antagonists and stabilize group muscles are especially important to prevent injuries. Comparing the quadrupedal and tripedal state, the quadrupedal state was characterized by involvement of the arms to prevent a fall. Here, horizontal forces are less important, and equilibrium is easier to maintain than in the vertical position.[69] The difficulty of gripping a hold thereby can be reflected by vertical and horizontal forces, which decreased with surface inclination of hold.[70] The tripedal state was characterized by less extensive contralateral supporting force transfer on the remaining holds, which reinforces safety; however, when removing a hold, vertical and horizontal forces applied to the left hand and left foot increased significantly.[33,71]

Postural control

Maintaining the position and body tension is needed to relieve the hands and prepare the next step in longer routes. Three important domains that help prevent climbers from falling are postural stability, accuracy and force. Postural stability even seemed to outweigh accuracy constraints in rock climbers, since accuracy requirements did not increase in the duration of the transport phase.[72] It was shown that posture leads to changes in the vertical forces applied on the remaining holds after release of a limb, except on the right-foot hold. The position with the trunk close to the wall and low contact forces at the holds was most favourable. Expert climbers can maintain the position longer with larger centre-of-mass distances from the wall during both static and dynamic moves.[58,73,74]

After dynamic moves, experienced athletes showed a shorter duration for pelvis vertical displacement at a plateau, indicating a lower fluency in beginners.[9] Another expert characteristic was systematic higher centre-of-mass oscillations with an alternating dynamic redistribution of body weight between the limbs in a double support phase (both feet fixed); furthermore, experts were able to allocate more vertical force from one remaining limb than controls while pushing upwards.[58] For a high accuracy, continuous attention was required. Attention requirements were significantly higher for two-reach conditions (the right hand to reach a hold, followed by a left-hand reach) compared to that for one-reach conditions (just the right hand necessary to reach one hold). Movement duration and velocity time profiles for reaching were not affected by accuracy requirements but were shortened by increased postural difficulty, indicating a hierarchical process of postural and precision constraints.[72,75] Elite climbers make use of a wider range of upper and lower limb moves, resulting in little exploratory moves and zeroed joint torques at the end of a motion. Pertaining to total joint torques generated, they were minimized in the inexperienced climbing style.[10,74,76] Vertical and horizontal force changes were synchronously initiated at one hold before the release of one leg, preparing the postural change for voluntary movement and counteracting the perturbations in this moment.[77] In the horizontal condition, the diagonal pattern is dominated by mechanical and anthropometric factors.[78] While the horizontal momentum was influenced by the conditions before the onset of the movement and was involved in control of the equilibrium, the vertical momentum was only influenced by the amplitude of the movement after its onset and contributes to the movement initiation.[79,80] Before movement initiation, advanced climbers spent more time in an isometric position and greater time shaking out and actively resting the arms.[81] The Hausdorff dimension can be used to measure amplitude, length, impulse, frequency and chaoticness of a signal; it increased with the difficulty of a hold. Weaker climbers produced larger normalized Hausdorff dimensions; the more experienced a climber was, the smaller the force applied to the hold, the shorter the contact time, the larger the coefficient of friction, and the smaller the Hausdorff dimension of the force-time signal compared to that of inexperienced climbers.[82–85]

Taken together, elite climbers rest longer in an isometric position to recover their arms. After that, they need a shorter time to contact the next hold with a higher friction. In experienced climbers, kinematic motions corresponded better to the muscle fibres (close to their optimum length) used for climbing operations than in inexperienced climbers, which resulted in a minimization of muscle fatigue.[13,74] These motions require fast motor units, which seemed to have higher electromyograms from 60 to 100% of their maximal voluntary contraction.[86] The kinematic motions could be measured with the jerk coefficient (as a third time derivative of position or the rate of change of acceleration) as a valid indicator of the smoothness of the trajectory during multijoint limb motion that can depict a complexity of route finding, which decreases with practice.[1,87,88] Kinematics change in speed climbing, where contact time on a handhold shortens with more experience.[89]

Jumps

More speed is reached when climbing incorporates jumping. In successful leaps, the vertical take-off velocity was higher than what was required, while for the jump, the feet produced 1.8 times the force of the hands.[90]

In unsuccessful jumps, injuries could occur, which more often arise from affection or overuse of the flexor tendon pulleys. The greatest "bowstringing" effect is caused by the flexor digitorum profundus tendon in the crimp grip position and over the A2 pulley. Longer holds need more force than one tendon can provide, which can be explained by the quadriga effect (a connection between the flexor digitorum profundus muscles), which seems to be especially important in the slope grip and crimp grip positions. A comparison of both positions showed that the maximum force of the isolated slope grip was 20% higher than that of the isolated crimp position.[91–94] To improve the hold, chalking hands is common within climbing halls, but the beneficial effect has been questioned by Li et al. because the friction coefficient was decreased by magnesium carbonate.[95] Kilgas et al. confirmed no beneficial effect of chalking on friction, but chalking contributed to longer hold times of the climbers.[96] On chalked surfaces, dry hands could deliver a better hold, but on clean surfaces, powder chalk provided better friction than a dry hand or liquid chalk.[2,97] Intriguingly, the experience of climbing could increase the ratio of friction to normal force close to the point of impending slippage.[97]

Psychology

Since success in climbing depends on a combination of strength of both the body and mind, some psychological traits of the athletes help them to climb unimpeded, while others hamper the ascent. We compared 17 studies dealing with the psychological determinants of success in climbing, consisting of 648 athletes (age 26.71 ± 6.16 years; BMI 18.70 ± 3.96 kg/m^2; years climbing 4.08 ± 3.10 years), out of which 16 studies had a prospective design.

The "climber's personality" itself was comparable to the personality of athletes in other sports. Rock climbers in general were described as being high in vigour and mental endurance and low in tension, depression, anger, confusion and mood disturbance. They were introverted and motivated to achieve success. This kind of personality was initially described as the “iceberg profile” by Morgan et al.[41,98,99] Taking great risks was not a common issue for climbers. Predominantly male climbers with high self-efficiency took calculated additional risks, but only when they felt confident in their abilities.[100–102]

Anxiety could be an obstacle affecting the ascent. Somatic anxiety is not just an issue in casual climbers, but likewise has an impact on the elite athlete. Sanchez et al. and Hardy and Hutchinson reported that somatic anxiety was higher in successful climbers compared to that in unsuccessful climbers, which in turn correlated with higher levels of effort.[103,104] Comparing the same route in athletes with high versus low levels of anxiety, it was demonstrated that as anxiety increases, movements in general increased, while novices showed higher heart rates and blood lactate levels on the higher route.[105–107] This phenomenon was underlined by the fact that as climbers recall “fear words” (like “death”, “failure” or “crisis”), their climbing efficiency and distance decreased.[108] It seems that tension and anxiety are constant companions for the climber independent of the level of skill.

Psychologically preparing a route can be helpful, and it seems to be essential that the “route preview” involves the recalling of clusters of information, which mainly consist of functional (not structural) aspects of the wall. These aspects require motor competence to recall and perform on a route.[109–111] Via eye tracking, it was demonstrated that the “sequence of blocks” strategy to plan a route (2–4 handholds per block) was the most effective way to adapt to a difficult route.[112] Focus is crucial. When athletes needed to both memorize and climb, their performance (number of holds) suffered while their climbing distance did not.[113] For the former, a cognitive-motor potential for interaction is necessary, which in turn is directly influenced by the observer's experience and expertise.[114] This is why elite climbers seemed to be more focused than their inexperienced counterparts, which was demonstrated by fewer errors in complex reaction tests.[41]

As it was shown in various different sports, experience is a major factor of success. Greater self-confidence and lower heart rate prior to the ascent led to a greater possibility of reaching the top.[115–118]

Training effects

In every sport, repetition of routines helps to gain experience. Thus, time spent in training was shown to have the greatest impact on climbing performance, even more so than anthropometric parameters and flexibility.[60] In 7 prospective studies (athletes: 189; age 27.32 ± 6.12 years; BMI 21.78 ± 0.89 km/m^2; years of climbing experience 6.58 ± 4.44 years), we found that with a protocol of four training sessions (1 h, separated by 2 days of rest), the number of falls, duration of the ascent, as well as the jerk coefficient were reduced.[119] After eight weeks, more moves and harder climbing due to muscular hypertrophy and muscular endurance were assessed.[120] Specially designed “high resistance-few repetitions training” or “low resistance-high repetitions training” did not result in a beneficial effect compared to regular training sessions.[121] A favourable impact of four weeks of fingerboard training (3 times per week for 150 min) compared to boulder sessions could be demonstrated regarding grip strength and dead hang time.[14] Next to this static strength training, dynamic eccentric-concentric training of the finger flexors improved the maximal achievable grade of climbing in a time-dependent manner, especially for on-sight and boulder styles.[122,123] Generally, with indoor rock climbing, cardiorespiratory fitness and muscular endurance could be enhanced.[124]

A reduction in climbing-related injuries may be achieved via training for the brachioradialis and flexor digitorum muscles, which showed high activation during typical climbing moves.[68] Training reduced the contact time, mean force, maximal force and impulse, while the mean and maximal friction and the smoothness factor increased.[2,125]

Recovery

Especially when frequently performing climbing sports or when planning long and time-intensive climbing routes, recovery strategies may be beneficial and help to improve performance. We enrolled 5 studies that addressed recovery (athletes: 73; age 30.22 ± 6.30 years; BMI 21.28 ± 1.09 kg/m^2; years climbing 7.70 ± 8.0 years). Passive recovery (performing a 9-s passive test, “shaking out” or grasping a handgrip vibration machine) did not affect climbing performance.[34] Active recovery (pedal on a cycle ergometer at a constant workload) and water immersion preserved performance during exhausting climbing trials and difficult sport climbing and removed more lactate than electromyostimulation and passive recovery.[126,127] Moving great muscle mass (e.g., walking) seemed to be inferior to climbing an easy 12-m route (4c french) for recovery.[128] These methods stretched their limits as handgrip strength and endurance remained depressed after 20 min of resting recovery, but strength seemed to recover faster than endurance.[39]

Conclusion

In biomechanical studies, the characteristic parameters of elite climbers were great whole-hand grip strength and endurance, postural stability with high centre-of-mass oscillations, anticipatory postural adjustments with a small Hausdorff dimension, optimized kinematic motions with a low jerk coefficient, higher-than-required jumping velocity and chalky hands on clean surfaces. Physiologically, forearm flexors play an important role in climbing success; their strength-to-weight radio, aerobic and vasodilatory capacity, re-oxygenation, conductance and thus endurance were significantly higher in elite vs. recreational climbers. Their oxygen uptake reached a maximum of 70% of their VO_2 peak, indicating an efficient climbing style. Furthermore, long finger and bent-arm hang times were typical in elite climbers. The anthropometric data indicated that the “optimal” climber had low skinfold thickness and body fat, large bone-to-tip pulp and great forearm volume. A “climber's personality” is characterized by the “iceberg profile”. Anxiety is quite common among climbers and preparing a route in mind via “sequence of blocks” next to a steady focus during the rise can improve performance. The best way to succeed in climbing is constant training, while fingerboard training and dynamic eccentric-concentric training helps to push the “redpoint grade”. For recovery, active recovery (cycle ergometer, easy routes) is superior to passive recovery. Even though not all cragsmen will reach an elite level, considering the abovementioned factors can help every climber reach their “personal Everest”.

Limitations

This review summarizes the literature on factors associated with climbing performance. The great variability in study populations, methods and climbing subcategories impedes comparability between the different approaches. Only a small number of available research is prospective, blinded and randomized which does not allow to pool results for statistical analysis of bigger numbers than the presented.

Future research

Upcoming studies should distinctly segregate between the different climbing subcategories. The biomechanical and -physiological differences between male and female climbing styles should be examined in large-scaled prospective, randomized, controlled studies. Comprehensive research on training and recovery strategies should help to assess strategies for the different climbing groups to improve their skills in the long term and avoid injuries.

Contributors

DS and GS concepted the work and wrote the initial draft, AFS and WL revisited and edited it. All authors approved the final manuscript.

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Data sharing

Original data is available on personal request from the corresponding author.

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Appendix A. Supplementary data

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