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Human Kinetics
ORIGINAL INVESTIGATION

Physical and Physiological Determinants of Rock Climbing

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Purpose: Rock climbing performance relies on many characteristics. Herein, the authors identified the physical and physiological determinants of peak performance in rock climbing across the range from lower grade to elite. ***Methods:*** Forty four male and 33 female climbers with onsight maximal climbing grades 5a–8a and 5a–7b+, respectively, were tested for physical, physiological, and psychological characteristics (independent variables) that were correlated and modeled by multiple regression and principal component analysis to identify the determinants of rock climbing ability. ***Results:*** In males, 23 of 47 variables correlated with climbing ability ($P < .05$, Pearson correlation coefficients .773–.340), including shoulder endurance, hand and finger strength, shoulder power endurance, hip flexibility, lower-arm grip strength, shoulder power, upper-arm strength, core-body endurance, upper-body aerobic endurance, hamstrings and lower-back flexibility, aerobic endurance, and open-hand finger strength. In females, 10 of 47 variables correlated with climbing ability ($P < .05$, Pearson correlation coefficients .742–.482): shoulder endurance and power, lower-arm grip strength, balance, aerobic endurance, and arm span. Principal component analysis and univariate multiple regression identified the main explanatory variables. In both sexes, shoulder power and endurance measured as maximum pull-ups, average arm crank power, and bent-arm hang, emerged as the main determinants ($P < .01$; adjusted $R^2 = .77$ in males and .62 in females). In males, finger pincer ($P = .07$) and grip strength also had trends ($P = .09$) toward significant effects. Finally, in test-of-principle training studies, they trained to increase main determinants 42% to 67%; this improved climbing ability 2 to 3 grades. ***Conclusions:*** Shoulder power and endurance majorly determines maximal climbing. Finger, hand, and arm strength, core-body endurance, aerobic endurance, flexibility, and balance are important secondary determinants.

Keywords: strength, endurance, power, flexibility, anthropometry

Climbing has gained in popularity standards, and Olympic recognition, but not the scientific attention that other sports have received. As a sport, climbing takes many forms. For recreational, competitive, and exercise training purposes, sport climbing has evolved as the widest reaching subdiscipline.[1] The safe and controlled environment of fixed protection (bolts or topropes) of sport climbing allows a full focus on athletic and gymnastic challenges,[2,3] and as such, it is characterized by sustained, repetitive, and complex bouts of intense upward motion that tax physical capacity in the upper limbs and upper and core body.[4,5] Growth of indoor facilities has further facilitated this trend.[1]

Thus, the current study is based upon the notion that the highest level of sport climbing ability and performance is at least partly determined by the limits of those characteristics. Accordingly, changes to those affect maximal climbing performance. Previous studies have identified many of those characteristics, such as upper-body and shoulder strength[6–8] including explosive power,[5,6,9] forearm grip and finger strength,[5,10–13] upper-body endurance capacity[10,14] and local muscle aerobic oxidative and postocclusion reoxygenation capacity,[12,15,16] as well as anthropometric characteristics and body composition and mass.[17,18] Other studies have, however, suggested forearm grip and finger strength,[7,17,19] anthropometric factors and body composition,[5,20] flexibility[20] and aerobic capacity, and maximal oxygen uptake (VO_2max)[21] may be less important. However, most of the above studies have assessed only a limited number of determinants; addressed cohorts with limited ability ranges, not always used sports-specific methodology, mostly excluded or underrepresented females, and rarely established the relative importance of individual characteristics compared with others. For instance, the 2 sexes may not share some or any characteristics.[11] Therefore, information on physical and physiological parameters that dictate progress in climbing remains incomplete, such that designing informed and evidence-based specific training programs for specific purposes and cohorts becomes difficult, to the degree that this unmet need hinders optimal progress in both recreational and professional athletes trying to reach their potential.

The aim of this study was, therefore, in a comprehensive testing regime in both sexes and across the complete and widest available spectrum of climbers from lower grade to elite standard and in a standardized and unbiased manner, to assess the physical and physiological factors that may dictate climbing performance, to thereby identify the relative importance of each factor for determining climbing ability and performance in sport climbing.

Methods

Subjects

Approximately 44 males and 33 females volunteered as subjects (Table 1). They were screened for maximal onsight (complete a climb on first attempt) rock climbing ability to balance number of subjects in each sport climbing grade; the French sport climbing grade scale was used and transformed to a linear scale to allow for statistical modeling (5a = 1, 5a+ = 2 . . .). This resulted in males: 3 to 4 subjects/grades 5a–7c and 1 for grades 7c+ and 8a; females: 3 to 4/grades 5a–7a, 2 for grades 7a+ and 7b, and 1 for grade 7b+.

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The institutional review board (University of Glasgow) approved the study, and it was performed in accordance with the Declaration of Helsinki. Subjects were health screened and signed informed consent forms prior to commencement. Exclusion criteria included regular smoking, medication, and preexisting medical conditions contraindicative to exercise testing. Subjects were asked to avoid exhaustive exercise and alcohol within 48 hours and food and fluids except water within 2 hours of each test, each separated by a week, and all subjects were familiarized with the equipment and protocols. The dominant limb was used for single-limb tests.[11,20]

Design

Observational cross-sectional and prospective research.

Methodology

Climbing ability was self-reported as the highest consistently completed indoor onsight grade and confirmed or assessed if unknown by a 12- to 15-m onsight test-climb during top-rope conditions (Glasgow Climbing Centre, Glasgow, United Kingdom), secured and belayed by certified climbing instructors. Self-reported and assessed grades were in agreement, as previously reported.[22] Immediately before the climb, subjects completed a Competitive State Anxiety Inventory-2 questionnaire,[23,24] to assess self-confidence and cognitive and somatic anxiety.

Body height and weight, leg and arm lengths, arm span, and finger and hand lengths, and resting blood pressure were measured, with body mass index and "ape index" (arm span/body height) calculated.[5,12,20]

Hip flexibility was measured by the foot-raise test, with the subject standing next to a wall with straight arms extended to 90° and palms flat on the wall and then lifting the right foot as high as possible,[11] and by a leg-span test by measuring the maximum achievable distance between feet.[11] Hamstring/lower-limb and lower-back flexibility was measured by a sit-and-reach box (HaB-direct, Southam, United Kingdom) test where the subject from a sitting position and straight legs reached forward as far as possible to hold for 3 seconds.[11]

Balance was measured by the subject standing on the balls (metatarsal) of one foot for as long as possible until failure.

Hand-eye spatial coordination was measured by the subject holding a card in front of them and marking a dot on the front. They then made 3 attempts to mark a dot on the back of the card as close to the original dot as possible, with the average distance between front and back dots recorded. Foot-eye spatial coordination was measured by the subject standing on one foot on a climbing wall, with the other foot hanging, a forward-pointing marker attached underneath, and a card placed 30 cm diagonally up. The subject marked a dot on the card and made 3 attempts to mark another dot as close to the original as possible, with the average distance from the target recorded.

Arm biceps (upper arm) and grip (lower arm), hand and finger pincer, and open-hand finger strength were measured during isometric maximal voluntary contractions (three 5-s efforts), whereby the highest maximum force was recorded (PrimusRS; BTE Technologies, Hanover, CO). During each test, the subject stood with the elbow at 90°, and was instructed to grip (arm grip test) and supine grip (biceps test) a gauge, pinch a plate between thumb and other digits (pincer test), and push down a plate with extended fingers (open-hand finger test). The dynamometer has been validated for similar purposes.[25]

Shoulder power and power endurance were recorded by lying in a supine position while turning the PrimusRS arm crank ergometer against isotonic resistance at 20% of maximum isometric force, for a 20-second maximum effort. The maximum isometric force, maximum and average power, and power decline as a measure of power endurance were recorded.

Measurements of climbing-specific upper-body, shoulder, and core-body endurance and power were made using a pull-up board (Beastmaker 1000; Beastmaker, Sheffield, United Kingdom).[11,17] A leg-raise hang-test recorded maximum hanging time with stretched legs lifted to 90° of the body, a bent-arm hang-test recorded the maximum time hanging from the pull-up board with elbows at 90°, and a maximum pull-up test recorded the maximum number of pull-ups from full arm extension to chin above board.

For aerobic capacity, an incremental exercise test measured VO_2max by an exhaustive ramp treadmill (PPS Med; Woodway, Weil am Rhein, Germany) test.[26] With the speed fixed at 8 km/h, the gradient increased by 2% every 2 minutes until volitional exhaustion. Similarly, peak oxygen uptake (VO_2peak) was measured during upper-body exercise using an arm crank ergometer (Top XT; Technogym, Bracknell, United Kingdom), with speed at 60 rpm and resistance increasing every minute.

Table 1 Subject Characteristics

	Male (n = 44)	Female (n = 33)
Age, y	25.7 (4.7)	29.2 (7.0)
Height, cm	175.8 (4.6)	164.0 (4.4)
Body weight, kg	67.5 (6.3)	61.2 (5.9)
BMI, kg/m^2	21.8 (1.9)	22.7 (1.8)
Ape index (arm span/height)	1.00 (0.03)	1.01 (0.02)
VO_2max, mL/kg/min	56.1 (4.7)	43.9 (6.3)
HR_{max}, bpm	196.2 (4.4)	192.8 (5.2)
BP, mm Hg	122/75 (8/5)	119/77 (6/4)
Climbing experience, y	8.5 (9.0)	7.5 (8.5)

Abbreviations: BMI, body mass index; BP, blood pressure systole/diastole; bpm, beats per minute; HR_{max}, maximal heart rate; mm Hg, millimeters of mercury; VO_2max, maximal oxygen uptake. Note: Subject characteristics at the inclusion of the study. Data are expressed as mean (SD).

Training Study

Finally, we recruited 6 male (27.3 [3.1] y, 173.2 [6.5] cm, 68.0 [3.2] kg; climbing grades 6a–6c) and 6 female (26.5 [2.6] y, 162.1 [3.7] cm, 63.1 [3.9] kg; climbing grades 5a–6b+) climbers: males trained maximum pull-ups (n = 3) and balance (n = 3), whereas females trained bent-arm hangs (n = 3) and leg-raise hangs (n = 3; the respective main determinants and variables that only insignificantly showed weak trends to correlate with climbing ability). Training was performed as 3 sets to failure with 4-minute breaks, 2/week for 4 weeks, with climbing training continuing at will. Pretests and posttests including climbing ability were measured as described above.

Statistics

Climbing ability was set as the dependent variable, whereas other variables were treated as independent. Pearson correlation coefficients assessed the relationships between the dependent and independent variables. Next, a principal component analysis (PCA), with components extracted by eigenvalue >1 (Kaiser criterion and Varimax rotation) and multiple univariate stepwise linear regression was constructed to model and attribute relative importance to each individual independent variable for determining the variability in the dependent variable (climbing ability); both forward and backward stepwise modes for elimination of insignificant variables were applied. Training effects were evaluated by the Wilcoxon signed-rank test. Throughout, significance was set at $P < .05$. Data were normally distributed (Shapiro–Wilk test of normality) and are expressed as mean (SD). Statistical analysis was computed by SPSS (version 24; IBM, Armonk, NY).

Results

Correlations Between Climbing Ability and Independent Variables

In males (climbing ability 5a–8a), 23 of the 47 (~50%) independent variables statistically significantly correlated with climbing ability (Table 2), with Pearson correlation coefficients .773–.340, while 5 variables showed trends toward statistical significance ($P = .05–.1$).

In females (climbing ability 5a–7b+), 10 of the 47 (~20%) independent variables statistically significantly correlated with climbing ability (Table 3), with Pearson correlation coefficients .742–.482, while 3 variables showed trends toward statistical significance ($P = .05–.1$). Thus, ~30% age points (~50% to ~20%) fewer parameters of physical and physiological capacity correlated with climbing ability in females versus males.

Upper-Body, Shoulder, and Core-Body Endurance and Power

Climbing ability showed the closest relationship to climbing-specific upper-body and shoulder endurance and power, measured by the maximum pull-ups and bent-arm hang-time, including after body weight normalization, as assessed by linear regression (Figures 1A–1D) and linear correlation (Tables 2 and 3).

In males, a close relationship between climbing ability and maximum pull-ups and bent-arm hang-time was followed by a close relationship between climbing ability and measurements of shoulder power, albeit with lower linear regression goodness-of-fit and Pearson correlation coefficients for both average and maximum power during a 20-second arm crank test (Figures 1E and 1G; Table 2). In females, by contrast, 20-second average arm crank power normalized for body weight showed only a trend toward significant correlation to climbing ability (Table 3), whereas linear regression showed a trend toward statistical significance between climbing ability and average 20-second power (Figure 1F inset; normalized for body weight: linear regression goodness-of-fit $r^2 = .106$, $P = .06$). Other measurements of shoulder power measured during the arm crank test did not show a significant relationship to climbing ability in females (Figure 1H; Table 3).

The ability to sustain power (arm crank 20-s power decline) did not show a significant relationship with climbing ability in either sex (Tables 2 and 3; linear regression not shown).

Core-body endurance measured as maximum leg-raise hang-time was also found to correlate significantly with climbing ability in males (Figure 1I; Table 2), but not females (Figure 1J; Table 3), though a trend toward statistical significance occurred, including after normalization to body weight (Figure 1J inset: linear regression goodness-of-fit $r^2 = .095$, $P = .08$).

Arm, Hand, and Finger Strength

In males, climbing ability showed a significant relationship with all measurements of arm, hand, and finger strength (Table 2): upper-arm biceps strength (Figure 2A), lower-arm grip strength (Figure 2C), hand and finger pincer strength (Figure 2E), and open-hand finger strength (Figure 2G), including after normalization to body weight (Figures 2A, 2C, 2E, 2G insets).

By contrast, females showed a weaker relationship between climbing ability and arm, hand, and finger strength (Table 3), and only lower-arm grip strength showed a significant relationship with climbing ability (Figure 2D), including after normalization to body weight (Figure 2D inset), However, upper-arm biceps strength showed a trend toward statistical significance to climbing ability (Figure 2B), including after normalization to body weight (Figure 2B inset: $P = .08$).

Aerobic Endurance

Aerobic endurance capacity in both upper and whole body (VO_2peak and VO_2max, respectively) showed a statistically significant relationship with climbing ability in both sexes (Tables 2 and 3; Figure 3).

Flexibility, Balance, and Coordination

In males, hip, hamstring/lower-limb, and lower-back flexibility showed a statistically significant relationship with climbing ability (Table 2; Figures 4A and 4C), whereas the foot-raise test; also a measure of hip flexibility did not correlate significantly with climbing ability (Table 2). By contrast, no measurements of flexibility showed a significant relationship with climbing ability in females (Table 3; Figure 4B and 4D).

Balance correlated significantly with climbing ability in females (Table 3), including a significant linear regression goodness-of-fit (Figure 4F), whereas in males, only a trend toward statistical significance occurred (Table 2; Figure 4E).

Neither hand–eye nor foot–eye spatial coordination showed a significant relationship to climbing ability in either sex (Tables 2 and 3).

Body Dimensions

Body weight, body mass index, or body height did not correlate significantly with climbing ability in either sex (Tables 2 and 3). However, body height showed a weak trend toward a significant linear regression in males (Figure 5C) and females (Figure 5D).

Arm span showed a weak, but insignificant trend toward correlation (Table 2), but a significant linear regression (Figure 5E) with climbing ability in males. In females, “ape index,” but not arm span showed a significant linear correlation (Table 3) and regression (Figure 5F) with climbing ability; however, it should be noted, the slope was negative and with a very small coefficient of the increment (−0.002843 [0.0009281]).

Measurements of arm, hand, finger, and leg lengths did not show significant relationships with climbing ability in either sex (Tables 2 and 3).

Anxiety and Self-Confidence During Climbing

Measurements of cognitive or somatic anxiety or self-confidence showed detrimental levels but did not discriminate between different levels of ability in either sex (Tables 2 and 3), though a weak trend toward a significant correlation between self-confidence and climbing ability occurred in males (Table 2).

Table 2 Correlations Between Climbing Ability Versus Independent Variables: Male Climbers

Variable *Climbing ability (5a–8a) vs:*	Range	Pearson correlation coefficient	Statistical significance, *P*
Pull-ups, n	5.0–27.0	.773	.000
Bent-arm hang, s	18.3–97.3	.731	.000
Bent-arm hang/weight, s/kg	0.3–1.4	.712	.000
Pull-ups/weight, n/kg	0.1–0.5	.707	.000
Pincer strength, N	93.6–253.3	.667	.000
Arm crank power$_{ave}$, W	142.8–350.2	.609	.000
Leg span, cm	123.9–182.4	.609	.000
Arm crank power$_{ave}$/weight, W/kg	1.9–5.0	.597	.000
Pincer strength/weight, N/kg	1.4–4.0	.593	.000
Grip strength, N	385.1–802.5	.582	.000
Leg span/height, cm/cm	0.7–1.0	.569	.000
Arm crank power$_{max}$, W	532.1–1265.5	.562	.000
Grip strength/weight, N/kg	5.6–12.6	.559	.000
Arm crank power$_{max}$/weight, W/kg	7.7–20.4	.556	.000
Biceps strength, N	186.9–398.7	.546	.000
Biceps strength/weight, N/kg	2.9–6.1	.488	.000
Leg-raise hang, s	9.94–58.8	.461	.001
VO_2peak, mL/kg/min	26.1–45.8	.458	.001
Leg-raise hang/weight, s/kg	0.13–0.91	.450	.001
Sit-and-reach, cm	4.0–43.0	.440	.002
Sit-and-reach/height, cm/cm	0.0–0.2	.419	.013
VO_2max, mL/kg/min	46.1–65.2	.383	.018
Open-hand finger strength, N	153.7–337.3	.340	.032
Arm span, cm	163.2–185.8	.291	.061
VO_2peak %VO_2max, %	49.5–80.5	.283	.063
Open-hand finger strength/weight, N/kg	2.1–4.8	.263	.089
Balance, s	12.7–283.4	.259	.094
Self-confidence, AU	15.0–36.0	.252	.098
Body height, cm	163.2–185.8	.243	.123
Arm length, cm	73.2–83.6	.239	.162
Little finger length, cm	5.5–6.8	.196	.222
Hand length, cm	17.6–20.3	.192	.223
Hand coordination, cm	0.4–1.2	.183	.267
Body weight, kg	58.3–87.3	.159	.304
Foot raise, cm	101.9–142.1	.148	.336
Ring finger length, cm	6.7–8.0	.103	.510
Cognitive anxiety, AU	9.0–28.0	.094	.558
Index finger length, cm	6.4–8.2	.073	.645
Middle finger length, cm	7.2–8.8	.072	.645
Foot raise/height, cm/cm	0.6–0.8	.066	.680
Arm crank power$_{\%decline}$, %	54.2–91.5	−.003	.981
VO_2max–VO_2peak, mL/kg/min	10.8–31.5	−.090	.664
Ape index, cm/cm	0.95–1.06	−.135	.487
BMI, kg/m^2	17.4–27.1	−.180	.352
Somatic anxiety, AU	9.0–28.0	−.191	.345
Leg length, cm	75.4–100.5	−.195	.344
Foot coordination, cm	0.2–1.3	−.133	.310

Abbreviations: AU, arbitrary unit; ape index, arm span/height; BMI, body mass index; VO_2max, maximal oxygen uptake; VO_2peak, peak oxygen uptake. Note: Correlation between independent variables and climbing ability (onsight French Sport climbing grade), ranked in order of correlation. Shades represents significance <0.05 (white), 0.05-0.1 (light gray) and >0.1 (dark gray).

Table 3 Correlations Between Climbing Ability Versus Independent Variables: Female Climbers

Variable *Climbing ability (5a–7b+) vs:*	Range	Pearson correlation coefficient	Statistical significance, *P*
Bent-arm hang, s	1.3–63.0	.742	.000
Pull-ups, n	0.0–20.0	.734	.000
Pull-ups/weight, n/kg	0.0–0.4	.720	.000
Bent-arm hang/weight, s/kg	0.0–1.1	.716	.000
Grip strength/weight, N/kg	4.1–8.4	.603	.000
Balance, s	10.2–188.0	.576	.000
Grip strength, N	238.7–520.1	.557	.000
VO_2max, mL/kg/min	26.6–57.3	.524	.002
VO_2peak, mL/kg/min	16.8–39.6	.515	.002
Ape index, cm/cm	0.97–1.04	.482	.004
Arm crank $power_{ave}$/weight, W/kg	1.3–3.4	.308	.081
Leg-raise hang, s	3.2–42.0	.306	.083
Leg-raise hang/weight, s/kg	0.04–0.68	.301	.084
Biceps strength/weight, N/kg	1.6–5.1	.288	.104
Arm crank $power_{ave}$, W	60.5–214.0	.284	.109
Biceps strength, N	86.4–271.1	.277	.118
Body height, cm	155.1–176.0	.275	.120
Foot raise, cm	88.0–191.5	.273	.124
Arm length, cm	47.5–62.4	.263	.139
Pincer strength, N	59.6–169.3	.253	.155
Cognitive anxiety, AU	10.0–30.0	.246	.167
Somatic anxiety, AU	10.0–28.0	.244	.168
Foot raise/height, cm/cm	0.6–1.1	.237	.184
Leg span, cm	123.0–186.5	.230	.198
Open-hand finger strength, N	83.4–285.1	.230	.197
Pincer strength/weight, N/kg	1.0–3.3	.224	.211
Sit-and-reach, cm	18.0–43.5	.206	.251
Arm crank $power_{max}$/weight, W/kg	4.0–12.4	.203	.258
Open-hand finger strength/weight, N/kg	1.8–5.1	.190	.293
VO_2peak %VO_2max, %	40.8–85.6	.174	.332
Sit-and-reach/height, cm/cm	0.1–0.3	.165	.359
Arm crank $power_{max}$, W	180.7–937.2	.163	.365
Leg span/height, cm/cm	0.8–1.1	.158	.378
Ring finger length, cm	6.3–7.9	.120	.509
Middle finger length, cm	7.0–8.6	.112	.538
Little finger length, cm	4.9–6.5	.110	.540
Index finger length, cm	6.1–7.7	.107	.555
Hand length, cm	16.1–19.5	.092	.613
VO_2max–VO_2peak, mL/kg/min	4.3–24.7	.078	.665
Hand coordination, cm	0.0–1.1	.021	.906
Arm span, cm	155.5–175.6	–.024	.896
Body weight, kg	45.5–75.5	–.082	.651
Foot coordination, cm	0.3–1.2	–.115	.504
Arm crank $power_{\%decline}$, %	48.6–86.5	–.124	.486
Leg length, cm	62.5–99.0	–.142	.431
BMI, kg/m^2	18.0–27.2	–.214	.235
Self-confidence, AU	12.0–36.0	–.269	.103

Abbreviations: AU, arbitrary unit; ape index, arm span/height; BMI, body mass index; VO_2max, maximal oxygen uptake; VO_2peak, peak oxygen uptake. Note: Correlation between independent variables and climbing ability (onsight French Sport climbing grade), ranked in order of correlation. Shades represents significance <0.05 (white), 0.05-0.1 (light gray) and >0.1 (dark gray).

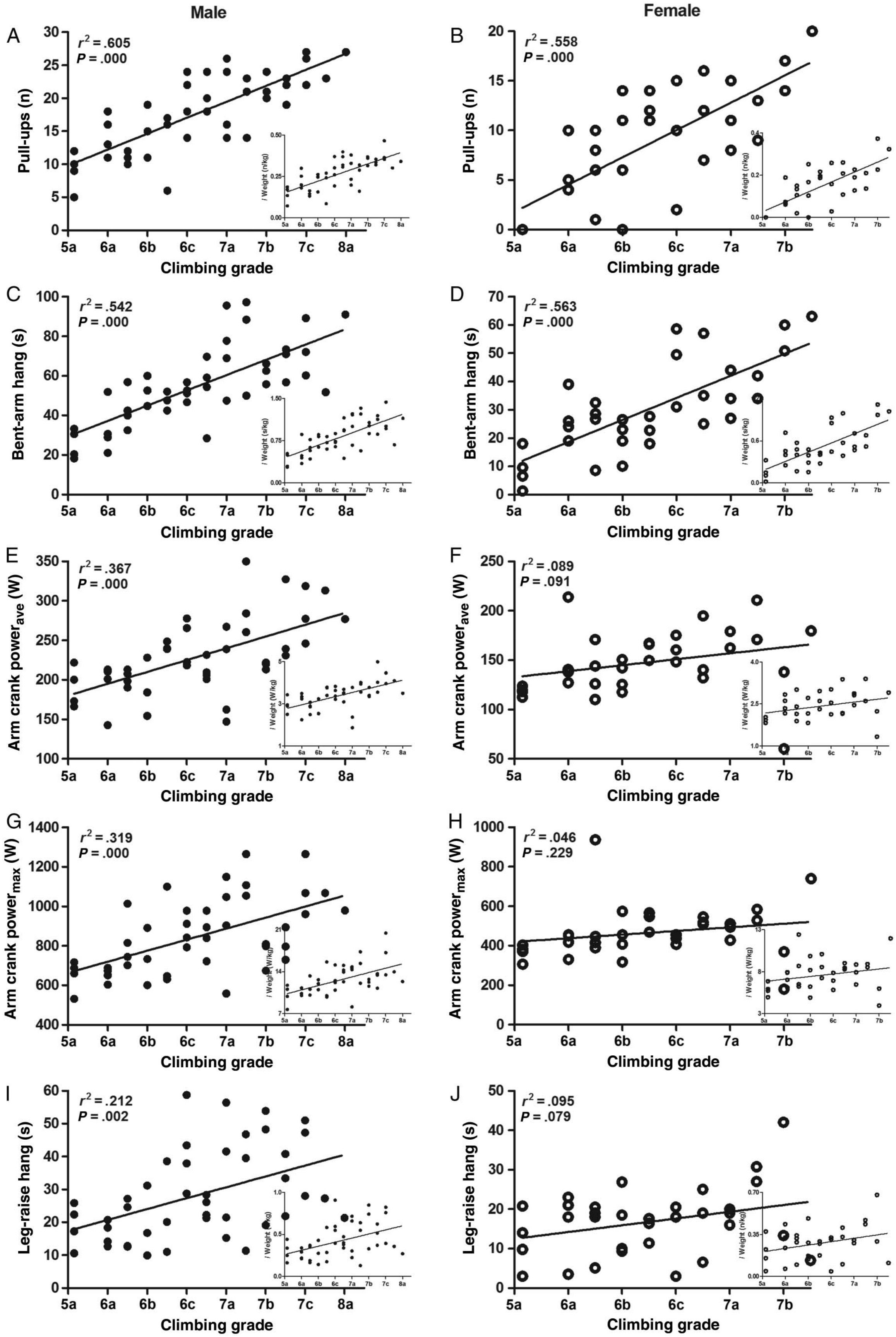

Figure 1 — Relationships and coefficients of determination (r^2) between climbing ability and maximum achievable pull-ups (A and B), bent-arm hang-time (C and D), average 20-second arm crank power (E and F), maximum arm crank power (G and H), and leg-raise hang-time (I and J), in male (left) and female (right) climbers, respectively. Insets show relationships after normalizing for body weight. Individual data with linear regression.

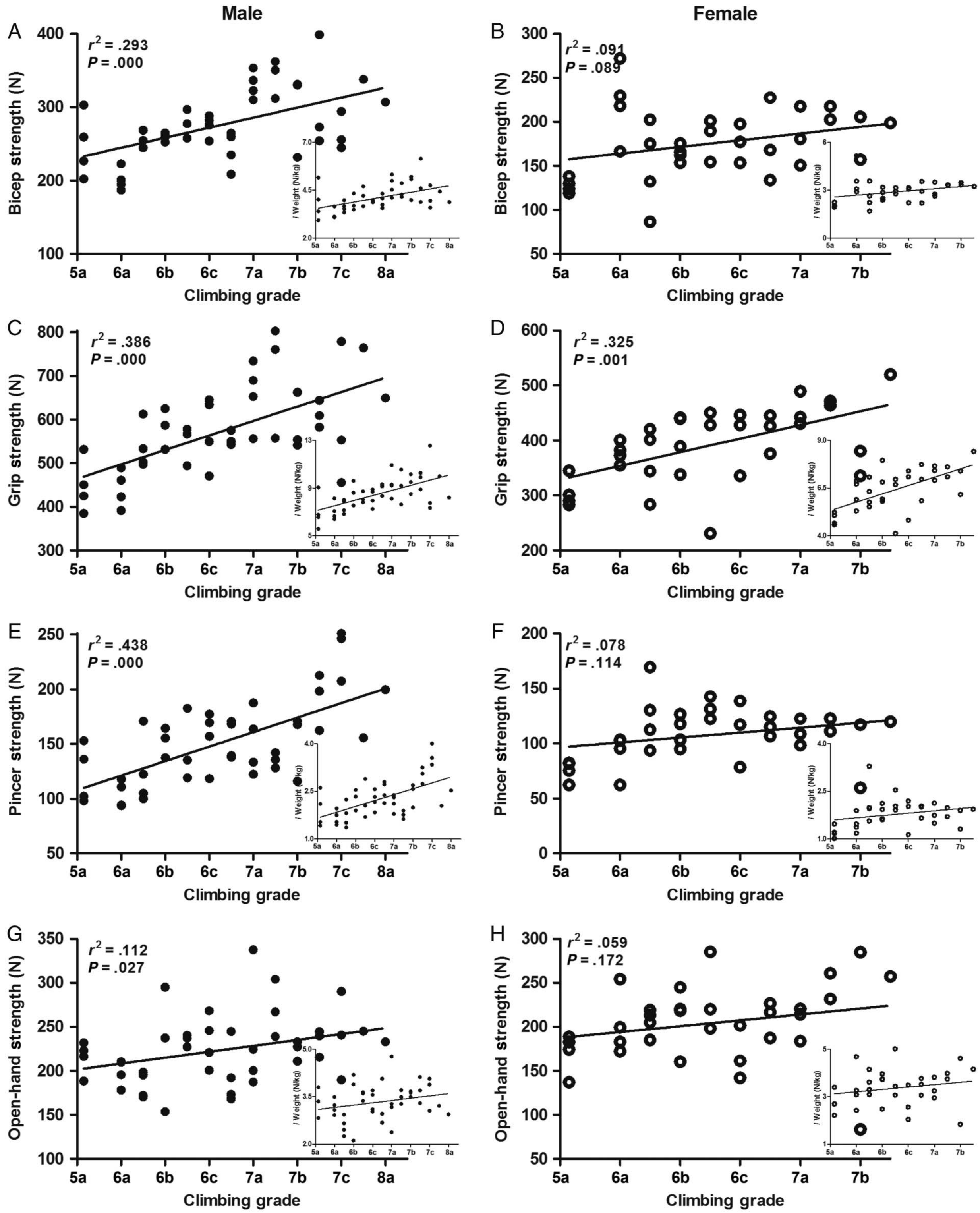

Figure 2 — Relationships and coefficients of determination (r^2) between climbing ability and maximum arm biceps strength (A and B), arm grip strength (C and D), finger pincer strength (E and F), and open-hand finger strength (G and H), in male (left) and female (right) climbers, respectively. Insets show relationships after normalizing for body weight. Individual data with linear regression.

PCA and Multiple Univariate Linear Regression

The PCA and forward multiple regression identified the main explanatory variables that determined the variation in climbing ability. In males, shoulder power and endurance, that is, maximum pull-ups, average arm crank power, and bent-arm hang emerged as the main determinants, explaining in total 77% (59%, 14%, and 4% individually) of the variation (Figure 6A). Pincer and grip strength had trends ($P = .07$ and $P = .09$) toward significant

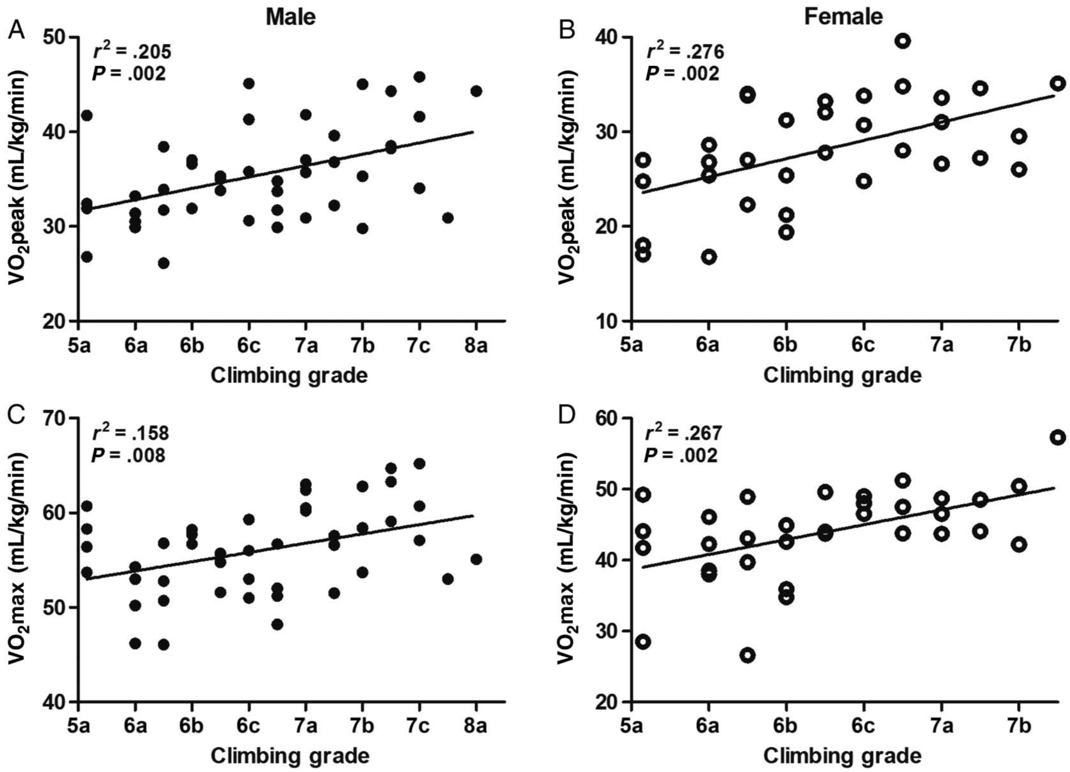

Figure 3 — Relationships and coefficients of determination (r^2) between climbing ability and aerobic capacity, measured as upper-body peak oxygen uptake (VO_2peak; A and B) and whole-body maximal oxygen uptake (VO_2max; C and D), in male (left) and female (right) climbers, respectively. Individual data with linear regression.

effects, while in a model only including nontrainable variables to assess the relative importance of body dimensions, hand length emerged as the only significant explanatory variable (unstandardized coefficient b 0.70 ± SE 0.78, adjusted R^2 .08 ($P = .04$), residual SD 3.52), whereas arm span had a trend ($P = .09$) toward a significant effect.

In females, shoulder power and endurance, that is, bent-arm hang and maximum pull-ups also emerged as the main determinants for climbing ability, explaining in total 62% (54% and 8% individually) of the variation (Figure 6B), while the "ape index" emerged as the only significant explanatory variable when modeling nontrainable body dimension variables (unstandardized coefficient b −78.44 ± SE 25.88, adjusted R^2 .21 [$P = .01$], residual SD 2.59).

Backward regression, multiple regression with or without variables (principle components) identified by eigenvalue >1 by PCA and a model only including trainable variables yielded similar results (not shown).

Training Study

Finally, we trained the main determinants, maximum pull-ups in males and bent-arm hangs in females, to increase 42% and 67%, respectively. Upon this, climbing ability increased 2 (1) and 2.7 (1.5) grades, respectively (Figures 6C and 6D). We also trained variables without significant correlation to climbing ability; balance in males and leg-raise hang in females, both with comparable insignificant correlation coefficients (Tables 2 and 3) and coefficients of determination (Figures 1J and 4E) to climbing ability. Training also increased these variables by 44% and 49%, respectively, but in this case, climbing ability did not improve (Figures 6C and 6D).

Discussion

This study represents an unprecedented comprehensive effort to identify the physical and physiological factors that determine performance and enable gains in climbing. We assessed a wide grade range of climbers from novice lower grade to dedicated experts in both sexes. This allowed us to characterize the different climbers and identify the main barriers to progression that must be overcome to perform at a higher level.

First, in males, 50% of the assessed parameters correlated with climbing ability. These included, in rank order, shoulder endurance, power, and power endurance, hand and finger strength, hip flexibility or range of motion, lower- and upper-arm strength, core-body endurance, aerobic capacity, hamstrings/lower-limb and lower-back flexibility, and open-hand finger strength. In females, fewer parameters (20%) correlated with climbing ability. These included, in rank order, shoulder endurance and power, lower-arm strength, balance, aerobic capacity, and arm span ("ape index"), whereas in contrast to males, power endurance, finger strength, upper-arm strength, and flexibility were less important.

Second, PCA and multiple regressions identified the main determinants of climbing ability. These were shoulder power and endurance, explaining 77% and 62% of the variation in climbing ability in males and females, respectively. On further examination, maximum pull-ups, arm cranks, and bent-arm hangs accounted for 59%, 14%, and 4%, respectively, of the variation in males, while

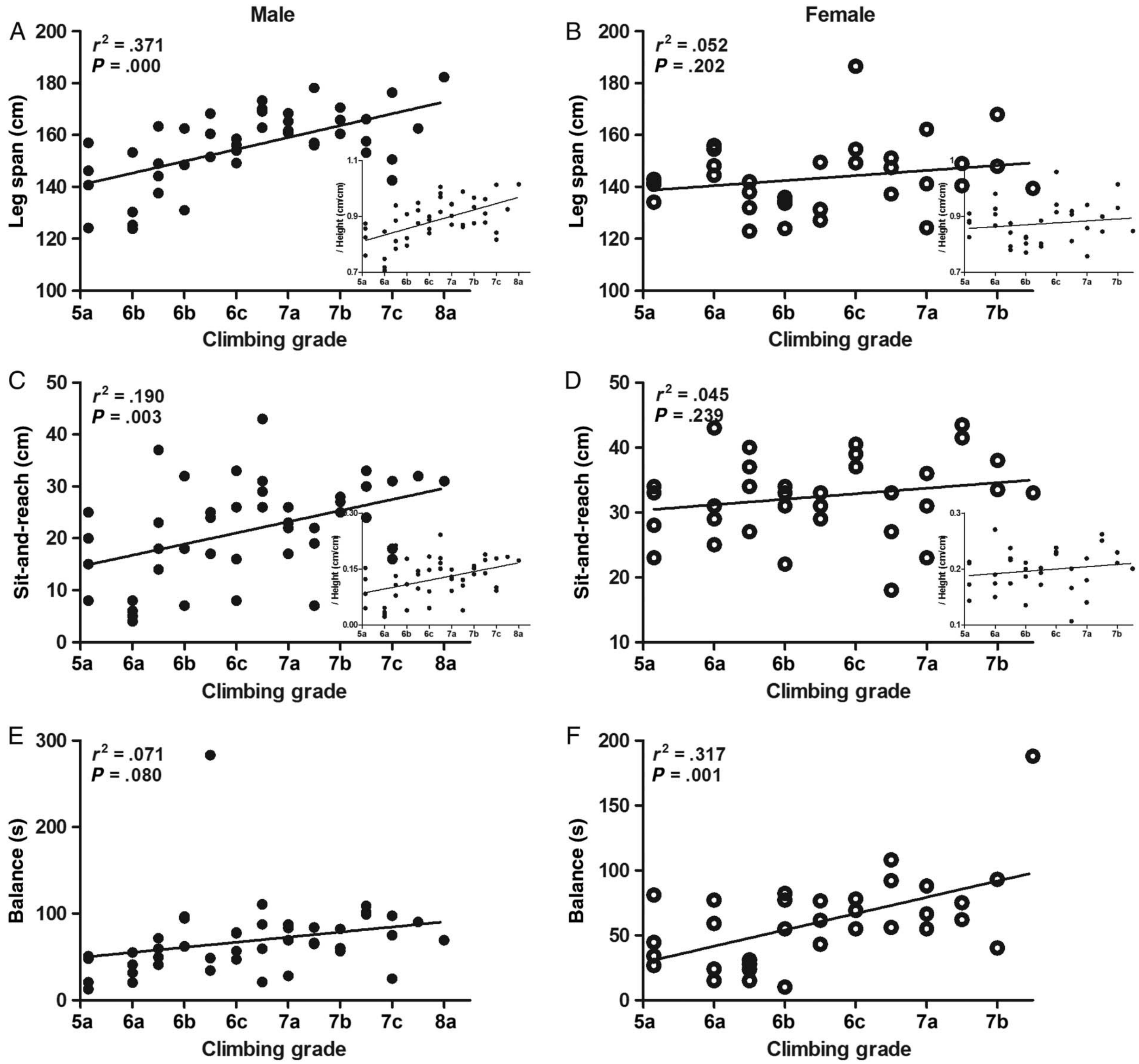

Figure 4 — Relationships and coefficients of determination (r^2) between climbing ability and flexibility, measured as leg-span for hip flexibility (A and B) and sit-and-reach test for hamstring and lower-back flexibility (C and D), and balance (E and F), in male (left) and female (right) climbers, respectively. Insets show relationships after normalizing for body height. Individual data with linear regression.

bent-arm hangs and pull-ups accounted for 54% and 8% in females, whereas finger and arm strength also tended to contribute to climbing ability in males. The fact that multiple regressions returned only a few significant parameters was expected and may be explained by extensive internal correlations between different variables.

The emphasis on the physical capacity of the shoulders as an important determinant for climbing ability, and the further focus on arm, hand, and finger strength is in line with previous studies,[11,12,19,20] but specification of relative contributions is novel. Similarly, flexibility and aerobic capacity contributing to climbing ability has previously received less support[2,4,11,20,21]; however, a recent report indicated that climbing taxes aerobic capacity sufficient to stress VO_2max,[27] and as such this favors a high aerobic capacity in climbers.

It remains unknown why female climbers relied on fewer parameters and were less determined by those, but a possibility is they relied more on factors not assessed here, for example, technique. Nonetheless, our approach and analysis represents a step forward for identifying key performance indicators for climbing and thereby informing specific cohorts on training strategies, compared with previous studies where climbing ability has been modeled with less resolution, precision, and specificity.[5,28]

The identified determinants and most of the parameters that correlated with climbing ability are trainable and should receive attention in training programs. In a small-scale proof-of-principle training study, we demonstrated that improving the main determinants also improved climbing ability by 2 to 3 grades. This training was performed in conjunction with other climbing training, with which we did not interfere. Hence, climbing training could explain the observed effect, but this is unlikely as the climbers had a history of >5 years of climbing training without experiencing similar gains in performance. By contrast, when variables without significant correlation or regression to climbing

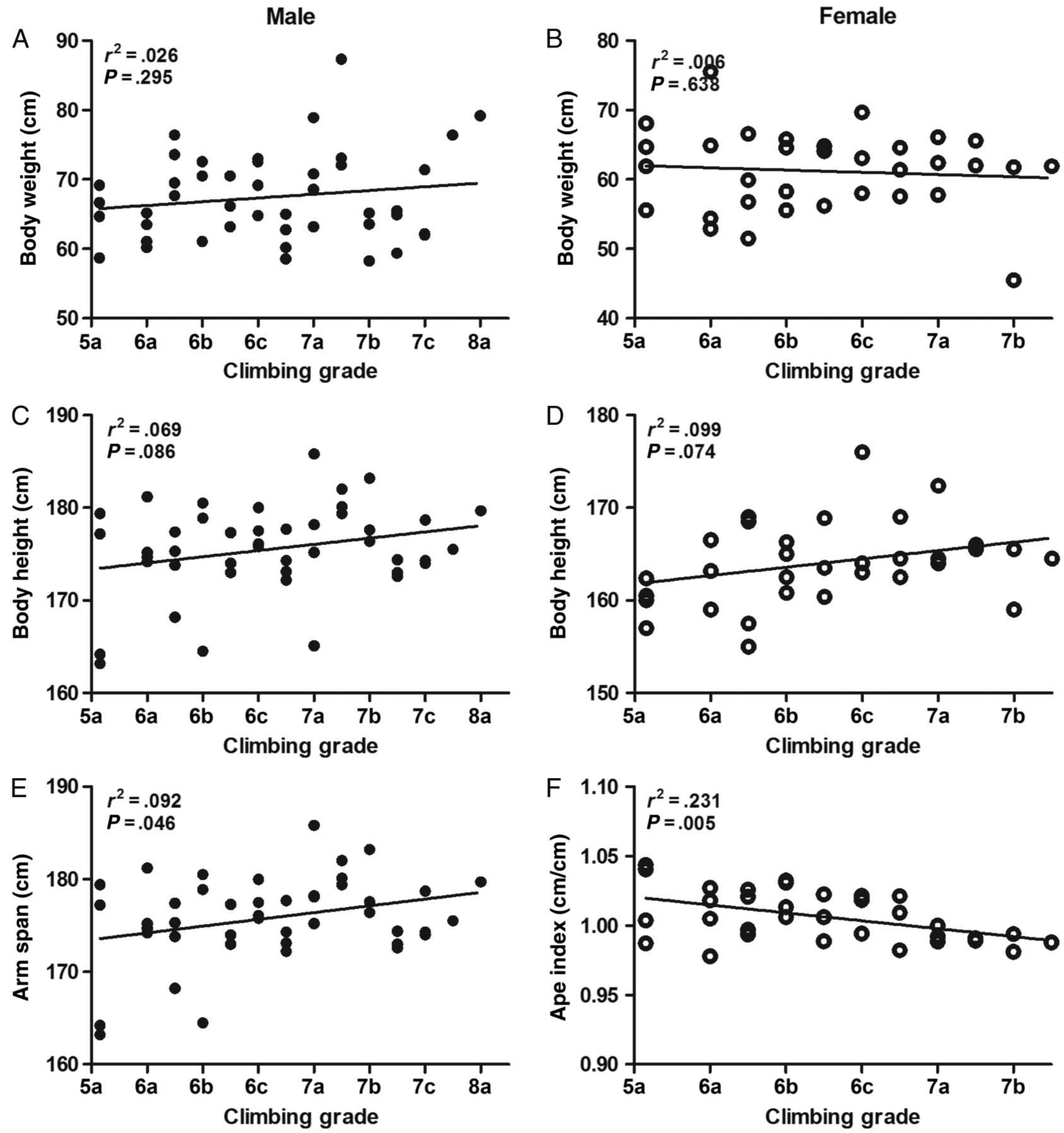

Figure 5 — Relationships and coefficients of determination (r^2) between climbing ability and body dimensions, measured as body weight (A and B) and body height (C and D) in male (left) and female (right) climbers, respectively, as well as arm span in male climbers (E) and "ape index " (arm span/body height) in female climbers (F). Individual data with linear regression.

ability (balance and leg-raise hang) improved by similar magnitudes, climbing ability did not improve. This strengthens the role of the main determinants identified here as key performance indicators, though the full effect of training should be studied in more depth. Our results also suggest, with the possible exception for hand and arm reach, that nontrainable anthropometric and body dimension factors matter less for climbing ability, as previously observed.[5,11,17,20] Thus, gains in climbing may be less restricted by the specific bodytypes or somatotypes; however, we caution that the subjects in this study were homogeneous with respect to body mass and dimensions, and neither was the study designed to investigate this aspect.

Notwithstanding the above, a successful training program should be balanced and seek to improve a wide spectrum of physical and physiological capacities, especially if pursuing climbing of various styles. We must, however, point out that the recruitment of climbers to our study via an indoor climbing facility with mainly short and steep (overhanging) routes may have favored shoulder endurance, power, and power endurance as the main determinants of climbing ability.[3] Other subdisciplines or climbing styles not investigated here may differ, and we did not assess technique, economy, recovery, or resistance to fatigue, which may all contribute toward climbing ability.[12,15,16,23,29,30] Finally, although we balanced numbers and sought to recruit at least 3 subjects in each grade to achieve the necessary statistical power, reduced availability of elite climbers restricted numbers in the highest grades. This may have limited the analysis.

Practical Applications

Several important practical applications may be deduced from this study: (1) improvements to shoulder power and endurance and to a lesser extent finger and arm strength will improve climbing performance; (2) these and further determinants of climbing are

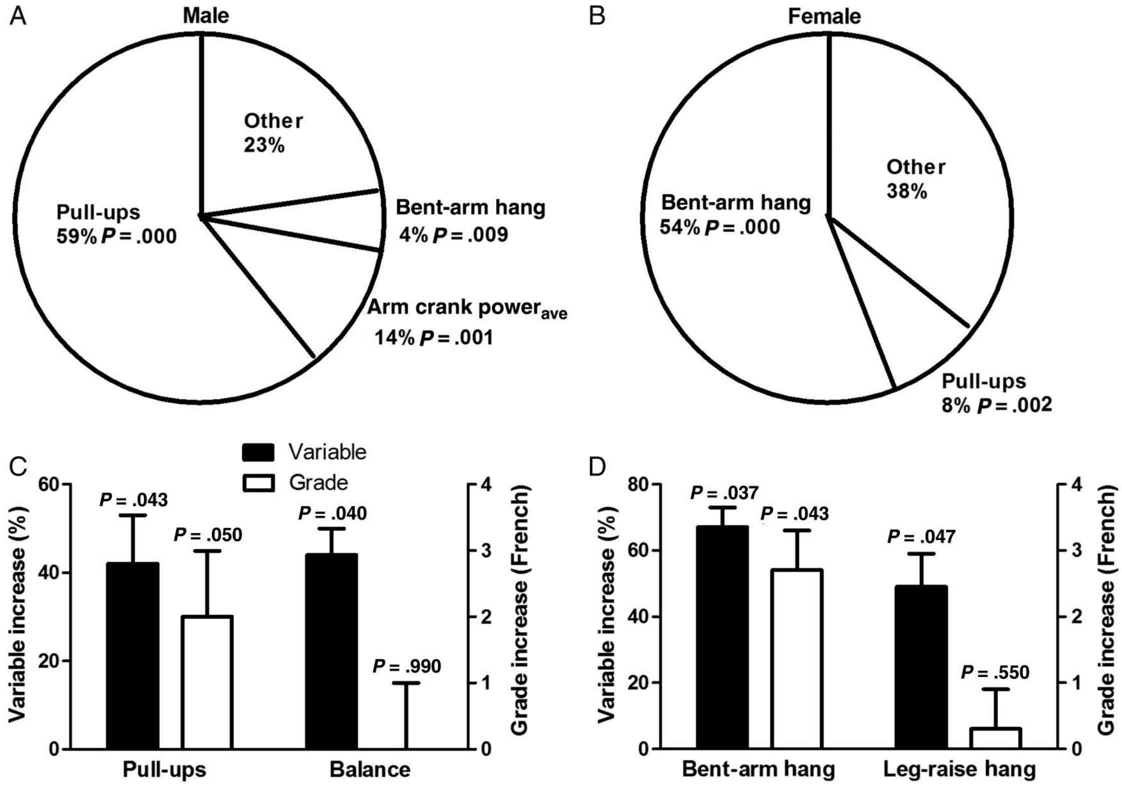

Figure 6 — Principal component analysis and multiple univariate stepwise linear regression identified the main explanatory variables that determined climbing ability. Males (A): maximum pull-ups, average arm crank power, and bent-arm hang: unstandardized coefficients b 0.48 ± SE 0.06, 0.03 ± SE 0.01, and 0.06 ± SE 0.02, respectively, adjusted R^2 .77; .59, .14, and .04, respectively, and residual SD 1.73. Females (B): bent-arm hang and maximum pull-ups: unstandardized coefficients b 0.14 ± SE 0.02 and 0.22 ± SE 0.08, respectively, adjusted R^2 .62; .54, and .08, respectively, and residual SD 1.76. When males (C) trained maximum pull-ups (n = 3) or balance (n = 3), and females (D) trained bent-arm hangs (n = 3) or leg-raise hangs (n = 3) for 8 weeks, the independent variables increased (left y-axis), but climbing grade only increased when main determinants maximum pull-ups (males) or bent-arm hangs (females) increased (right y-axis), and not when balance or leg-raise hangs increased.

trainable; and (3) body weight and dimensions do not stop progress in climbing. These applications relate to all climbers regardless of ability or sex, but may especially pertain to those that climb relatively short, but steep routes.

Conclusions

Peak performance in climbing is achieved at least partly as a result of well-developed physical and physiological characteristics, and high gains are accomplished by focused and dedicated training that improves those characteristics. Here, we have identified the characteristics that need to be overcome for continued progression and success. They include shoulder endurance, power, and power endurance, hand and finger strength, lower- and upper-arm strength, flexibility, core-body endurance, balance, and aerobic capacity, with shoulder power and endurance emerging as the main determinants. These key performance indicators should be included in training for climbing and if improved, will lead to improved performance.

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