Performance Assessment for Rock Climbers: The International Rock Climbing Research Association Sport-Specific Test Battery

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Purpose: To examine the validity and reliability of a battery of 10 measures designed to assess the key physiological parameters for successful rock climbing performance. *Methods:* In phase 1 of the research, an expert panel, using the Delphi method, established a 10-item test battery based on the key determinants of climbing performance. In phase 2, the tests were assessed for validity and reliability to examine their suitability as sport-specific measures of rock climbing performance. A total of 132 rock climbers, from 7 countries, volunteered to take part in the study. Each climber visited their nearest laboratory on 3 separate occasions in order to enable the required tests and retests to be completed. A minimum of 7 days was allowed between visits. *Results:* The 10 tests established for phase 2 were designed as sport-specific measures of flexibility, strength, power, and endurance. Results indicated that, while reliable, the flexibility and strength tests were only partially successful in differentiating across climber abilities. The power and endurance tests, however, performed well with regard to validity and reliability, with the finger hang and powerslap tests being most strongly correlated with performance ability ($P < .0005$ to $P < .002$). *Conclusion:* The authors' data suggest that climbing may require a threshold level of flexibility and strength for successful performance, beyond which further improvements may not be required. In contrast, the finger hang and powerslap tests were not only reliable measures but also differentiated between climber abilities from lower grade to elite levels.

Keywords: endurance, flexibility, power, strength, successful rock climbing

Rock climbing is an increasingly popular sport with a growing research database, particularly since its inclusion in the Olympic program for Tokyo 2021.[1–3] The sport of rock climbing actually consists of a number of different disciplines including sport (lead) climbing, bouldering, speed climbing (which are the Olympic formats), deep-water solo, traditional climbing, ice climbing, and mixed climbing. While there is an increasing depth of research in the field, there has been a lack of consistency in reporting studies and also in the use of performance tests; specifically, there has been a lack of sport-specific tests that have been assessed for validity and reliability.[4]

Rock climbing is a demanding sport requiring psychological, skill-related, and physiological components for successful performance. In regard to the physiological aspects, 4 parameters have been regularly cited by coaches and researchers as key components of climbing that underpin performance.[5] These physiological components are strength, power, flexibility, and endurance.[5–8] Given the importance of these factors for climbing, it is important to identify valid and reliable sport-specific tests that assess each of these parameters for use by researchers and coaches working with climbers.

The International Rock Climbing Research Association (IRCRA) was formed in 2011 to create a nexus for collaboration not only between countries and institutions but also between researchers, climbers, and coaches. In addition, through its biennial Congress and website forums, the IRCRA aims to bring greater consistency to research reporting. Examples of the IRCRA's work can be found in the publication of their position statement in regard to climbing grades.[4] In this document, the IRCRA established a recommended format for study reporting to facilitate comparison between studies, clearer ability descriptors, and a numerical scale to bring greater consistency to statistical analyses.[4]

At the 2014 IRCRA Congress, held in Pontresina, Switzerland, the need for sport-specific assessment tools was highlighted by researchers and coaches. As a result of these discussions, a working group was established to develop a sport-specific battery of tests for coaches, climbers, and researchers. A key aspect of this development work was to ensure that the tests were valid, and reliable measures were taken so that they could be used as measurement tools for future intervention and cohort studies. The resultant multicenter trial established a collaboration between researchers and coaches from 7 countries across the globe with the purpose being to identify and assess the validity and reliability of a sport-specific test battery for rock climbing.

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Methods

This study involved 2 phases, with phase 1 being the development of the test battery and assessment for face and content validity. In phase 2, the developed tests were assessed for construct validity and test−retest reliability. While not a health study per se, the Consensus-based Standards for the Selection of Health Measurement Instruments was used to guide the development of the study and to evaluate the quality of each of the tests in the battery.[9] After design and review using the Consensus-based Standards for the Selection of Health Measurement Instruments checklist, the study achieved good to excellent Consensus-based Standards for the Selection of Health Measurement Instruments rating prior to commencement. The study was approved by the University of Derby institutional research ethics committee (LSREC_1516_01). Informed consent from all participants was received before participation.

Phase 1

Following the IRCRA Congress in Pontresina, a working group comprising of academics, coaches/practitioners, and climbers (n = 20) was formed to develop the battery of tests using the Delphi method.[10] Details of the working group can be found in the IRCRA Test Manual (see Supplementary Material [available online]).[11] The working group endorsed the physiological parameters of strength, power, flexibility, and endurance, as previously identified in the research, but in addition included a fifth element of core stability, due to its importance with regard to quality movement in climbing. The battery of tests for the study underwent several stages in development, beginning with a desktop study. The desktop study identified the published sport-specific tests that had undergone validity and reliability assessment. This led to the inclusion of the flexibility assessment,[8] maximal finger strength,[12] and powerslap tests[5] in the final test battery, as tests 1, 2, 3, and 5, respectively. Following this, in an iterative process, the working group further developed the climbing-specific foot raise[8] to create tests 1 and 2 and then went on to develop, pilot test, revise, and agree on a further 6 tests for inclusion in the final test battery, ensuring that each of the agreed physiological components, including core stability, were assessed.

Each of the tests was examined for face and content validity prior to inclusion in the test battery through a process involving internationally recognized experts (n = 3) who met in person to revise and further develop each test to ensure the content validity of each test after face validity had been agreed by members of the working group (n = 6). The review process included the development of specific test apparatuses, in situ observations of climber performance on each of the tests, and a subjective assessment of the sport-specificity of each test. Full details of the tests including test apparatus specifications and protocols can be found in the test manual (see Supplementary Material [available online]).[11] The final test battery, along with its associated physiological parameter(s), can also be found in IRCRA Test Manual (see Supplementary Material [available online]).[11]

Phase 2

Participants

As a multicenter trial, this study represents one of the largest completed with rock climbers, with 132 participants (mean [SD]) age 27.3 (7) years, body mass 65 (11) kg, height 170.5 (9) cm, body mass index 22.4 (2.5) kg/m^2, body fat 17.7% (8%), who had 6.6 (6) years climbing experience and were, at the time of the study, training 2.5 (1) sessions per week. The participants consisted of 45 female and 87 male climbers, of whom 12 were tested in Austria, 21 in Chile, 15 in both the Czech Republic and France, 33 in Spain, and 36 in the United Kingdom. In Spain, the data were collected at 2 centers, one in Cadiz, the other in Madrid (Spain 1 and Spain 2, respectively). In 2011, the IRCRA published a classification system for climbers to provide a suggested ability-based nomenclature for reporting of climbing grades.[4] This classification system being based on the validity of self-reported grades as had been previously demonstrated.[13] The climbers, who completed a health history and informed consent prior to commencing their participation, self-reported as being of lower grade (20), intermediate (30), advanced (63), and elite (19) level. Specific characteristics of the group can be found in Table 1. The climber experience and health history questionnaires can be found on pages 22 and 33 of the Test Manual (see Supplementary Material [available online]),[11] respectively.

Procedure

To assess the construct validity and reliability of each of the tests, a protocol for testing was established as shown in the IRCRA Test Manual (see Supplementary Material [available online]).[11] To ensure each climber arrived at the laboratory in a similar physical condition, a minimum of 7 days was required between visits, and the participants were asked to rest completely in the 24 hours prior to each test. For each of the 3 laboratory visits, a 5-minute rest was allowed between tests. On each visit to the laboratory, the participants completed a standardized warm-up, which is described in detail in the test manual. The warm-up briefly consisted of 5 minutes of walking and jogging, 5 minutes of general mobilizing, and 5 minutes of specific exercises, such as pull-ups, leg raises, and reduced weight finger hangs, which mimicked the movement required in the tests. The warm-up was developed from methods used in previous research.[14–16] Anthropometric measurements were made as described in the test manual, and it included height, mass, arm span, forearm volume, body density, and skinfold thicknesses.[17–19] Version 1.6 of the test manual[11] was followed at each of the test centers, along with e-mail and telephone clarifications, to ensure consistency of the method. In addition, videos were watched at each test center to ensure that the method for each test was the same across the study. Each test center built the test apparatuses to the specifications supplied in the test manual. For the leg raise tests (T1 and T2), both left and right legs were tested for all participants. In T1, rotation at the shoulders was allowed, while for T2, no rotation at the shoulders was allowed, so the shoulders had to remain parallel to the test board during text execution. For the finger strength test (T3), both open and crimped holds were tested. For a description of different holds common to rock climbing, see Peters.[20] For powerslap test (T5) and the bent-arm hang (T7), left and right arms were tested.

Construct validity for each of the tests was examined by ability level. (Higher grade climbers expected to have higher scores than lower grade climbers.) As can be seen in the IRCRA Test Manual (see Supplementary Material [available online]), for all tests with the exception of tests 3 and 5 (as described previously) and the 2 core stability tests (T9 and T10), were repeated to assess test−retest reliability between and across centers. At each of the centers, the researchers followed the protocol as described in the test manual to administer each of the tests.[11]

Table 1 Number of Participants in Each Ability Category and Mean (SD) Characteristics for the Climbers in the Study

	All	Lower grade	Intermediate	Advanced	Elite
N					
Male	87	13	19	44	11
Female	45	7	11	19	8
Age, y					
Male	27.3 (8)	23.84 (7)	31.15 (7)	27.54 (8)	27.59 (7)
Female	27.2 (8)	24.6 (8)	29.21 (8)	28.4 (6)	26.18 (11)
Body mass, kg					
Male	69.8 (14)	80.68 (15)	68.81 (8)	67.58 (8)	71.45 (5)
Female	57.3 (13)	67.25 (13)	58.32 (7)	56.56 (10)	49.24 (5)
Height, cm					
Male	174.6 (27)	177.51 (6)	174.93 (8)	172.99 (7)	176.75 (2)
Female	162.3 (25)	164.05 (6)	166.16 (8)	161.92 (9)	158.76 (6)
Arm span, cm					
Male	180.3 (33)	180.99 (4)	179.1 (9)	179.61 (9)	185.49 (2)
Female	163.8 (35)	165.75 (7)	167.63 (8)	162.38 (8)	163.99 (6)
Body mass index, kg/m^2					
Male	22.8 (4)	25.59 (4)	22.45 (2)	22.56 (2)	22.88 (2)
Female	21.7 (4)	24.91 (4)	21.12 (2)	21.45 (2)	19.5 (1)
Body fat, %					
Male	13.7 (6)	18.38 (5)	13.15 (6)	13.63 (5)	11.86 (2)
Female	24 (7)	28.46 (7)	24.79 (5)	24.35 (7)	18.81 (4)
Years climbing					
Male	7.4 (6)	3.52 (6)	6.95 (6)	8.22 (6)	13 (7)
Female	5.2 (4)	2.65 (2)	3.77 (3)	5.71 (5)	7.82 (3)
Sessions per week					
Male	2.7 (1)	1.05 (0.7)	2.79 (1)	2.92 (1.3)	3.56 (1)
Female	2.5 (1)	0.81 (0.4)	1.75 (0.6)	2.71 (1.1)	4 (1)

Statistical Analysis

Distributions, descriptive statistics, analyses of variance, correlations, and regressions were calculated using SPSS (version 25.0; IBM SPSS Statistics Inc, Chicago, IL), while Bland–Altman plots[21,22] were calculated using Microsoft Excel (version 2016 MSO 16.0.4738.1000; Microsoft Redmond, Washington, WA). Data were assessed for violations of the assumptions of normality of distribution using the Shapiro–Wilk test with results showing Gaussian distribution. A 1-way analysis of variance with least-significant-difference post hoc comparisons as necessary was used to explore the effects of ability level on scores for each of the 10 tests. To ascertain the reliability of the tests, a series of Bland–Altman plots were completed, and coefficients of variation were calculated to examine the levels of agreement. Cronbach alpha and intraclass correlations were calculated to assess test–retest reliability. Data are reported as mean (SD), and $P \leq .05$ was set for accepting statistical significance.

Results

The means and SD for each of the tests are shown in Figure 1. As can be seen from this figure, the tests that appeared through visual inspection to differentiate climbers by ability category were the finger strength (T3—open and crimped, left and right), the finger hang (T4), the powerslap (T5), the bent-arm hang (T6), 1-arm bent-arm hang (T7—left and right), and pull-ups test (T8).

Tests 1 and 2 (leg raise tests—flexibility) and tests 9 and 10 (plank and leg raise, respectively—core stability) did not appear to differentiate between climbers of differing abilities. The results of the analysis of variance tests (see Table 2) indicated that there were significant differences between groups for all tests with the exception of test 1 (right) and test 2 (left and right).

Visual inspection of the data in Table 2 suggests that in principle scores on tests improved with climbing ability; that is, high-grade climbers appeared to score higher on tests than their lower-ability counterparts. With regard to assessing construct validity, tests 4 and 6 performed well in differentiating between all grades of climbers. Test 5, when left and right powerslap were considered together, showed increased scores by ability. Test 8 showed good construct validity apart from differentiation between intermediate and advanced level climbers. Test 7 (single-arm bent-arm hang), which was similar to test 6 in showing significant differences by group, lacked differentiation for lower grade, intermediate, and advanced climbers. In these groups, there were several climbers who could not hold the 1-arm position at all, whereas they could with the 2-arm version (test 6). Tests 1, 2, 3, 9, and 10 performed poorly with respect to differentiation and could not be said to hold construct validity for climbing.

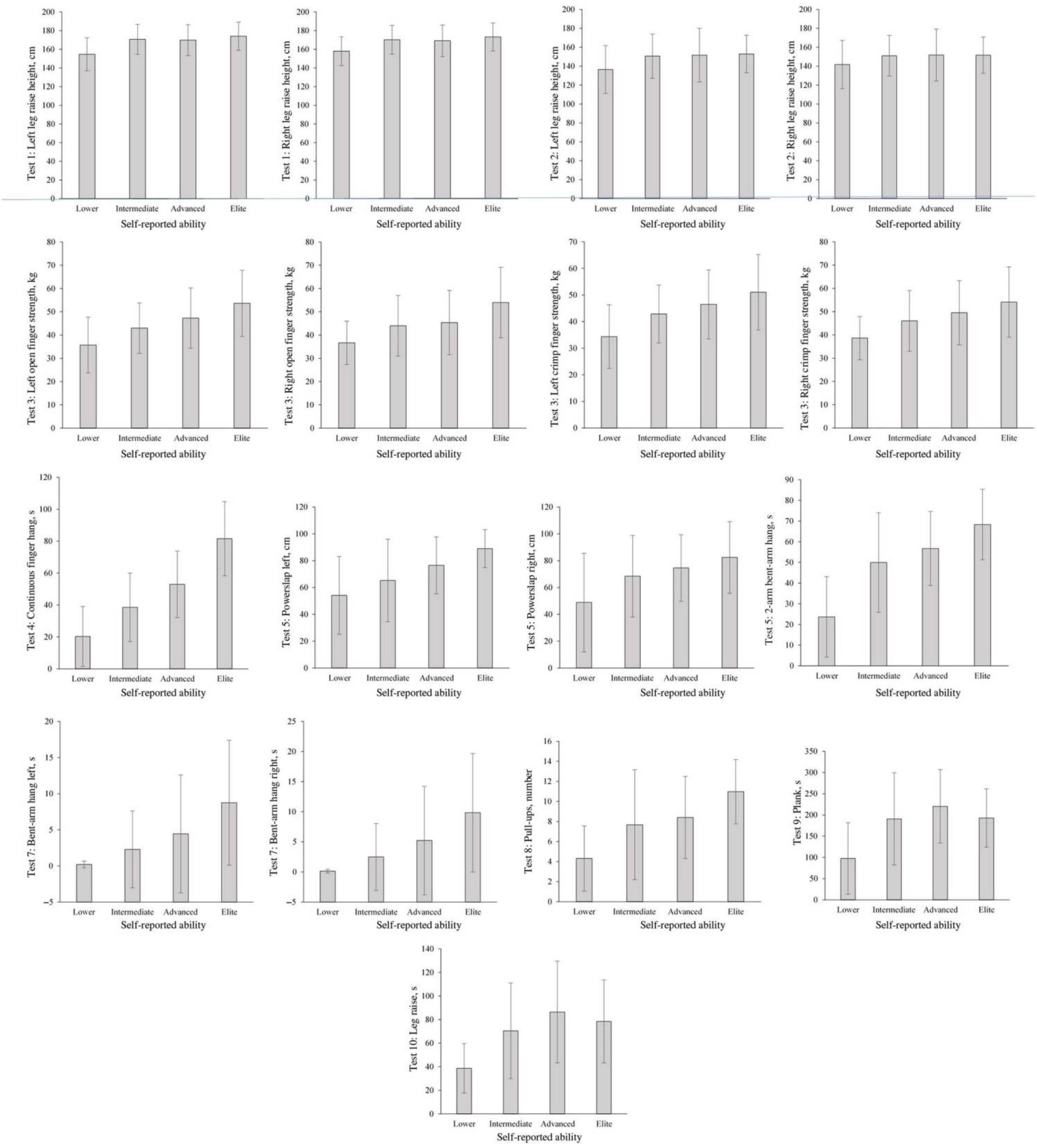

Figure 1 — Raw score means and SD for each of the tests, left and right hand shown as appropriate. *Note.* Results for test 1 are for leg raise with rotation and for test 2 are leg raise without rotation.

Table 2 Results of ANOVA Tests for the International Rock Climbing Research Association Test Battery

	ANOVA								
Test	*F*	*P*	η_p^2	1–2	1–3	1–4	2–3	2–4	3–4
Test 1: Left leg raise									
Combined	4.218	.007	.101	*	*	*			
Male	7.167	<.0005	.228	*	*	*			*
Female	0.299	.826	.024						
Test 1: Right leg raise									
Combined	2.588	.057	.064						
Male	5.167	.003	.175	*	*	*			*
Female	0.251	.860	.02						
Test 2: Left leg raise									
Combined	0.994	.399	.026						
Male	3.032	.035	.111	*	*	*			
Female	0.611	.612	.048						
Test 2: Right leg raise									
Combined	0.642	.589	.017						
Male	1.711	.172	.066						
Female	0.425	.736	.034						
Test 3: Left open finger strength									
Combined	4.42	.006	.127		*	*		*	
Male	8.788	<.0005	.305		*	*	*	*	*
Female	4.021	.017	.309	*	*	*			
Test 3: Right open finger strength									
Combined	3.707	.014	.106		*	*		*	
Male	5.901	.001	.219		*	*		*	*
Female	2.551	.077	.221		*	*			
Test 3: Left crimp finger strength									
Combined	3.997	.010	.113		*	*			
Male	4.811	.004	.186		*	*		*	
Female	3.528	.028	.282		*	*		*	
Test 3: Right crimp finger strength									
Combined	3.145	.029	.094		*	*			
Male	4.413	.007	.181		*	*		*	*
Female	6.132	.003	.405						
Test 4: Continuous finger hang									
Combined	24.235	<.0005	.394	*	*	*	*	*	*
Male	12.430	<.0005	.341	*	*	*		*	*
Female	16.618	<.0005	.581		*	*	*	*	*
Test 5: Left powerslap									
Combined	6.758	<.0005	.151		*	*	*	*	
Male	9.220	<.0005	.275	*	*	*		*	*
Female	12.746	<.0005	.508		*	*	*	*	*
Test 5: Right powerslap									
Combined	4.347	.006	.103	*	*	*			
Male	5.171	.003	.175	*	*	*			
Female	7.891	<.0005	.390	*	*	*	*	*	
Test 6: 2-arm bent-arm hang									
Combined	15.259	<.0005	.287	*	*	*		*	*
Male	13.122	<.0005	.350	*	*	*		*	*
Female	8.432	<.0005	.406	*	*	*		*	

(continued)

Table 2 *(continued)*

Test	ANOVA *F*	*P*	η_p^2	1–2	1–3	1–4	2–3	2–4	3–4
Test 7: Left bent-arm hang									
Combined	4.478	.005	.105		*	*		*	*
Male	4.756	.004	.163		*	*		*	*
Female	3.764	.019	.234			*		*	*
Test 7: Right bent-arm hang									
Combined	4.856	.003	.113		*	*		*	*
Male	5.689	.001	.189		*	*		*	*
Female	1.863	.153	.131						
Test 8: Pull-ups									
Combined	5.464	.002	.113	*	*	*		*	*
Male	8.088	<.0005	.260	*	*	*		*	*
Female	8.397	<.0005	.426		*	*		*	*
Test 9: Plank									
Combined	7.385	<.0005	.163	*	*	*			
Male	3.697	.015	.132	*	*				
Female	6.311	.001	.338	*	*	*			
Test 10: Leg raise									
Combined	5.723	.001	.113	*	*	*			
Male	2.329	.082	.088						
Female	4.890	.006	.290		*	*	*		

Abbreviation: ANOVA, analysis of variance.
*Significant post hoc difference between these groups ($P < .05$), also indicated by bold *P* values.

About reliability, only tests 4, 6, and 8 were assessed for test–retest reliability, as these were the tests which displayed strong construct validity. Test 5, the powerslap test, performed well in regard to construct validity and had already been assessed for test–retest reliability in a previous study, so this was not replicated in our test protocol (5). The results of Cronbach alpha and intraclass correlations tests can be seen in Table 3. As can be seen from Table 3, all 3 tests displayed strong test–retest reliability as a whole (across countries) and also within each country. The only exception being French data for the finger hang and 2-arm bent-arm hang which had a moderate result (0.771 and 0.624; 0.657 and 0.480, respectively).

The Bland–Altman plots for each of the 3 tests can be seen in Figure 2. As can be seen in this figure, there were good levels of agreement between tests. Table 4 provides the coefficient of variation for tests 4, 5, 6, and 8. Taken across all grades, the tests demonstrated very good to acceptable levels of variation. On tests 4 and 8 for lower grade females, the variation >30% is not acceptable.

Tests 4, 5, 6, and 8 demonstrated strong construct validity, showed good levels of agreement, and displayed strong test–retest reliability. Table 5 provides details of regression modeling for tests 4, 5, 6, and 8. As can be seen from this modeling, the variance explained across all models was higher for females (R^2 = .52–.58) than for males (R^2 = .31–.36). For both males and females, the variance explained increased only marginally when moving from model 2 to 3 and including the 2-arm bent-arm hang (T6) and pull-ups (8).

Discussion

Research across many sports has highlighted the benefits of valid and reliable, sport-specific tests for monitoring performance in athletes.[23–25] Although a generally more recent area of research focus, the need for sport-specific measurement tools for rock climbing has been recognized by coaches and researchers alike, and there are an increasing number of studies examining novel tests for the sport.[1,5,8,12,26,27] These studies have, however, been limited in regard to the total number and ability levels of the participants. The mission of the IRCRA is to foster collaboration not only between researchers, coaches, and climbers but also between countries to increase our knowledge and understanding of the sport. This is increasingly important from a performance perspective since the inclusion of rock climbing in the Olympic schedule for the Tokyo 2021 Olympic Games. The collaboration brought about through the IRCRA enabled the establishment of the largest rock climbing study to date with data collected from centers in 7 countries where climbing is a popular performance and recreational activity. The aim of the resultant study was to examine the validity, reliability, and performance assessment potential of 10 sport-specific performance measures for rock climbing.

Researchers identified flexibility, power, strength, and endurance as the key performance parameters for rock climbing, with the recognition that core stability plays an additional key role in successful performance.[5–8,12,26] Through the Delphi method, an expert panel identified, developed, and refined the protocol for 10 sport-specific rock climbing tests to be included in the study. The key finding of the study was that tests 4, 5, 6, and 8, namely the finger hang, powerslap, 2-arm bent-arm hang, and the pull-ups tests respectively, demonstrated high levels of validity and reliability as sport-specific measures. As shown in Table 1, these tests were designed to assess climbing-specific endurance and power. The remaining tests, tests 1, 2, 3, 7, 9, and 10, which assessed climbing-specific flexibility, strength, endurance, and core stability did not

Table 3 Cronbach Alpha, ICC, and Lower and Higher Limits for Tests 4 (Finger Hang), 6 (2-Arm Bent-Arm Hang), and 8 (Pull-Ups)

	C alpha	ICC	95% lower	95% higher
Finger hang				
All				
Combined	.937	.881	.835	.915
Male	.939	.887	.831	.925
Female	.926	.865	.758	.927
French				
Combined	.771	.624	.182	.860
Male	.834	.724	.292	.912
Female	—	—	—	—
Czech				
Combined	.982	.962	.890	.987
Male	.975	.952	.816	.989
Female	.979	.955	.756	.993
Austria				
Combined	.944	.895	.672	.970
Male	.931	.875	.329	.986
Female	.819	.722	−.106	.952
Britain				
Combined	.932	.869	.738	.937
Male	.916	.839	.650	.931
Female	.836	.747	.036	.952
Chile				
Combined	.946	.887	.737	.953
Male	.924	.825	.473	.945
Female	.917	.861	.451	.971
Spain S1				
Combined	.909	.844	.578	.947
Male	.888	.81	.437	.945
Female	—	—	—	—
Spain S2				
Combined	.945	.887	.734	.954
Male	.959	.919	.764	.974
Female	.916	.84	.389	.970
2-arm bent hang				
All				
Combined	.944	.894	.852	.925
Male	.926	.864	.797	.910
Female	.954	.913	.841	.954
French				
Combined	.657	.480	−.016	.794
Male	.112	.062	−.577	.626
Female	—	—	—	—
Czech				
Combined	.962	.928	.804	.957
Male	.893	.824	.385	.958
Female	.961	.913	.558	.987
Austria				
Combined	.974	.929	.674	.982
Male	.937	.900	.315	.989
Female	.988	.892	−.032	.987
British				
Combined	.927	.842	.649	.928
Male	.872	.740	.438	.888
Female	.941	.875	.430	.981
Chile				
Combined	.919	.808	.493	.925
Male	.774	.567	.074	.842
Female	.979	.938	.626	.988
Spain S1				
Combined	.978	.956	.872	.985
Male	.976	.955	.848	.987
Female	—	—	—	—
Spain S2				
Combined	.905	.830	.623	.929
Male	.964	.931	.797	.978
Female	.844	.757	.061	.954
Pull-ups				
All				
Combined	.99	.972	.922	.986
Male	.984	.953	.855	.979
Female	.987	.969	.922	.985
French				
Combined	.986	.967	.896	.989
Male	.978	.947	.806	.985
Female	—	—	—	—
Czech				
Combined	.991	.974	.856	.993
Male	.901	.728	.078	.935
Female	.958	.904	.510	.968
Austria				
Combined	.989	.971	.884	.992
Male	.997	.995	.969	.999
Female	.860	.663	−.540	.943
British				
Combined	.995	.986	.954	.995
Male	.992	.977	.893	.992
Female	.986	.972	.878	.994
Chile				
Combined	.989	.971	.904	.989
Male	.984	.960	.837	.988
Female	.961	.916	.656	.982
Spain S1				
Combined	.969	.923	.731	.976
Male	.956	.890	.586	.970
Female	—	—	—	—
Spain S2				
Combined	.960	.886	.567	.961
Male	.854	.635	.053	.881
Female	.986	.965	.823	.993

Abbreviations: ICC, intraclass correlations. Note: When participant numbers were ≤3, the statistics were not calculated.

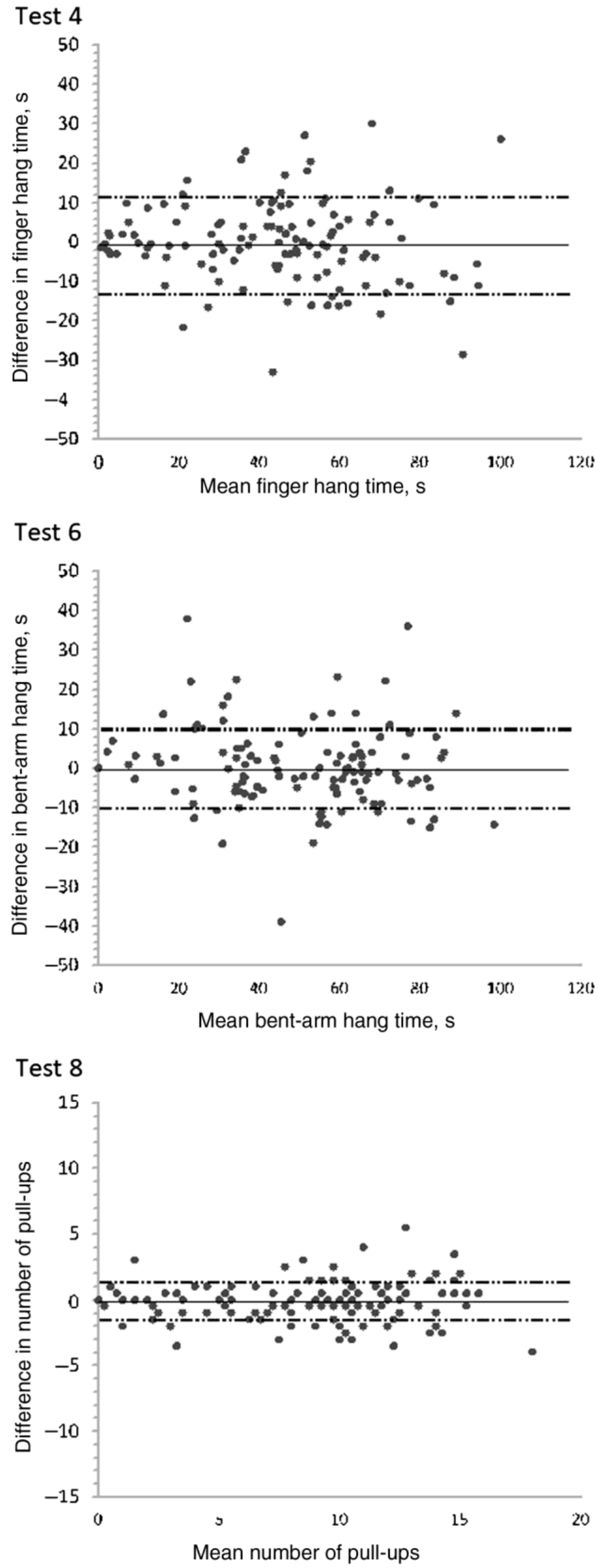

Figure 2 — Bland–Altman plots for finger hang (test 4), 2-arm bent-arm hang (test 6), and pull-ups (test 8).

Table 4 Coefficients of Variation for Each of the Selected Tests

Test	All, %	Lower grade, %	Intermediate, %	Advanced, %	Elite, %
Test 4: Finger hang					
All	18	32	22	12	13
Male	16	25	18	12	10
Female	24	53	29	11	16
Test 5: Powerslap					
All	7	14	11	4	3
Male	4	6	5	3	3
Female	13	34	23	6	2
Test 6: 2-arm bent hang					
All	15	24	17	11	18
Male	13	13	18	11	9
Female	19	56	15	11	27
Test 8: Pull-ups					
All	14	19	18	13	5
Male	10	10	11	9	6
Female	24	47	31	20	5

perform as well in regard to validity for rock climbing and in their current forms could not be considered as sport-specific measures across all ability levels.

Flexibility, the component designed to be assessed in tests 1 and 2, had been studied in a wider series of flexibility tests by Draper et al.[8] In this 2-phase pilot study, with 46 and then 21 participants, 6 flexibility measures were assessed for validity and reliability. This study found significant differences between elite climbers and lower grade (novice) and intermediate climbers but not advanced climbers.[8] Our research could not support this finding with only the left foot raise in test 1 identifying a significant but limited difference between the groups (Table 3). Taken together, our study and the previous one perhaps suggest that flexibility is important for climbing, but there may be a threshold above which this fitness component becomes a lesser determinant of performance. Examining the data from the 2 studies, it is a threshold that perhaps differentiates advanced and elite climbers from intermediate and lower grade climbers. Once this threshold is reached, flexibility is not a critical component that differentiates performance at advanced and elite levels. Further research in this area might examine the potential of a new combination of tests, such as the lateral foot raise test and foot-loading flexibility test,[8] to examine whether there is a further differential improvement in flexibility above the intermediate level. In future work with athletes at lower grade and intermediate levels, it may be beneficial to assess flexibility to examine if it is a rate limiter for performance improvement. However, for higher grade climbers perhaps only after returning to climbing after injury would assessment of flexibility merit inclusion in a battery of tests for climbers of advanced and elite level.

Strength, particularly grip strength, has been highlighted by coaches and researchers as a key component of fitness for climbers.[7,12,15] Our results lend support to the importance of strength for rock climbers with significant differences in strength across groups for finger open and crimp with both right and left hand. The results, however, indicate significant differences between advanced and elite climbers in comparison to lower grade climbers and elite climbers with intermediate climbers, but the tests do not differ across all categories of climbers. This data suggest that there is a threshold that distinguishes elite and advanced climbers from lower ability climbers, but not across all grades of climbers.

Test 7, the 1-arm bent-arm hang (right and left arm), also assessed endurance in a similar manner to test 6 (the 2-arm version); however, results showed that this test had limitations regarding lower grade, intermediate and advanced climbers, many of whom scored zero for this test. While the group means, as shown in Figure 2, reveal increases in the mean score by ability group, the results also revealed that all the lower grade climbers, and many of the intermediate and even advanced level climbers, scored zero for the test, meaning that they were not able to hold this position at all. For the 2-arm version, test 6, all climbers were able to score on the test, and it did provide good differentiation between ability groups. As a result of this finding, test 7 could only be recommended as a performance measure for elite climbers; however, test 6 provides a valid and reliable measure for all climbers.

Core stability was identified by our expert panel as an important component for climbing performance. As a consequence, tests 9 and 10 were designed, in an exploratory manner, as potential measures of core stability that might distinguish climbers of differing abilities. Results of testing revealed a similar pattern for both tests, with performance improving up to the advanced level, but with mean scores for elite climbers not as high as those for advanced climbers. Furthermore, intermediate, advanced, and elite climbers performed significantly ($P < .05$) better on both tests than lower grade climbers. Both tests were conducted to volitional failure, and it is possible that while advanced climbers displayed greater core stability than lower grade and intermediate climbers, the elite climbers reached their volitional limit earlier due to psychological aspects, which provides a limitation to both tests. This finding is in keeping with work by Leetun et al,[28] along with Weir et al,[29] who found that while core stability is likely an important performance parameter that is difficult to measure reliably and may be highly sport-specific. Further research on sport-specific measures would be required for climbing, prior to their inclusion in a battery of tests

Table 5 Results of Regression Modeling Using Tests 4, 5, 6, and 8 (Finger Hang, Powerslap, 2-Arm Bent-Arm Hang, and Pull-Ups, Respectively), With the Dependent Variable of Climbing Ability

	Dependent variable: Climbing ability			
	B	SE *B*	*β*	*P*
Combined				
Model 1: $R^2 = .39$; $\Delta R^2 = .38$; $P < .001$*				
Finger hang	0.109	0.013	0.621	.001*
Model 2: $R^2 = .46$; $\Delta R^2 = .45$; $P < .001$*				
Finger hang	0.082	0.015	0.465	.001*
Powerslap	0.060	0.016	0.314	.001*
Model 3: $R^2 = .47$; $\Delta R^2 = .45$; $P < .001$*				
Finger hang	0.077	0.017	0.437	.001*
Powerslap	0.036	0.023	0.191	.123
Bent arm	−0.007	0.024	−0.032	.769
Pull-ups	0.186	0.132	0.193	.162
Female				
Model 1: $R^2 = .52$; $\Delta R^2 = .51$; $P < .001$*				
Finger hang	0.095	0.015	0.723	.001*
Model 2: $R^2 = .56$; $\Delta R^2 = .53$; $P < .001$*				
Finger hang	0.077	0.019	0.582	.001*
Powerslap	0.044	0.028	0.230	.122
Model 3: $R^2 = .58$; $\Delta R^2 = .53$; $P < .001$*				
Finger hang	0.069	0.022	0.526	.004*
Powerslap	0.031	0.032	0.158	.343
Bent arm	−0.034	0.036	−0.176	.354
Pull-ups	0.313	0.221	0.303	.167
Male				
Model 1: $R^2 = .31$; $\Delta R^2 = .30$; $P < .001$*				
Finger hang	0.110	0.020	0.556	.001*
Model 2: $R^2 = .35$; $\Delta R^2 = .33$; $P < .001$*				
Finger hang	0.088	0.022	0.445	.001*
Powerslap	0.071	0.034	0.230	.001*
Model 3: $R^2 = .36$; $\Delta R^2 = .32$; $P < .001$*				
Finger hang	0.081	0.026	0.410	.002*
Powerslap	0.050	0.042	0.165	.229
Bent arm	0.002	0.031	0.008	.953
Pull-ups	0.147	0.177	0.120	.410

*$P < .05$.

for elite climbers. These tests might prove beneficial with lower grade and intermediate climbers in the context of studies designed to improve climber performance.

Practical Application

Valid and reliable sport-specific measures of physiological functioning are vital in the preparation of athletes for competition. The results of our research for the new Olympic sport of rock climbing verify the suitability of the finger hang and powerslap tests as valid and reliable sport-specific performance measures for use by researchers, coaches, and climbers. Coaches could use these tests to assess physiological adaptation brought about through prescribed training programs implemented for climbers from lower grade to the elite levels.

Conclusion

The results of our study suggest that if only one test was possible in a research context, the finger hang, test 4, is a reliable measure that can distinguish across all ability levels. If a more complete picture of climbing performance is required, then researchers might consider including tests 4 and 5 (finger hang and powerslap) with scores on these 2 tests able to account for 35% to 56% of the variance between climbers for males and females, respectively. Given the physiological overlap between tests 4, 6, and 8 and the lack of further explained variance through regression modeling when tests 6 and 8 (2-arm bent-arm hang and pull-ups) are added to the test battery, it can only be recommended to include the finger hang and powerslap in a test battery when using climbers of different ability levels. The results of our study indicate that future research is required to identify tests of flexibility, strength, and core stability that are specific to climbing and can differentiate between ability groups. Future studies should also examine the effect of age on scoring in these tests, in work similar to Malina et al[30] for soccer.

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