An all-out test to determine finger flexor critical force in rock climbers

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ABSTRACT

Purpose: The fatigue resistance of the finger flexors is known to be a key determinant of climbing performance. This study set out to establish the association between the single all-out assessment of finger flexor critical force (ff-CF) and the impulse above CF (W') on climbing performance (self-reported sport and boulder climbing ability). **Methods:** One-hundred and twenty-nine subjects completed an assessment of dominant arm ff-CF, comprised of a series of rhythmic isometric maximum voluntary contractions (CF defined as mean end-test force, kg; *W*' impulse above CF, kg•s). **Results:** The ff-CF protocol resulted in the same force decay to a plateau seen in previous isometric critical torque and critical force tests. Linear regression analysis, adjusting for sex, revealed that CF% body mass explained 61% of sport and 26% of bouldering performance and *W'* per kg body mass explained 7% sport and 34% bouldering performance. A combined model of CF% body mass and *W'* per kg body mass, after adjustment for sex differences was able to explain 66% of sport climbing and 44% of bouldering performance. **Conclusions:** The results illustrate the relevance of the CF threshold in describing the fatigue resistance of the finger flexors of rock climbers. Given ff-CF ability to describe a considerable proportion of variance in sport climbing and bouldering ability we expect it to become a common test used by coaches for understanding exercise tolerance and for determining optimal training prescription.

KEYWORDS

aerobic capacity; exercise testing; fatigue; criterion validity; endurance testing

INTRODUCTION

Rock climbing requires repeated isometric contractions of the finger flexors, which are responsible for the flexion of the metacarpophalangeal and interphalangeal joints[1]. These contractions cause regular periods of ischemia in the forearm muscles; the extent of this ischemia and the subsequent recovery from it has been shown to differentiate between ability groups of rock climbers[2]; as well as disciplines[3], and is likely to be a trainable characteristic[4]. As such, the fatigue resistance of the finger flexors is considered one of the most important factors in climbing performance and it is common for climbers to use a 'fingerboard' for the training of the finger flexors.

While methods for the determination of maximal finger flexor strength in rock-climbers have been described in the literature[5], until recently no tests to determine functional aerobic metabolic capacity, delineating steady and non-steady states existed. Our research group recently presented the first data on the sensitivity of a three session force-time model for determining critical force (CF) in the finger flexors of rock climbers[6], along with the work capacity that may be completed above CF, termed *W'* (often described as the "energy store" component[7]). CF is the maximal force output that still results in a metabolic steady state characterised by a plateau in $\dot{V}O_2$ and in inorganic phosphates[7, 8]. Our paper demonstrated the sensitivity of a simple test for the determination of CF, using equipment readily available to climbers and coaches in most climbing gyms. However, the 'traditional' method that the test was based on, requires subjects to exercise to exhaustion multiple times under different constant workloads, often on separate days, and as a result may be less repeatable and may not always be convenient or practical.

A potential alternative approach would be to identify CF using an 'all-out' test. According to the concept of critical power (CP; the isotonic equivalent of CF), if *W*' is fully utilized (reduced to zero), the maximum power output possible would be CP[9-12]. In other words, if there was a method to completely deplete *W*', the remaining power output should equal to CP. For example, Coats, Rossiter[9] noted that CP was the greatest power output that could be maintained after a fatiguing cycle exercise (i.e., an exercise where *W*' is depleted). In the 3-minute cycling test, the authors asked subjects to perform an all-out effort to deplete *W*' after which the power sustained was equal to CP; this has previously been termed the end-test power (EP)[10-12]. The same relationship between CP and EP has been shown to be true for isometric work and thus CF[13].

Isometric single bout, all-out CF tests have been validated for a number of synergistic muscle groups and exercise modalities, including the forearms using handgrip dynamometry[13]. However, given the lack of specificity of handgrip dynamometry to climbing performance[14, 15], any test of finger flexors CF (ff-CF; force analogue of CP) in climbers must use work to relief ratios and hand and body positions representative of those found in the sport. Thus the primary aim of the present study was to use a climbing specific maximal effort rhythmic isometric fingerboard test to estimate ff-CF in order to assess 1) how much variance in self-reported sport climbing (longer, endurance focused) and bouldering (short and powerful) climbing performance may be explained by CF and W'; 2) what is the combined contribution of CF and W' to climbing performance while adjusting for sex; 3) is there a relationship between maximal isometric finger flexor strength and CF.

METHODS

Subjects

One-hundred and twenty-nine (61 female, 68 male) active climbers of intermediate to higher elite ability (International Rock Climbing Research Association [IRCRA]) grading scale[16]) volunteered to participate in the study (described in **Table 1**). Subjects were recruited on the basis of being familiar with climbing specific forearm training and exhaustive forearm exercise using a fingerboard (at least 3 times per month for the past 3 months), free from injury and having no known musculoskeletal, cardiovascular or respiratory diseases or illnesses. Written informed consent and medical health questionnaires were completed prior to participation. Institutional ethical approval from the University of Derby Human Sciences Research Ethics Committee [15-1819-DGs] was granted prior to data collection and all protocols conformed to the principles of the Declaration of Helsinki.

Table 1: *Subject characteristics, mean ± standard deviation.*

	Female	**Male**
N	61	68
Age (years)	33.9 ± 9.5	30 ± 8.6
Body Mass (kg)	59.2 ± 6.6	72.3 ± 8.8
Height (cm)	164.5 ± 5.8	176.9 ± 7
BMI (kg/m^2)	21.9 ± 4.5	23.1 ± 2.1
Experience (years)	8.6 ± 7.4	7.4 ± 7.3
Performance (sport) (range 11 to 28 IRCRA)	17.4 ± 5.9	18.8 ± 7.9
Performance (bouldering) (range: 12 to 28 IRCRA)	19.5 ± 6.5	21.1 ± 5.6

BMI = body mass index, experience = number of years' experience rock climbing, performance IRCRA international rock climbing research association numeric grading scale

Self-reported climbing ability. Subjects reported their red-point (RP: climb completed after prior practice) grade for which they have completed three successful ascents on three different routes (at the grade) within the six months prior to data collection for both bouldering (short powerful climbs close to the ground) and sport climbing (longer more endurance-focused climbs, using ropes). Subjects also provided data on their preferred discipline; in the form of the discipline they spent the most time practicing. The validity of self-reported climbing ability has previously been established by Draper, Dickson[17], and data were collected following the guidelines set out by the IRCRA[16]. Participants were allocated to groups based on their preferred discipline of sport and/or boulder. Participants were assigned to a single discipline if they (a) indicated a single specialisation, (b) only reported one grade or (c) spent more than 75% of their time practicing a single discipline. If the climber reported between 26 and 74% of their time spent in both disciplines they were included in both groups, unless the difference between the two grades exceeded ± three IRCRA grades. Following this, the bouldering sub-group consisted of 76 and the sport climbing subgroup 85 subjects, with 32 included in both data sets. The grade range was 12 to 28 IRCRA (French grading scale: f6a+ to f8c+) and 16 to 27 IRCRA (Vermin grading scale: V3 to V12) for the sport and boulder group, respectively.

Design

In order to determine the association between a single ‘all-out’ test of ff-CF in rock climbers, subjects completed a single assessment of their maximal isometric finger flexor strength (MIFS) and all-out ff-CF test along with providing demographic details of their climbing history and ability. Subjects were assessed in a rested state (having performed no heavy exercise in the 24 hours preceding the test), having refrained from consuming food and caffeinated drinks for 3 hours prior. Before the assessment, each subject provided health history, informed consent, demographic data, and self-reported RP climbing ability. Subjects were briefed on the purpose of the assessment before completing their own thorough warm-up, followed by a standardised warm-up, they were familiarised with the hand position and intermittent testing protocol. Once completed, they participated in the all-out ff-CF assessment.

Methodology

Data collection. All MIFS and ff-CF assessments were performed on a purpose built climbing specific dynamometer, fitted with a 20 mm deep wooden rung with 10 mm radius. All data were recorded at a frequency of 80 Hz. Prior to each assessment, the dynamometer was calibrated and between each test was returned to 0 kg. Force is presented in kg (rather than Newtons) for ease of comparison with previous literature and for easier interpretation by coaches and climbers.

Hand and body positioning. All tests were performed in a one-handed half-crimp position (90° flexion at the proximal interphalangeal joint [PIP] with the thumb not engaged in the grip). In accordance with Baláš, Panáčková[15], subjects were instructed to ‘hang’ with their dominant arm extended above the head (~170 to 180° shoulder flexion), maintaining a slight bend in the elbow with shoulders engaged. Body position was controlled, asking subjects to maintain level shoulders, with their chest square to the rung and the same foot as the hand being tested in front of the other (***Figure 1***). For both the MIFS and ff-CF tests, subjects were instructed to develop as much force on the rung as possible by ‘hanging’ (not ‘pulling’) from the edge. If the subject was capable of generating force that was close to, or greater than, their own body mass then weight was added to a climbing sit harness around their waist so that they remained with their feet on the ground.

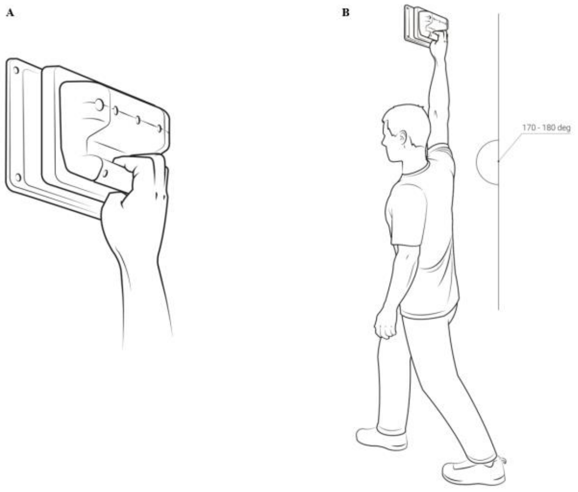

Figure 1: *A) Half-crimp grip position on the 20mm rung. B) Standardised body position with level shoulders, chest square to the dynanometer and the same foot as the hand being tested in front of the other.*

Warm-up. Before beginning the assessment protocol all subjects completed a standardised self-directed warm-up consisting of 5-minute pulse-raising activity; mobilising (walking jogging skipping, etc); 5-minutes of climbing; and a series of 7:3s work-to-rest ratio hangs on the testing edge in a half-crimp position at 50% and 75% of perceived maximum force.

Determination of maximal isometric finger strength (MIFS). MIFS was determined by performing a series of three single-handed 5-s maximal isometric contractions on the rung. Only the dominant arm was tested. Subjects were provided with 120s rest between each attempt; 120s was determined to be sufficient based on extensive testing of the protocol and has been previously documented in the literature[5, 6, 18]. Force (kg) and time (s) data were recorded continuously throughout. Peak force data are reported as absolute units (kg) and relative to body mass (%).

Determination of finger flexor critical force (ff-CF). The determination of CF was based on the methodology of Kellawan and Tschakovsky[13] involving fatiguing muscle actions of the finger flexors. ff-CF was determined by performing a series of rhythmic isometric maximum voluntary contractions on the rung, in a half crimp position (**Figure 2**) with a 7:3s work-to-rest ratio, as previously used when assessing climbers CF[6]. During the ‘work’ phase, subjects were instructed to produce as much force as possible whilst maintaining a half crimp position. During the ‘rest’ phase, to standardise, practice subjects were instructed to be in the anatomical position, during which they could apply climbing chalk but not shake their forearms or hands (shaking of the hands is known to aid recovery e.g. Baláš, Michailov[19]). Throughout the tests, subjects were able to visually observe their force output, which was continuously displayed on a screen. Subjects were verbally encouraged to reach their maximum force on every contraction, to achieve a ‘square wave’ during each maximal voluntary contraction, and to engage only the muscles of the forearm rather than ‘pulling up’. Force (kg) and time (s) data were recorded continuously throughout. Length (s), peak and mean force (kg) and the force-time impulse (kg•s) were determined for every contraction for all tests. CF was defined as mean end-test force, using the last six contractions of the test (the last 60 s[10]). A one standard deviation (SD) cut-off was used for the inclusion of contractions in the calculation of end-test force to reduce the effects of erroneous contractions occurring due to slippage or the adjustment of hand position, that occurred in a small number of assessments. The W' was calculated as the impulse measured above the end-test force during the ff-CF test.

Initially, ff-CF assessments were 30 contractions in length (five-minutes; n = 46), however, it was observed that subjects were able to achieve a plateau in their end-test force output after 24 contractions (four minutes; n = 83). Given the maximal nature of the testing, the discomfort caused when asking subjects to complete maximal contractions and the possibility of injury when performing maximal contractions when highly fatigued, the decision was made to reduce the testing time to four minutes for subsequent assessments (n = 83). While the data presented uses end-test force from the last 60s of both 5- and 4-min tests, cutting off the data at 4-min for all assessments does not produce materially different results or change the conclusions of the paper. Indeed, for the 5-min tests the agreement between 4- and 5-min end-test force was good (ICC = 0.650), with only small positive bias (+1.6 kg [LoA of -1.9 to 5.2 kg]). We speculate that the positive bias was due to an element of involuntary pacing[20], as the subjects knew of the remaining min of the test. Given these considerations, the decision was made to use data from the last 60-s of each respective test.

The reliability of a similar handgrip ff-CF protocol has been demonstrated by Kellawan and Tschakovsky[13] with excellent test-retest reliability (n = 10) with small within-subject test-retest variation (coefficient of variation 6.8%), small change in the test-retest group mean (typical error 15.3 N, 5.5%), and a high test-retest correlation (Pearson product correlation coefficient (r) =0.91, intra-class correlation coefficients (ICC) = 0.94, p = 0.01). ff-CF pilot data from our lab (n = 7) also demonstrated excellent test-retest reliability with small bias (CF: mean difference (MD) = -0.03 kg, limits of agreement (LoA) = -2.45 to 2.4 kg; *W*': MD = -139 kg•s, LoA = -976 – 698 kg•s) and meet the ICC criterion value (0.75) for excellent reliability[21] (CF ICC = 0.96; W' ICC = 0.87).

Statistical Analysis

Normal distributions were ascertained, and homogeneity of variance was confirmed after visual assessment of the frequency histogram and Shapiro–Wilk's test, respectively. All values are reported as mean ± SD. All analysis was conducted using the SPSS statistical software package (IBM SPSS statistics, release 25, 2017, SPSS Inc., Chicago, IL, USA). To examine the extent to which the physiological responses (CF, CF as a % body mass, W' and W' per kg body mass) predicted self-reported sport and boulder climbing performance, a series of linear regression analyses were performed. Physiological responses were entered into separate models as independent variables both with and without adjustment for the covariate of sex (female coded 1, male coded 0), a combined CF as a % body mass and W' per kg body mass model was also calculated.

RESULTS

ff-CF test characteristics

All subjects were able to complete the CF test in full. In almost all cases, the force decayed to a plateau, a typical example is shown in ***Figure 2***. A small number did not fit this typical pattern, with only a small decline in force across the test and/or considerable end-test variability, these have been excluded (n = 8), of note these subjects were all lower ability with RP grades of < 15 on the IRCRA scale (f6c) and were observed during both the longer 5-minute assessments (n = 4) and shorter 4 minute assessments (n = 4). Subjects reached the onset of a plateau (defined as within 10% of end-test force) in 156.9 ± 47.1s.

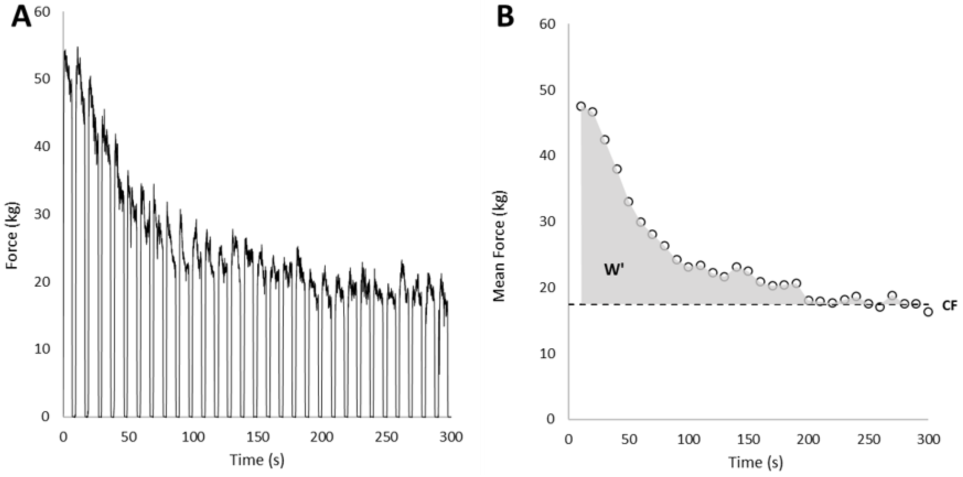

Figure 2: *Force output during a maximal effort CF test in a representative subject. Panel A: Raw force trace. Panel B: Mean contraction force, plotted for all contractions, with CF (kg) shown as a dashed line, representing mean end-test force; and W' (kg•s) shown as a grey shaded area, representing the sum of the impulse above end-test force.*

Association between ff-CF, W' and self-reported climbing ability

Linear regression analysis (***Table 2 and Figure 3***) revealed that the association between physiological variables and self-reported ability were greatest when expressed as a percentage of body mass, for brevity only these will be discussed. The CF as a % body mass was positively associated with both sport and boulder performance. After adjustment for sex differences, a 1% increase in CF was associated ($p < .0005$) with an increase of 0.292 (95% CI: 0.236 to 0.347) sport climbing grades (IRCRA) and 0.174 (95% CI: 0.089 to 0.258) boulder climbing grades (IRCRA). The percentage of variance (R^2) explained were 61% and 26% for sport and boulder disciplines, respectively. The *W'* per kg body mass was not associated with sport climbing performance but was positively associated with boulder performance. After adjustment for sex differences, a 1 kg·s increase in W' per kg body mass was associated ($p < .0005$) with an increase of 0.182 (95% CI: 0.112 to 0.253) in boulder climbing grades (IRCRA). The R^2 explained was 34%. A combined model of CF as a % body mass and *W'* per kg body mass produced significant models for both sport climbing and bouldering, after adjustment for sex differences, the R^2 explained was 66% for sport and 44% for bouldering performance.

Table 2: Linear regression models: association between CF (calculated from end-test force), CF as a percentage of body mass (CF % BM), W' (impulse measured above the end-test force during the ff-CF test) and W' per kg body mass (W' x kg BM) and sport and boulder climbing ability.

	Independent variable	**Linear Regression Models**		***β***	**LCI**	**UCI**	**P**	**R^2**	**AdjR^2**
Sport red-point performance (IRCRA)	CF	Model 1	*Unadjusted*	.397	.306	.488	< .0005	.490	.484
		Model 2	*Sex (F=1, M=0)*	.412	.309	.516	< .0005	.493	.480
	CF % BM	Model 1	*Unadjusted*	.302	.247	.357	< .0005	.604	.599
		Model 2	*Sex (F=1, M=0)*	.292	.236	.347	< .0005	.618	.608
	W'	Model 1	*Unadjusted*	.001	.000	.002	.193	.022	.009
		Model 2	*Sex (F=1, M=0)*	.000	-.002	.001	.776	.081	.057
	W' x Kg BM	Model 1	*Unadjusted*	.093	.000	.186	.050	.048	.036
		Model 2	*Sex (F=1, M=0)*	.047	-.056	.151	.356	.089	.066
	CF % BM **&** W' x Kg BM	Model 1	*Unadjusted*						
			CF % BM	.308	.257	.358	< .0005	.673	.665
			W' x Kg BM	.112	.057	.167	< .0005		
		Model 2	*Sex (F=1, M=0)*						
			CF % BM	.309	.256	.361	< .0005	.673	.660
			W' x Kg BM	.114	.050	.178	.001		
Boulder red-point performance (IRCRA)	CF	Model 1	*Unadjusted*	.238	.123	.353	< .0005	.196	.185
		Model 2	*Sex (F=1, M=0)*	.200	.066	.334	.004	.210	.187
	CF % BM	Model 1	*Unadjusted*	.194	.109	.279	< .0005	.230	.219
		Model 2	*Sex (F=1, M=0)*	.174	.089	.258	< .0005	.284	.263
	W'	Model 1	*Unadjusted*	.003	.002	.004	< .0005	.281	.270
		Model 2	*Sex (F=1, M=0)*	.002	.001	.004	< .0005	.266	.265
	W' x Kg BM	Model 1	*Unadjusted*	.200	.132	.269	< .0005	.328	.319
		Model 2	*Sex (F=1, M=0)*	.182	.112	.253	< .0005	.356	.338
	CF % BM **&** W' x Kg BM	Model 1	*Unadjusted*						
			CF % BM	.148	.074	.222	< .0005	.454	.439
			W' x Kg BM	.170	.107	.234	< .0005		
		Model 2	*Sex (F=1, M=0)*						
			CF % BM	.140	.056	.215	< .0005	.467	.444
			W' x Kg BM	.160	.094	.225	< .0005		

Note: β = beta, regression equation; LCI= lower confidence interval (95%); UCI= upper confidence interval (95%); F female; M male

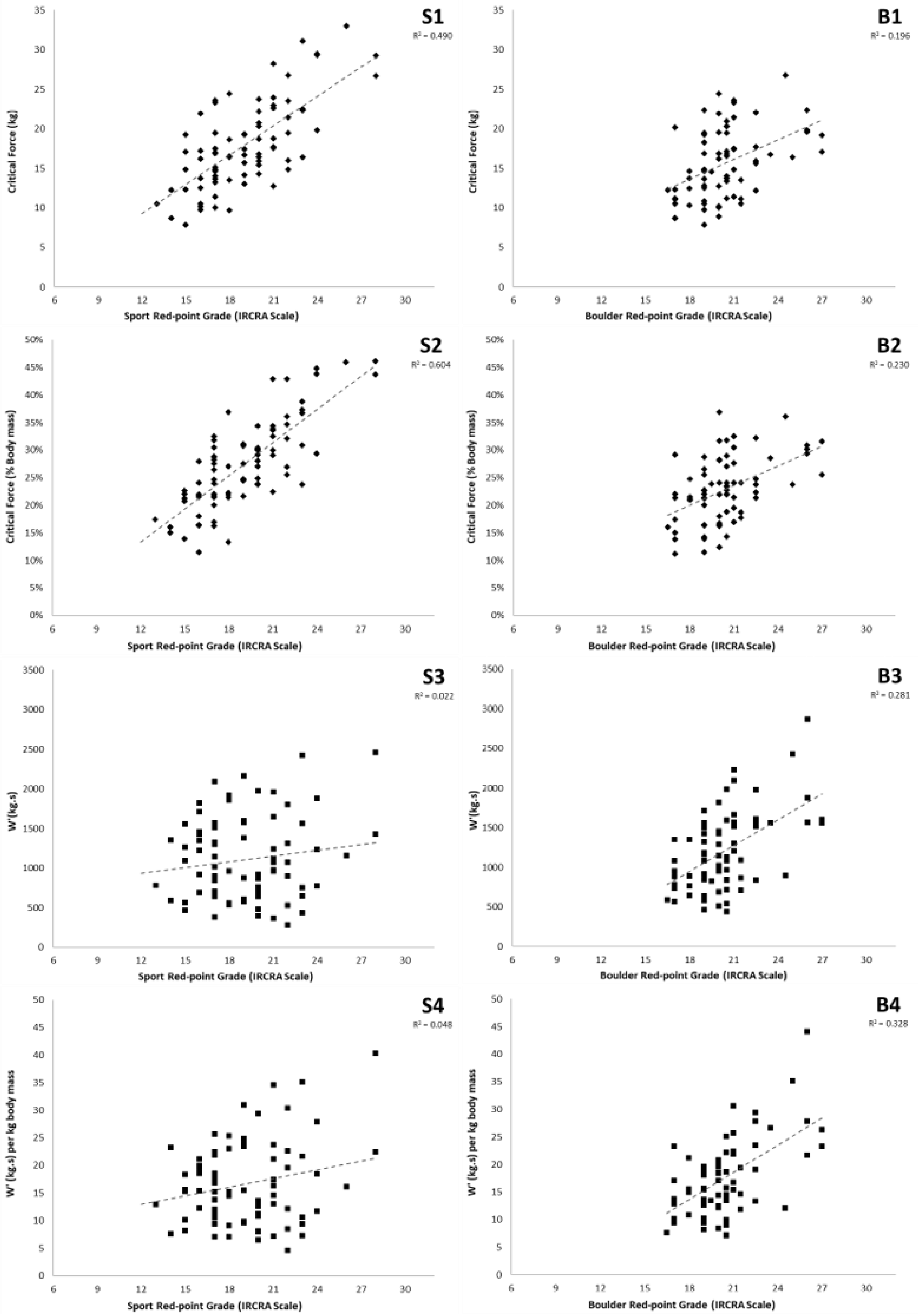

Figure 3: *Linear regression models for CF (critical force, calculated from end-test force; Panels 1), CF as a percentage of body mass (CF % BM; Panels 2), W' (impulse measured above the end-test force during the ff-CF test; Panels 3) and W' per kg body mass (W' x kg BM; Panels 4) and sport (Panel prefix S) and boulder (Panel prefix B) climbing ability (IRCRA international rock climbing research association numeric grading scale).*

Association between ff-CF, W' and peak MIFS

There was a significant association with MIFS peak force and both CF ($R^2 = 0.301$; $p < 0.0005$) and *W*' ($R^2 = 0.445$; $p < 0.0005$), illustrated in **Figure 4**. The strength of the relationship increased for both when sex was entered as a covariate ($R^2 = 0.585$, $p < 0.0005$ and $R^2 = 0.613$, $p < 0.0005$ for ff-CF and *W*', respectively). The strength of the relationship between 40% MVC, a commonly used exercise intensity in climbing training and research, and CF is shown in **Figure 4c** ($R^2 = 0.300$; $p < 0.0005$).

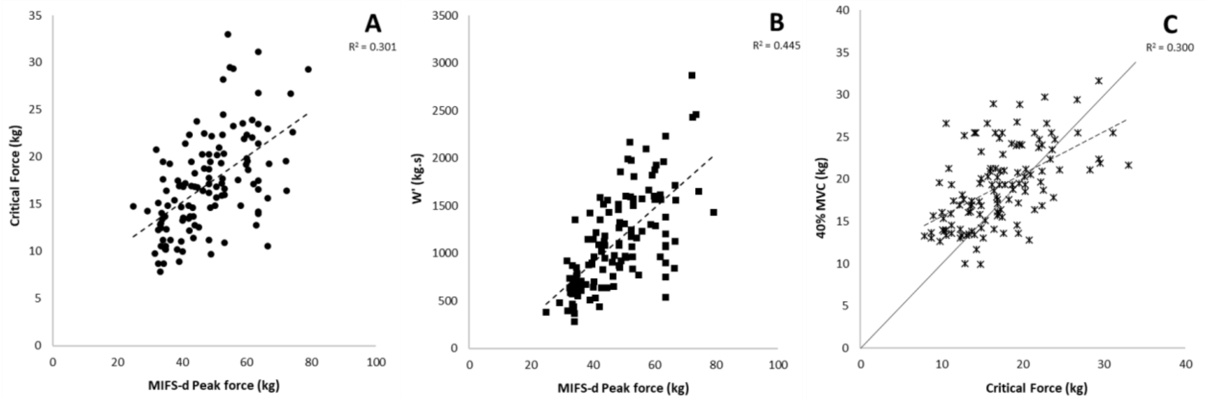

Figure 4: *The association between MIFS peak force and Panel A: ff-CF (kg) $R^2 = 0.301$; $p < 0.0005$ and Panel B: W' (kg.s) $R^2 = 0.445$; $p < 0.0005$. Panel C The relationship between the percentages of MVC that ff-CF occurs at and 40% of MVC, solid line is the line of identity where ff-CF = 40% MVC $R^2 = 0.300$; $p < 0.0005$.*

DISCUSSION

The key findings of this study were: 1) The ff-CF protocol, comprised of a series of rhythmic isometric maximum voluntary contractions of the finger flexors in a flexed 'half-crimp' position, resulted in the same force decay to a plateau that has been seen in isometric critical torque[10] and CF[13] tests. 2) The association between ff-CF and self-reported climbing ability was excellent, particularly when values were expressed relative to body mass. Combined, ff-CF as a percentage body mass and *W'* per kg body mass produced significant models for both sport climbing and bouldering; after adjustment for sex differences, the models R^2 were 66% for sport and 44% for bouldering performance. 3) There was a strong positive association between MIFS and both ff-CF and *W'*. Together, these findings support the use and applicability of an all-out test of ff-CF in climbers for identifying CF and *W'*.

The decay in force to a plateau across each test was, on the whole, consistent with previous all-out tests across exercise modalities including critical power[22], critical speed[23], critical torque[10] and CF[13]. The mean time to a plateau of the subjects in the present study was 157s (~16 contractions). However, of the 129 ff-CF tests conducted, a small number (*n* = 8; 6% of subjects) did not fit the typical pattern, with only a small decline in force and/or considerable end-test variability and as a consequence they were excluded from analysis. Notably, these subjects were all lower ability with sport grades of <15 on the IRCRA scale (<f6c) and boulder grades of <19 on the IRCRA scale (< Font 6B+). It would appear that the test is not appropriate for climbers of a lower ability, who are likely to be newer to the sport and do not currently have the ability to effectively perform a test of this nature. For those who the test is appropriate for, we would recommend the use of a 4-min test when using a 7:3s work to relief ratio and, while it is not possible to predict a suitable test time for other work-relief ratios, it is likely that less frequent and/or shorter contractions will require a longer test to fully deplete *W'*.

The fatigue resistance of the finger flexors is frequently cited as one of the most important factors when describing physical climbing performance along with maximal force production. However, intermittent exhaustive tests conducted at percentages of MVC (typically 40% or 60%) have only been shown to differentiate between climbers of polar abilities (i.e. non-climbers and those of elite ability)[1, 24] but not when there is only a small ability difference[24, 25], or between disciplines[3]. Further, as far as we are aware, there is no research looking at the relationship between time to exhaustion during intermittent contractions and self-reported climbing ability. Consequently, not only is the present study the first to demonstrate the feasibility of a single session all-out assessment of ff-CF in climbers, it is also the first to show the extent of the importance of the fatigue resistance of the finger flexors across a wide range of abilities. The combined model, after adjustment for sex differences explained 67% of sport and 47% of bouldering performance (R^2). Differences in the relative contribution of ff-CF and *W'* were also observed between disciplines, with a greater importance placed on ff-CF in sport climbing and *W'* in bouldering performance models. Given the longer, endurance focused nature of sport climbing the fatigue resistance provided by higher CF is intuitive, likewise a greater energy store component, *W'*, and relatively lower CF fits the modality of the short, powerful nature of bouldering.

Exhaustive tests using intermittent contractions at percentages of climbers MVC have been used to investigate the exercise capacity of the finger flexors of climbers, with varying success[1, 3, 24, 25], as previously discussed. Based on the findings of previous research and the results of the present study there would be value in using ff-CF or using exercise intensities based on percentages of ff-CF, but not MVC, as the dependent variable in future research for two reasons. Firstly, it is well-established that percentages of MVC are not related to metabolic exercise intensity domains[26, 27]. Secondly, unlike in untrained subjects[13], there was a relationship between CF as a percentage of body mass and MVC. As a consequence, while this is unlikely to be a causal relationship, prescribing exercises at an intensity of 40% MVC, typical of many studies, may result in some individuals performing a task at intensities that were <CF and others >CF and working in dramatically different exercise intensity domains. The same issue was demonstrated by our previous two-arm data[6] and the present studies single-arm data clearly supports this finding (**Figure 4C**). Therefore, in the future, ff-CF tests should be used to determine exercise intensities in order to mitigate the potential confounding issue of exercise intensities based on MVCs.

This study has made significant steps in the development of a climbing specific method for the determination of single-arm isometric CF and *W'*; however, a number of limitations should be acknowledged. (1) The method described focuses on ff-CF, however, given the climbing specific testing position employed with the arm extended above the head with the shoulder engaged it is conceivable that performance is in part also limited by the strength and endurance characteristics of other muscle groups, for example the biceps and shoulder girdle. There would be value in establishing the relative individual contribution of the finger-flexors (e.g. using arm-fixation) and/or the upper arm and shoulder girdle (e.g. using a large hold/edge where the finger flexors are not the limiting factor). (2) Necessarily, the ff-CF test is maximal and performed at a set work-relief ratio, however this does not wholly represent the varying intensities and contraction lengths seen in the sport. Future research should consider the applicability of a test based on intermittent bouts of exercise[28]. Those wishing to employ the described methodology are also reminded that while a 4-min test is appropriate with 7:3 s work-relief ratio, it is likely that less frequent and/or shorter contractions will require a longer test. (3) While the results of the present study present compelling data on the association between self-reported ability and CF and W', further research is needed to (a) verify the results presented and their agreement with CF and W' ascertained through multiple constant work rate tests, (b) determine variables that may moderate the strength of the relationship between CF and W' and self-reported ability, and (c) establish the trainability of these characteristics.

CONCLUSIONS

To conclude, the results of the present study demonstrate the applicability of a climbing specific method for the determination of single-arm isometric CF and *W'*, highlighting the importance of the fatigue resistance of the finger flexors in rock climbing performance. For the majority who were able to reach a stable end-test force, ff-CF as a percentage body mass and *W*' per kg body mass produced significant models for both sport climbing and bouldering. Due to the clear relevance of ff-CF and the inconclusive results of exhaustive tests conducted at percentages of MVC, we would recommend that exercise intensities be determined relative to CF. Further research is necessary to determine if ff-CF and *W'* are trainable characteristics in climbers and the efficacy of interventions based on exercise intensities determined relative to ff-CF end-test force.

PRACTICAL APPLICATIONS

Where the equipment is available, the maximal isometric ff-CF protocol described provides researchers and coaches with a method of assessment that is highly relevant and quick to administer. We have previously set out a method of determining CF using equipment that is found in most climbing gyms and where a dynamometer is not available this may be used[6]. However, the present all-out ff-CF method offers several advantages, including being quicker, possibly more reliable due to the need for only one exhaustive test and the ability to also assess contraction duration, impulse, peak and average force. Due to its demanding nature, we recommend ff-CF as an advanced assessment to be completed only with climbers of a higher ability (at least sport f7a and boulder F6C). Finally, given its relevance to both sport climbing and bouldering ability we expect it to become a common test used by coaches for understanding exercise tolerance and for determining optimal training prescription.

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