The Determination of Finger Flexor Critical Force in Rock Climbers

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Abstract

Purpose: To determine if the mathematical model used for the estimation of critical force (CF) and the energy store component *W'* is applicable to intermittent isometric muscle actions of the finger flexors of rock climbers, using a multi-session test. As a secondary aim, the agreement of estimates of CF and *W'* from a single-session test were also determined. The CF was defined as the slope coefficient and *W'* the intercept of the linear relationship between total "isometric work" (W_{lim}) and time to exhaustion (T_{lim}). **Methods:** Subjects performed three (separated by either 20 m or >24 h) tests to failure using intermittent isometric finger flexor contractions at 45, 60 and 80% of their maximum voluntary contraction (MVC). **Results:** Force plotted against T_{lim} displayed a hyperbolic relationship, correlation coefficients of the parameter estimates from the work–time CF model were consistently very high ($R^2 > 0.94$). Climbers mean CF was 425.7 ± 82.8 N (41.0 ± 6.2% MVC) and *W'* 30882 ± 11820 N·s. Good agreement was found between the single and multi-session protocol for CF (ICC$_{(3,1)}$ = 0.900, 95% Confidence Interval [CI$_{95\%}$] 0.616 – 0.979), but not for *W'* (ICC$_{(3,1)}$ = 0.768, CI$_{95\%}$ 0.190 – 0.949). **Conclusions:** The results demonstrated the sensitivity of a simple test for the determination of CF and *W'*, using equipment readily available in most climbing gyms. While further work is still necessary, the test of CF described is of value for understanding exercise tolerance and determine optimal training prescription to monitor improvements the performance of the finger flexors.

Key Words: Rock climbing; exercise testing; anaerobic capacity; power–duration relationship; critical force

Introduction

Rock climbing requires repeated isometric contractions of the finger flexors, which are responsible for flexion of the metacarpophalangeal and interphalangeal joints[1]. These contractions cause regular periods of ischemia in the forearms; the extent of this ischemia and

the subsequent recovery from it has been shown to differentiate ability groups of rock climbers[2], 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. However, while methods for the determination of maximal finger flexor strength have been described in the literature[5], as yet there are no tests to determine functional aerobic metabolic capacity, delineating steady and non-steady states in rock-climbers.

During high-intensity muscular exercise, the time for which exercise can be sustained decreases as a hyperbolic function of increasing power, speed, tension, or force (e.g. power illustrated in *Figure 1*)[6]. Consequently, performance and the point of exhaustion, is highly predictable. When work data are plotted against time, it may be observed that power output falls as a function of the duration of exercise, and that it levels off (asymptotes on the abscissa). The point of levelling off is termed critical power (CP), and is defined as the maximum work that a muscle group can maintain for an extended duration without fatigue, while the work capacity that may be completed above CP is termed *W'* (often described as the 'energy store' component)[6]. While CP is limited by the availability of oxidative substrates (glycogen), hyperthermia and central fatigue, *W'* is limited by progressive depletion of high-energy phosphates and accumulation of metabolites associated with peripheral fatigue[7]. Despite the majority of research exploring isotonic muscle actions, the same relationship is also true of isometric muscle action, despite no mechanical work being done[8, 9]. Previous research investigating isometric work has utilised an analogue of mechanical work termed limit work (W_{lim}; N·s), which is calculated as the force (F; Newton [N]) of the isometric muscle action multiplied by the time to exhaustion (or limit time, T_{lim}; s) that the F can be maintained. As this paper is concerned with finger flexor force the isometric analogues critical force (CF; N) and *W'* (N·s) will be referred to (e.g. Hendrix et al.[8]).

Methods for the determination of CF have been demonstrated for a number of synergistic muscle groups[9, 10]. However, there is a paucity of data describing the use of CF tests in climbers, specifically for the finger flexors. While the importance of fatigue resistance of the finger flexors in climbers has been investigated[2, 11], this is the first study to utilise a threshold test applicable to climbing populations. Kellawan and Tschakovsky[10] have previously described a methodology for the determination of CF in the forearms, using grip dynamometry. However, given the lack of specificity of grip dynamometry to climbing performance[12, 13], there is a need for ecologically validated tests within the sport. Determining finger flexor CF would be advantageous in understanding exercise tolerance in climbers, and determining optimal training prescription and monitoring. Therefore, the present study aims to determine if the mathematical model used for estimating CF and *W'* is applicable to intermittent isometric muscle actions of the finger flexors of rock climbers, using a multi-session test. As a secondary aim, the agreement of estimates of CF and *W'* obtained in a single-session with 20 m of recovery will be compared to those obtained from the multi-session test (>24 h recovery).
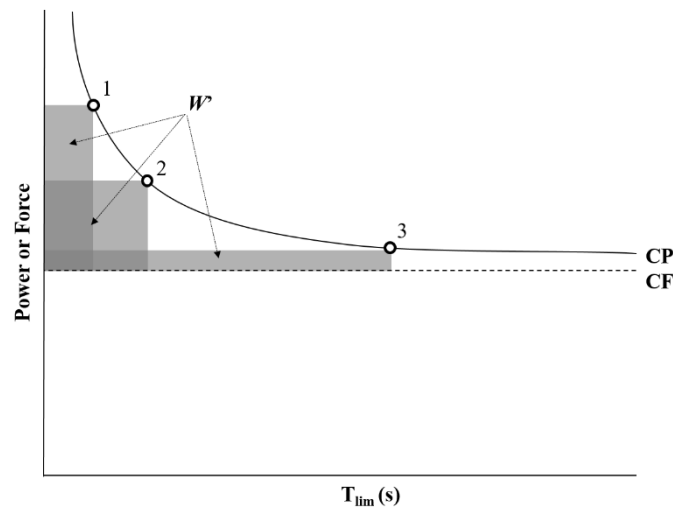
Figure 1: *Illustration of the power or force-time relationship for high intensity exercise. The numbered points (1 – 3) represent time-to-exhaustion for independent tests at the power or force designated for each. The hyperbolic relationship is defined by two parameters: the asymptote for power or force (critical power - CP, critical force - CF) and the curvature constant W' (represented by the rectangular boxes above CP/CF and expressed in kJ or N·s, respectively). The CP/CF defines the upper boundary of the heavy intensity domain and represents the highest power sustainable without drawing continuously upon W'. Severe-intensity exercise, above CP/CF, results in exhaustion when W' has been expended.*

Methods

Subjects

Eleven healthy male rock-climbers (mean ± SD: age 27 ± 6 yr, height 1.76 ± 0.06 m, body mass 69.2 ± 4.7 kg) volunteered to participate. Subjects were included based on having a minimum of three years climbing experience and no known cardiovascular or respiratory diseases or illnesses. Subjects were familiar with climbing specific forearm training, exhaustive forearm exercise and were free from injury. Using self-reported ability[14] the subjects were categorised as Advanced to Elite level climbers (maximum 6 month red-point grade of French 7b – 8b+; UIAA IX- – X+). The subjects gave written informed consent to participate in this study, which was approved by the Universities Human Sciences Research Ethics Committee (17-1718DGs), conforming to the Code of Ethics of the World Medical Association (Declaration of Helsinki).

Design

Subjects were required to visit the laboratory on four occasions. During the first visit, they completed a standardised warm-up, were familiarised with the equipment and testing protocol, completed the finger flexor maximum voluntary contraction (MVC) test as well as intermittent submaximal isometric contractions requiring 80%, 60%, and 45% of MVC to exhaustion, with a work to relief ratio of 7:3 s and 20 m of recovery between. The subsequent three visits were randomised in order. During each visit, subjects performed the same

standardised warm-up followed by one of the three separate series of intermittent isometric contractions to failure at 80%, 60%, or 45% of MVC. Force and T_{lim} were recorded on each occasion.

Subjects attended the laboratory at the same time of day (± 2 h) and in a rested state (having performed no heavy exercise in the 24 h preceding the test) having refrained from consuming food and caffeinated beverages for 3 h prior. Before each session subjects completed a standardised warm-up consisting of 5 m pulse-raising activity, mobilising (walking, jogging skipping etc.), 5 m of climbing, and 4 sets of 40 s of 7:3 hangs on the testing rung in a half-crimp position (*Figure 2a*). Each subjects attended four testing sessions, which were completed within a 2-week period, visits were separated by a minimum of 24 h.

Methodology

Testing rung and hand positioning: During all visits, each finger hang was performed on a Lattice Training (Sheffield, England) rung (20 mm deep, 10 mm radius; *Figure 2a*). All tests were performed in a two-handed half-crimp hang position (90° flexion at the proximal interphalangeal joint [PIP] with the thumb not engaged in the grip). In accordance with Baláš et al.[13], subjects were instructed to hang with arms extended above the head (180° shoulder flexion), maintaining a slight bend in the elbow with shoulders engaged (*Figure 2b*). To modify the load, weight in 0.5 kg – 5 kg increments were either added or removed using a pulley system attached to a climbing harness worn by the subject.
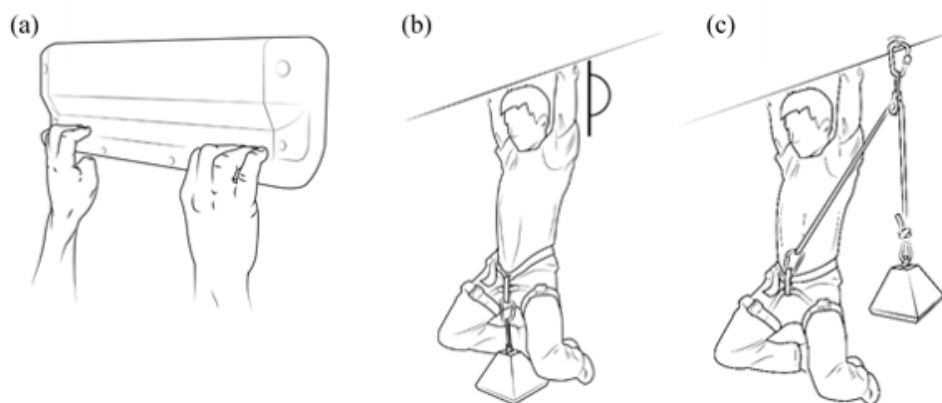

Figure 2: (a) 'half crimp' position, 90° flexion at the proximal interphalangeal joint (PIP) with the thumb not engaged in the grip; (b) climber performing two-handed hang on lattice rung, with slight bend in arms and engaged shoulders with additional weight; and (c) with assistance [Note: pulley and weight were located directly in front of the subject, this is not shown in the illustration]. Illustrations reproduced with permission from Lattice Training Images.

Determination of MVC: Finger flexor MVC was determined during the first visit by performing a two-handed half-crimp hang. The MVC was defined by the maximum weight held for seven seconds whilst maintaining a half crimp position. Subjects were allowed up to six attempts, weight was added to the subject's body mass until finger flexor and extensor MVC was achieved. A 2 m rest was provided between each MVC attempt.

Determination of Critical Force: The determination of CF was based on the methodology of Monod and Scherrer[9], and more recently Hendrix et al.[8], involving fatiguing muscle actions of the finger flexors at three different intensities. However, instead of continuous fatiguing isometric exercise used in these previous studies, subjects performed intermittent isometric exercises at a 7:3 work-to-rest cycle. Intermittent, but not continuous, time to failure were chosen as it has previously been shown to differentiate between climbers and non-climbers[1, 15]. During the 'work' phase, subjects were instructed to maintain a half crimp position while hanging at a predetermined percentage of their body mass (% MVC). 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 et al.[16]). The goal was to achieve time to exhaustion T_{lim} between 1 and 15 min, within which the time to failure should be hyperbolic[7]. Pilot work suggested that the CF lay below 45% MVC for most climbers, thus to ensure that fatigue would occur in less than 20 m, work was performed at 80%, 60% and 45% of MVC. Testing was halted if the subject exceeded 20 m. As previously described, weight was either added or subtracted from the subject's body mass using a harness and pulley system to achieve the desired percentage of MVC.

Exhaustion was defined as failure to complete a hang or failing to maintain the hold in the half crimp position, determined visually by the experimenter. Visual and audio cues were given via an electronic device to signal the work and rest intervals. Subjects were blind to the relative intensity of each trial (percentage of MVC) but were informed that the task was fatiguing, that they should keep going until they were no longer able to hold the rung, and that the accuracy of the test was reliant on continuing to failure. Elapse time and clocks were hidden from the subject's sight. Subjects were given verbal encouragement to reach task failure.

The W_{lim} for the intermittent isometric muscle actions was calculated by multiplying the F of the muscle actions by the T_{lim}. The CF was determined from the three submaximal tests (multi-session protocol and single-session protocol). Linear regression was used to provide two sets of CF and *W'* estimates from the results of these trials, using the work–time (eq. 1) and the 1/time models (eq. 2), see ***Figure 3 (b)*** and ***(c)***. The work-time model plots W_{lim} against T_{lim} (time to exhaustion; s), *W'* is given by the Y-intercept and CF as the slope of eq. 1. The 1/time model plots force against $1/T_{lim}$, CF is given by the Y-intercept and *W'* as the slope of eq. 2.

(eq. 1) $W_{lim} = T_{lim} \cdot CF + W'$

(eq. 2) $F = W' \cdot \left(\frac{1}{T_{lim}} \right) + CF$

W_{lim} = Work Limit (N·s); T_{lim} = Time limit (s); CF = Critical Force (N); W' = Energy store component (N·s); F = Force (N)

Statistical Analysis

Normal distributions were ascertained, and homogeneity of variances was confirmed after visual assessment of the frequency histogram and a Shapiro–Wilk's test, respectively. All values are reported as mean ± SD. Correlation coefficients were calculated for CF and *W'*

derived from the work–time and 1/time models. The agreement between the values of CF and W' obtained from the single session test was compared to the multi-session test by calculating the intra-class correlation coefficient (ICC, model 3.1)[17]. Bland–Altman plots were constructed for CF and W' and 95% limits of agreement (LoA) were calculated for both. Analysis was conducted using the SPSS statistical software package (IBM SPSS statistics, release 24, 2016, SPSS Inc., Chicago, IL, USA).

Results

Three parameter multi-session critical force protocol

All subjects data from the multi-session critical force protocol demonstrated a hyperbolic relationship between force (y-axis; N) and T_{lim} (x-axis; s), where the CF is indicated by the force asymptote and the W' is the curvature constant *(Figure 3a)*. *Figure 3* also demonstrates the derivation of the parameter estimates using the work–time (*b*) and 1/time models (*c*). Although there were no significant differences in the parameter estimates from the different CF models, and the correlation coefficients were consistently very high for both models (work–time model range, ($R^2 = 0.94 - 1.00$; 1/time model range, $R^2 = 0.86 - 1.00$), the work–time model generally fit the data better and was, therefore, used for subsequent analysis.
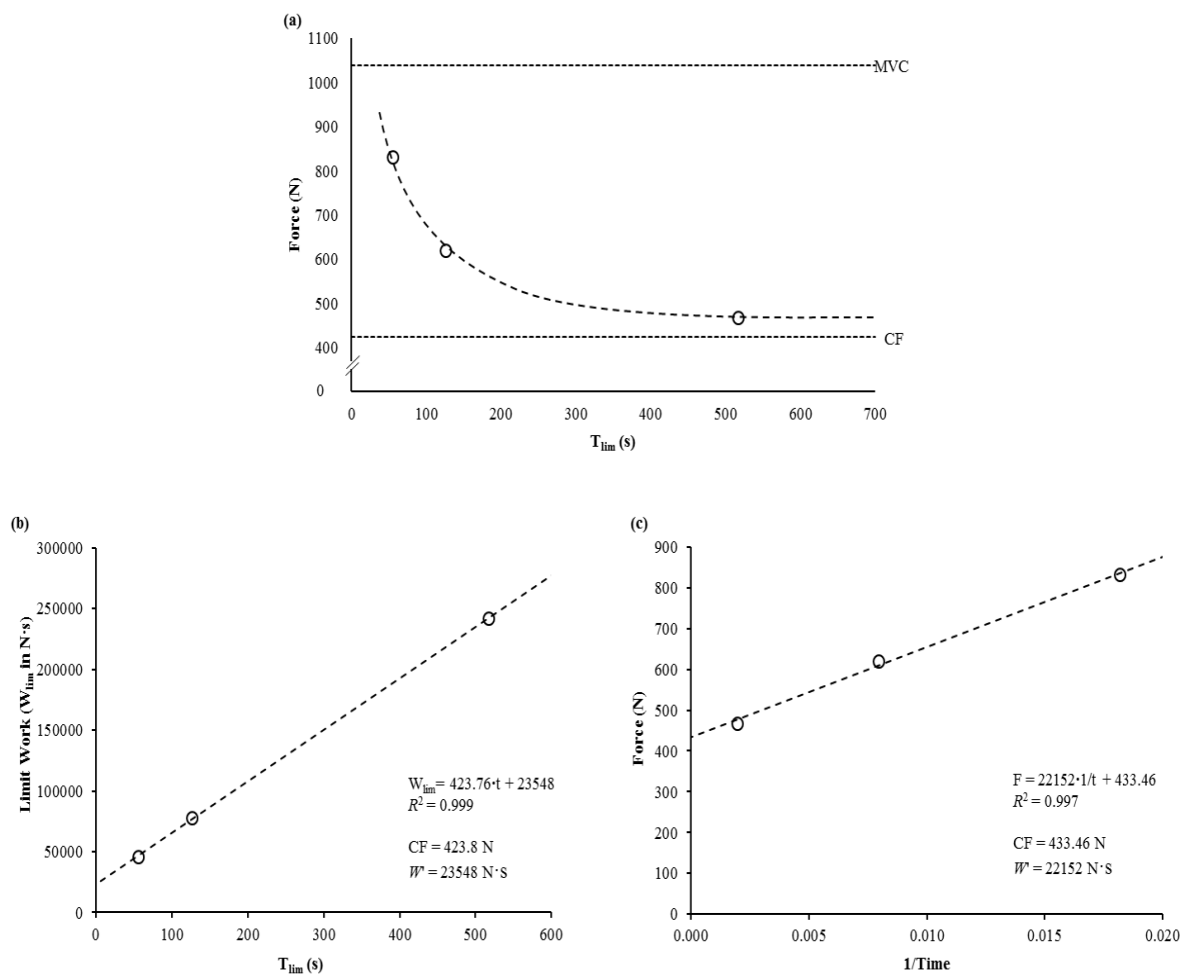

Figure 3: An example of the hyperbolic relationship between the force and time to task failure (A), and the critical force (CF) and the curvature constant (W') estimates from the linear work–time (B) and the 1/time (C) CF models, of a representative subject.

Mean CF was 425.7 ± 82.8 N (range: 260.1 to 486.4 N) and *W'* was 30882 ± 11820 N·s (range: 13824 to 54795 N·s) when the results of the multi-session trials were modelled using the work-time model (***Table 1***). Critical force expressed as a percentage of MVC was 41.0 ± 6.2%. All subjects continued to task failure at 80% and 60% MVC (mean T_{lim} 80%: 75 ± 29 s; 60% 235 ± 150 s), however, three of the 11 subjects did not reach volitional fatigue at 45% (T_{lim} 626 ± 360 s). The three subjects were invited to complete a fourth trial at 55% MVC, two reached task failure at this percentage, with CF of 53.5% and 48.0% MVC; the third (subject 9, ***Table 1***) did not reach task failure within 20 m, suggesting a CF lying between 55% and 60% MVC.

Table 1: *Two-arm isometric finger flexor strength and parameters of the force–duration relationship derived from the three parameter multi-session test using the work time model.*

Subject	Isometric Finger Flexor Strength (MVC)		Critical Force and *W'* (work–time model)			
	N	% BM	CF (N)	% MVC	*W'* (N.s)	*R²*
1**	898.8	121.7	*480.8*	*53.5*	*22585*	*1.00*
2	814.2	128.5	260.1	31.9	24275	0.94
3	949.1	131.3	331.2	34.9	24284	0.98
4	945.4	136.5	378.8	40.1	31038	1.00
5	946.7	146.9	378.5	40.0	37527	1.00
6	1093.8	147.3	466.1	42.6	34916	1.00
7	1039.9	155.2	423.8	40.8	23548	1.00
8	1091.4	156.7	410.9	37.6	54795	0.94
9*	949.1	160.2				
10**	1126.9	166.5	*541.0*	*48.0*	*13824*	*1.00*
11	1199.3	183.0	486.4	40.6	42028	0.99
Mean	1005.0	148.5	415.7	41.0	30882	0.99
SD	114.0	18.2	82.8	6.2	11820	0.02

Notes: Kg kilogram; BM body mass; % percentage; CF critical force; N·s newtons per second; MVC maximum voluntary contraction; W' energy store component; r correlation coefficient; SD standard deviation.
* Subject did not reach task failure at 45% MVC, invited to perform a forth trial at 55% MVC, and did not reach task failure.
** Subjects did not reach task failure at 45% MVC, invited to perform a forth trial at 55% MVC, these values were calculated from time to failure in this additional trial.

Comparison of single and multi-session three parameter protocols
Figure 4 illustrates the relationship and bias ± 95% limits of agreement between the multi-session and single session three-parameter CF protocols. The three subjects who did not reach task failure at 45% MVC were excluded from analysis. The ICC between the multi- and single-session protocol for CF was 0.900 (95% Confidence Interval [$CI_{95\%}$] 0.616 – 0.979), and for *W'* was 0.768 ($CI_{95\%}$ 0.190 – 0.949).
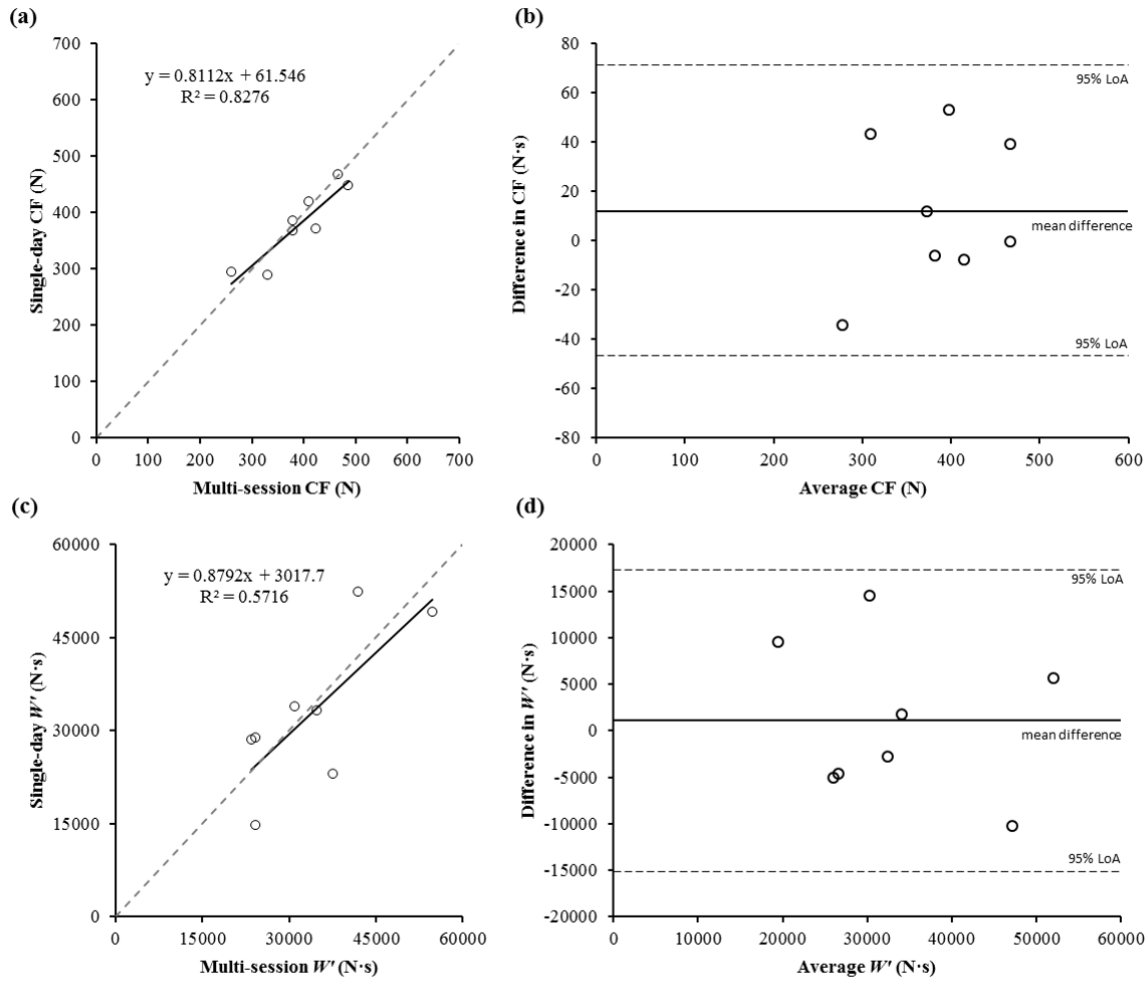
Figure 4: *Bland-Altman plots of the relationship (**a & c**) and limits of agreement (**b & d**) between the multi-session and single session three parameter critical force protocols for CF (**a & b**) and W' (**c & d**). In graphs (**b**) and (**d**), the solid horizontal line represents the mean difference between tests and the dashed lines represent upper and lower 95% limits of agreement (LoA).*

Discussion

The present study demonstrates that fatiguing intermittent isometric muscular contractions of the finger flexors to volitional exhaustion at multiple intensities results in the same type of relationship previously demonstrated for other synergistic muscle groups[9, 10]. Force plotted against T_{lim} displayed a hyperbolic relationship and correlation coefficients of the parameter estimates from both work–time and 1/time models were consistently very high. The observed relationships of the present study are comparable with previous research that has also shown a linear relationship between W_{lim} and T_{lim} for continuous isometric muscle contractions of the forearm flexors and extensors[9] and intermittent isometric finger flexor dynamometry[10]. The results show CF for two-arm intermittent isometric finger flexion to be $41.0 \pm 6.2\%$ of

MVC for advanced to elite rock climbers. In addition, we demonstrate that a single visit to determine CF is a reliable measure which overcomes the time-consuming and potentially disruptive nature of multi-session assessments[18, 19]. However, single-session W' was less reliable. The exact reason for differences in W' remain unclear, although differences in the energy-store component between ecologically valid settings and laboratory-based testing have been reported[19]. The results of the present study provide the first demonstration of the sensitivity of a three-parameter model for determining CF in the finger flexors of rock climbers. Given the use of CF in other sports, we expect it to become a common test used by coaches for understanding exercise tolerance in climbers and determining optimal training prescription. This is particularly likely given that rock climbing is now an Olympic sport.

The maximum steady state work rate that CF represents provides a useful tool for fitness diagnostics, monitoring of the physical impact of training, and a framework for exploring and understanding skeletal muscle bioenergetics and the metabolic and cardiorespiratory responses to exercise[7]. The present study has demonstrated the sensitivity of a simple test for the determination of CF, using equipment readily available to climbers and coaches in most climbing walls. Differences in the testing protocol, designed to maximise ecological validity in climbing population, confounds comparison with previous data from single-arm continuous muscle actions of the forearm flexors, middle finger flexors and finger flexors[8-10]. Notably, differences include, (1) continuous constant power exercise bouts are unlikely to provide relevant information on climbers performance given this test to failure cannot distinguish ability groups or disciplines within the sport[1, 15]. (2) Differences in work to relief ratio of intermittent tests are known to alter both CP and W'[20]. (3) Hand and arm positions influence climbers force production, positions that involve the hand above the shoulder, and with greater than 90-degree extension of the elbow are known to have greater criterion validity with climbing ability than handgrip dynamometry[13]. Further work is necessary to establish norms of CF and W' data for comparison between ability groups and disciplines, to gain further understanding of the potential mechanisms associated with the fatigue resistance of the finger flexors of climbers.

The ability to monitor alterations in CF and W' of the finger flexors in response to interventions, including training, is likely to be invaluable. Furthermore, as the determination of CF and W' allows for the accurate prediction of T_{lim} (s) at specific intermittent exercise intensities, performance capacity can be calculated. For instance, the force required to elicit a specific T_{lim} will be:

(eq. 3) $\qquad F = W'/T_{lim} + CF$

and the T_{lim} at a specified force is:

(eq. 4) $\qquad T_{lim} = W'/(F - CF)$

If the climber's MVC is 898.8 N, CF is 480.8 N and their W' is 22585 N·s the force required to elicit a T_{lim} of 120 s would be 669 N (74.4% MVC). Conversely, T_{lim} at 90% MVC (808.92 N) would be 68.8 s. It is also possible to optimise the design of interval sessions, taking into consideration the depletion of W' during the work interval and restoration of W' during the recovery interval, see Morton and Billat[21]. Feasibly, knowing an athlete's CF and W' would

allow the coach to develop exhaustive training sessions, resulting in beneficial adaptations without overreaching.

Previously, the force-time integral (analogous to W_{lim}) derived from a single bout of exhaustive exercise at a specific percentage of MVC, has been used as a performance marker to discriminate between factors including climbing disciplines, ability, and recovery techniques[1, 3, 11, 15]. The force used to determine the integral has typically been set at 40 or 60% of the climbers' finger flexor MVC. However, given that the myocellular environment and aerobic metabolism can differ dramatically between individuals working at the same percentage MVC, the use of intensities determined in this way may have confounded the findings in previous literature[10, 22]. This is especially true when the percentage of MVC work is completed at (e.g., 40% MVC) is around the CF of the task[7]. This is exemplified in the results of the present study, while agreement between MVC and CF ($p = 0.007$; $r = 0.788$) was greater than that seen in previous studies of the forearms[10], 40% of MVC would still result in some individuals performing a task <CF and others >CF (***Figure 5***). Therefore, the selection of exercise intensities relative to an individual's MVC could result in subjects exercising at different aerobic metabolic intensity domains, confounding the interpretation of results. Conversely, CF represents an intensity that reflects functional aerobic metabolic capacity, thus the findings of the present study, and those previously[10], suggest the adoption of CF for the determination of relative exercise intensities in future research.
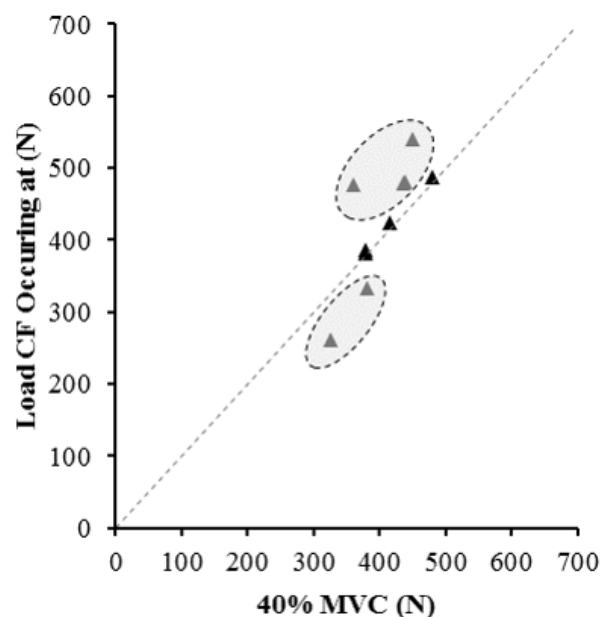

Figure 5: *Illustrating the relationship between the percentages of MVC that CF occurs at and 40% of MVC. Circles indicate where 40% of subjects MVC would represent a load more than 10% greater than or less than CF.*

Protocols that require multiple visits can be time-consuming and potentially disruptive to training programmes[18, 19]. Consequently, we also set out to determine the agreement of a

single session assessment of CF, thus subjects completed a single session test of MVC as well as three tests at 80, 60 and 45% of MVC. It is well documented that CP is unaffected by prior bouts of exercises, even when exhaustive[23-26]. Indeed, this was found to be true in the present study, CF differed by a small margin between the single and multi-session protocols. However, the agreement of W' was weaker, with considerably larger ICC confidence intervals. Differences between laboratory and field estimates of W' have been reported in the literature, W' (but not CP) has been found to be altered by prior high-intensity exercise, depending on the duration of subsequent recovery[27] and the extent of W' utilisation[23]. It is conceivable that the 20 m recovery period provided between tests was insufficient for complete W' reconstitution. Unlike CF, the effect of prior exercise on W' appears to be related to the duration and intensity of preceding exercise and the duration of recovery between exercise bouts[24, 25, 27]. Ferguson et al.[25] showed that W' recovered to 86% after 15 m of recovery following exhaustive constant work rate exercise. Similarly, Burnley et al.[24] and Vanhatalo and Jones[27] showed recovery to non-exhaustive exercise to occur in ~10 min. Consequently, 20 m was chosen as a practical duration allowing for recovery, while minimising the time for the athlete to cool down. However, given the error in W', it is possible that recovery time was inadequate. One potential theory is that the reconstitution of W' is exponential, Skiba, Chidnok, Vanhatalo and Jones[28] reported a time constant of ~377 s, suggesting a recovery duration of 25 m is required. It is also conceivable that this is related to the size of the exercising muscle(s), as the work of Skiba et al.[28] was in running performance. Therefore, future studies should consider longer recovery durations if a single session test is used for the assessment of CF in small muscle groups, such as the finger flexors.

This paper has made significant steps in the development of a climbing specific finger flexor CF protocol; however, a number of limitations should be acknowledged. (1) Both arm's finger flexors were tested together, pilot work identified that the greater amount of weight required for a single arm test increased the resistance of the pulleys used to adjust the load by an unacceptable amount. Given the difference in finger flexor oxygen kinetics between the dominant and non-dominant arms identified previously[4], future studies should consider the testing of single arms. (2) It was observed that subjects struggled with the perfect execution of the seven-seconds of work. Had it been measured, we would expect to observe that subjects were unable to produce a perfect square-wave of force production, as has previously been reported[10]. There is potential for variability as a result, especially as the rate of force production has been found to differentiate climbers of different disciplines[29]. Familiarisation and the experience of the subjects in the present study will have helped to reduce this; however, future work should consider the recording and calculation of actual work done. Finally, (3) the intermittent test against a fixed workload is not a perfect model of the changes in pace and length of isometric contractions of the finger flexors required for climbing. The sport involves frequent changes in exercise intensity, as dictated by the climbing route, performance may be better described by an intermittent model that takes into consideration both intense bouts of exercise and periods of rest and lower intensity exercise (see Jones and Vanhatalo[30] for a recent review).

Practical Applications

The present study has demonstrated the sensitivity of a simple test for the determination of CF, using equipment readily available to climbers and coaches in most climbing gyms. While further work is still necessary, the test of CF described is of value to coaches and climbers for understanding exercise tolerance and determine optimal training prescription to monitor improvements in the performance of the forearm flexors. Furthermore, it is recommended that future climbing studies should adopt CF for the determination of relative exercise intensities.

Conclusion

The performance of fatiguing intermittent isometric contractions of the finger flexors at three percentages of climbers MVC resulted in T_{lim} and force data with very high correlation coefficients for both work-time and 1/time CF models. The observed relationships are comparable with previous research that has also shown a linear relationship between force and T_{lim} for continuous isometric muscle contractions of the forearm flexors and extensors[9] and intermittent isometric finger flexor dynamometry[10]. The results show CF of the climbers for two-arm intermittent isometric finger flexion to be $41.0 \pm 6.2\%$ of MVC and W' to be 30882 ± 11820 N·s. The results demonstrate the sensitivity of the protocol for the determination of CF and W' in the finger flexors of climbers from an ecologically valid, climbing specific multi-session test and CF from a single session test.

References

1. Philippe M, Wegst D, Müller T, Raschner C, Burtscher M. Climbing-specific finger flexor performance and forearm muscle oxygenation in elite male and female sport climbers. *Eur J Appl Physiol*. 2012;112(8):2839-47.
2. Fryer S, Giles D, Palomino IG, Puerta AdlO, Romero VE. Hemodynamic and cardiorespiratory predictors of sport rock climbing performance. *J Strength Cond Res*. 2017.
3. Fryer S, Stone KJ, Sveen J, Dickson T, España-Romero V, Giles D, et al. Differences in forearm strength, endurance, and hemodynamic kinetics between male boulderers and lead rock climbers. *Eur J Sport Sci*. 2017;17(9):1177-83.
4. Giles D, Romero VE, Garrido I, de la O Puerta A, Stone K, Fryer S. Differences in oxygenation kinetics between the dominant and nondominant flexor digitorum profundus in rock climbers. *Int J Sport Physiol*. 2017;12(1):137-9.
5. Baláš J, Mrskoč J, Panáčková M, Draper N. Sport-specific finger flexor strength assessment using electronic scales in sport climbers. *Sports Tech*. 2014;7(3-4):151-8.
6. Poole DC, Burnley M, Vanhatalo A, Rossiter HB, Jones AM. Critical Power: An Important Fatigue Threshold in Exercise Physiology. *Med Sci Sport Exer*. 2016;48(11):2320-34.
7. Jones AM, Wilkerson DP, DiMenna F, Fulford J, Poole DC. Muscle metabolic responses to exercise above and below the "critical power" assessed using 31P-MRS. *Am J Physiol-Reg I*. 2008;294(2):R585-R93.
8. Hendrix CR, Housh TJ, Johnson GO, Weir JP, Beck TW, Malek MH, et al. A comparison of critical force and electromyographic fatigue threshold for isometric muscle actions of the forearm flexors. *Eur J Appl Physiol*. 2009;105(3):333-42.
9. Monod H, Scherrer J. The work capacity of a synergic muscular group. *Ergonomics*. 1965;8(3):329-38.
10. Kellawan JM, Tschakovsky ME. The single-bout forearm critical force test: a new method to establish forearm aerobic metabolic exercise intensity and capacity. *PloS One*. 2014;9(4):e93481.

11. Fryer SM, Stoner L, Dickson TG, Draper SB, McCluskey MJ, Hughes JD, et al. Oxygen recovery kinetics in the forearm flexors of multiple ability groups of rock climbers. *J Strength Cond Res*. 2015;29(6):1633-9.

12. Watts PB, Jensen RL, Gannon E, Kobeinia R, Maynard J, Sansom J. Forearm EMG during rock climbing differs from EMG during handgrip dynamometry. *J Exer Sci*. 2008;1(1):2.

13. Baláš J, Panáčková M, Kodejška J, Cochrane JD, Martin JA. The role of arm position during finger flexor strength measurement in sport climbers. *Int J Perf Anal Sport*. 2014;14(2):345-54.

14. Draper N, Giles D, Schöffl V, Konstantin Fuss F, Watts P, Wolf P, et al. Comparative grading scales, statistical analyses, climber descriptors and ability grouping: International Rock Climbing Research Association Position Statement. *Sports Tech*. 2015;8(3-4):88-94.

15. MacLeod D, Sutherland D, Buntin L, Whitaker A, Aitchison T, Watt I, et al. Physiological determinants of climbing-specific finger endurance and sport rock climbing performance. *J Sport Sci*. 2007;25(12):1433-43.

16. Baláš J, Michailov M, Giles D, Kodejška J, Panáčková M, Fryer S. Active recovery of the finger flexors enhances intermittent handgrip performance in rock climbers. *Eur J Sport Sci*. 2016;16(7):764-72.

17. Weir JP. Quantifying test-retest reliability using the intraclass correlation coefficient and the SEM. *J Strength Cond Res*. 2005;19(1):231-40.

18. Karsten B, Jobson S, Hopker J, Jimenez A, Beedie C. High agreement between laboratory and field estimates of critical power in cycling. *Int J Sports Med*. 2013;35(4):298-303.

19. Bartram JC, Thewlis D, Martin DT, Norton KI. Predicting Critical Power in Elite Cyclists: Questioning the Validity of the 3-Minute All-Out Test. *Int J Sport Physiol*. 2017;12(6):783-7.

20. Skiba PF, Jackman S, Clarke D, Vanhatalo A, Jones AM. Effect of work and recovery durations on W'reconstitution during intermittent exercise. *Med Sci Sport Exer*. 2014;46(7):1433-40.

21. Morton RH, Billat LVJEjoap. The critical power model for intermittent exercise. 2004;91(2-3):303-7.

22. Kent-Braun JA, Ng AV, Doyle JW, Towse TF. Human skeletal muscle responses vary with age and gender during fatigue due to incremental isometric exercise. *J Appl Physiol*. 2002;93(5):1813-23.

23. Simpson LP, Jones AM, Vanhatalo A, Wilkerson DP. Influence of initial metabolic rate on the power–duration relationship for all-out exercise. *Eur J Appl Physiol*. 2012;112(7):2467-73.

24. Burnley M, Davison G, Baker JR. Effects of priming exercise on VO2 kinetics and the power-duration relationship. *Med Sci Sport Exer*. 2011;43(11):2171-9.

25. Ferguson C, Rossiter HB, Whipp BJ, Cathcart AJ, Murgatroyd SR, Ward SA. Effect of recovery duration from prior exhaustive exercise on the parameters of the power-duration relationship. *J Appl Physiol*. 2010;108(4):866-74.

26. Burnley M, Doust JH, Vanhatalo A. A 3-min all-out test to determine peak oxygen uptake and the maximal steady state. *Med Sci Sport Exer*. 2006;38(11):1995-2003.

27. Vanhatalo A, Jones AM. Influence of prior sprint exercise on the parameters of the 'all-out critical power test' in men. *Exp Physiol*. 2009;94(2):255-63.

28. Skiba PF, Chidnok W, Vanhatalo A, Jones AM. Modeling the expenditure and reconstitution of work capacity above critical power. *Med Sci Sport Exer*. 2012;44(8):1526-32.

29. Fanchini M, Violette F, Impellizzeri FM, Maffiuletti NA. Differences in climbing-specific strength between boulder and lead rock climbers. *J Strength Cond Res*. 2013;27(2):310-4.

30. Jones AM, Vanhatalo A. The 'critical power' concept: applications to sports performance with a focus on intermittent high-intensity exercise. *Sports Med*. 2017;47(1):65-78.