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Reliability and Validity of Finger Strength and Endurance Measurements in Rock Climbing

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ABSTRACT

Purpose: An advanced system for the assessment of climbing-specific performance was developed and used to: (a) investigate the effect of arm fixation (AF) on construct validity evidence and reliability of climbing-specific finger-strength measurement; (b) assess reliability of finger-strength and endurance measurements; and (c) evaluate the relationship between finger flexor all-out test scores and climbing ability. **Methods**: To determine the effect of AF, 22 male climbers performed 2 maximal strength and all-out tests with AF (shoulder and elbow flexed at 90°) and without AF (shoulder flexed at 180° and elbow fully extended). To determine reliability, 9 male climbers completed 2 maximal strength tests with and without AF and an all-out and intermittent test without AF. **Results**: The maximal strength test without AF more strongly determined climbing ability than the test with AF (r^2 = .48 and r^2 = .42 for sport climbing; r^2 = .66 and r^2 = .42 for bouldering, respectively). Force and time variables were highly reliable; the rate of force development and fatigue index had moderate and low reliability. The maximal strength test with AF provided slightly higher reliability than without AF (intraclass correlation coefficient [ICC] = 0.94, ICC = 0.88, respectively). However, smaller maximal forces were achieved during AF (484 ± 112 N) than without AF (546 ± 132 N). All-out test average force had sufficiently high reliability (ICC = 0.92) and a relationship to sport climbing (r^2 = .42) and bouldering ability (r^2 = .58). **Conclusion**: Finger strength and endurance measurements provided sufficient construct validity evidence and high reliability for time and force parameters. Arm fixation provides more reliable results; however, the position without AF is recommended as it is more related to climbing ability.

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Evaluating and monitoring sport performance-limiting factors serves to optimize training workloads. It would particularly benefit rock and sport climbers as scientific support in these disciplines is still not a common practice. Research in rock climbing has demonstrated that the tests for assessment of climbers' physical fitness (i.e., strength and endurance as well as aerobic and work capacity) are much more informative when they reflect the specificity of the sport (España-Romero et al., 2009; Michailov, Mladenov, & Schöffl, 2009; Michailov, Morrison, Ketenliev, & Pentcheva, 2015; Vigouroux, Quaine, Labarre-Vila, & Moutet, 2006). Performance-limiting fatigue in climbing is generally localized to the finger flexors (i.e., cannot hold on anymore). Objective and standardized assessment of climbers' work capacity in these muscles necessitates the use of sport-specific ergometers and measuring systems. However, such equipment is not readily found in the market. Thus, dynamometers or ergometers have been adapted or specially designed (Grant, Hynes, Whittaker, & Aitchison, 1996; Michailov et al., 2015; Philippe, Wegst, Muller, Raschner, & Burtscher, 2012; Vigouroux et al., 2006). Further scientific developments have included instrumented climbing holds fitted with three-dimensional (3D) force sensors to estimate climbing efficiency through measuring dynamic parameters during climbing (Donath & Wolf, 2015; Fuss & Niegl, 2008).

With respect to the dynamometers, which were constructed to simulate climbing-specific conditions (i.e., finger grip and arm positions, intensity, type of muscle contraction), several studies have assessed maximal fingertip strength and have conducted continuous and intermittent endurance tests. Thus, physiological responses were investigated, abilities of major importance were discovered, suitable sport-specific tests were proposed, and facts useful for injury prevention were established (Baláš, Mrskoč, Panáčková, & Draper, 2014; Baláš, Panáčková, Kodejška, Cochrane, & Martin, 2014; Fryer, Stoner, Dickson, et al., 2015; Fryer, Stoner, Lucero, et al., 2015; Fryer, Stoner, Scarrott, et al.,

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2015; Macleod et al., 2007; Philippe et al., 2012; Vigouroux & Quaine, 2006; Vigouroux et al., 2006). It has been shown that finger flexor muscles make the highest contribution during climbing (Deyhle et al., 2015; Koukoubis, Cooper, Glisson, Seaber, & Feagin, 1995). Researchers have also found that performance-limiting factors of major importance are sport-specific strength endurance and strength relative to body mass (España-Romero et al., 2009; Grant et al., 1996; Michailov, 2014; Michailov et al., 2009). Rock climbing required intermittent isometric forearm muscle contractions, which were considerably longer than the rest intervals. The ratio was 4:1, and the average contact time with the hold was 8.2 s (Michailov, 2014). Logically, elite climbers' forearm endurance was explained by enhanced local vasodilatory capacity, reoxygenation during rest intervals, and deoxygenation during contractions (Ferguson & Brown, 1997; Fryer, Stoner, Dickson, et al., 2015; Fryer, Stoner, Lucero, et al., 2015; Fryer, Stoner, Scarrott, et al., 2015; Macleod et al., 2007; Philippe et al., 2012).

Ferguson and Brown (1997) first drew attention to the importance of forearm endurance testing through rhythmic isometric contractions. They conducted one sustained test and one rhythmic test with a relative intensity of 40% of maximal voluntary contraction (MVC). The climbers were able to perform significantly longer compared with controls only on the rhythmic test. Ferguson and Brown calculated and displayed the target force on a pen chart recorder for the participants to observe during the test. Vigouroux and Quaine (2006) used an oscilloscope to provide participants with constant visual feedback of their generated force and a target force of 80% of MVC. Macleod et al. (2007) developed software to give visual and audio feedback for both the force and timing of contraction and maintenance of the target force (40% MVC ± 2.5%) was visually assisted using color lights (green for correct force, blue for excessive force, and red for too little force). Their results demonstrated that climbing-specific work capacity depends on both local aerobic and strength components. Therefore, to distinguish elite climbers from controls, Macleod et al. used not only the test's time but also the force-time integral (FTI), which was more informative to distinguish between groups. Philippe et al. (2012) used target zone limits of ± 5% and adapted a test apparatus by fixing a wooden ledge to a board as a hold, which was placed between two vertical alloy profiles serving as rails, and by ensuring vertical adjustments of the hold, which was fixed to a strain gauge through a wire cable.

The actual force during testing at some degree of MVC will always vary according to the target force set, and there will be a delay entering the target zone. Nevertheless, none of the previous studies explained whether the calculation of contraction time and FTI was performed using data only in the target zone, which can be especially important during intermittent testing. Moreover, positions with shoulder flexion and abduction and elbow flexion were used for standardized measurements (Macleod et al., 2007; Vigouroux & Quaine, 2006). The angle of the elbow joint was 90º, but the upper arm and forearm were not fixed in a way that would reduce the contribution of the shoulder girdle muscles. Consequently, climbers pulled with their shoulder girdle muscles to increase their fingertip force production. This technique can lead to smaller fingertip forces compared with positions with straight arms for which body mass is used to load the hold (Baláš, Panáčková, et al., 2014).

One can assume that fixating the arm during testing will lead to higher test reliability due to more standardized conditions (e.g., body and arm position), but it may reduce climbing specificity and compromise the meaningfulness of the test. Moreover, during sustained contractions at a % MVC to assess finger endurance, neither time nor FTI distinguished climbing ability level sufficiently (Fryer, Stoner, Scarrott, et al., 2015; Macleod et al., 2007; Philippe et al., 2012). As intermittent tests were shown to assess local aerobic capacity (Baláš et al., 2016), another test to asses anaerobic capacity is warranted. The concept of an all-out test might be more suitable to assess anaerobic capacity of finger flexors if total muscle performance (average force) and force decline are provided by the testing device. Furthermore, no study has determined the reliability of the sport-specific finger endurance tests, and the sport-specific dynamometers developed by researchers in the rock climbing field were pioneering but had their limitations. For a wider practical application of sport-specific finger strength and endurance assessments, the abilities of the measuring system should be further developed. Thus, the aims of the present study were to: (a) investigate the effect of arm fixation (AF) on construct validity evidence and reliability of climbing-specific finger strength measurement; (b) assess reliability for climbing-specific finger strength and endurance tests; and (c) evaluate the relationship between finger flexor all-out test scores and climbing ability. All testing measured fingertip strength as it is climbing-specific, unlike handgrip dynamometry. For achieving these aims, an advanced system for sport-specific performance assessment in sport climbing was developed.

Methods

Experimental approach to the problem

As a first stage, a new 3D system (Figure 1) for performance assessment in rock climbing (3DSAC) was developed by the National Sports Academy in Sofia,

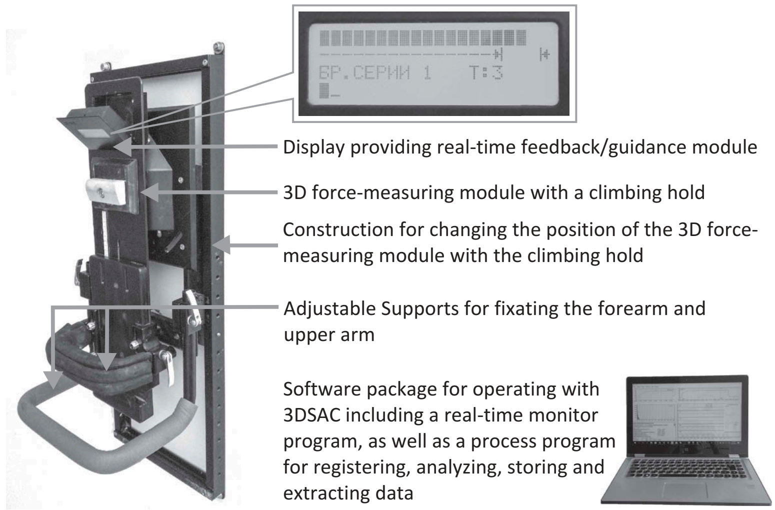

Figure 1. The newly developed three-dimensional (3D) system for performance assessment in rock climbing (3DSAC) and its components.

Bulgaria, in collaboration with the Institute of Space Research and Technologies at the Bulgarian Academy of Sciences. The development process complied with the following essentials: (a) improvement in real-time feedback assistance and wireless data transfer, (b) precise calculation of several mechanical parameters using a climbing hold mounted on a 3D force-measuring module, (c) fixation of the arm enabling standardized test conditions, (d) advanced software with the option to modify work parameters of new test protocols and for exercise prescription during training, and (e) ease of extraction of results to facilitate data processing. After the 3DSAC was developed, a study was completed in two phases. The first phase sought to compare the scores from maximal strength and all-out testing with and without AF (Figure 2) and their relationship with climbing ability. Climbing ability was represented by self-reported climbing grades, which were found to be a valid and precise reflection of climbing ability level despite slight overestimation and underestimation in men and women (Draper et al., 2011). Until now, self-reporting has been used in climbing-related studies to determine climbing ability level. In the second phase, test–retest reliability was assessed for maximal strength testing with and without AF and for all-out and intermittent endurance tests without AF. Both phases of the study served to determine whether a more standardized position with AF or a less standardized but more sport-specific position without AF was more useful when testing climbers' finger flexor muscle strength and endurance. The study was also designed to introduce a new all-out test providing information on construct-related validity evidence and reliability of parameters measured during climbing-specific finger flexor maximal strength, all-out, and intermittent endurance tests. The study was approved by an institutional review board. All participants were informed of the benefits and risks of the investigation and signed informed consent prior to any testing.

Figure 2. Testing positions with and without arm fixation.

Participants

Two groups of climbers volunteered to participate in the study. They reported their redpoint (RP) grade ability level (highest difficulty of a route, which a climber can climb after the route has been previously rehearsed) in sport climbing and in bouldering on their preferred scale, which was transferred to the

International Rock Climbing Research Association [IRCRA] Scale (Draper et al., 2015). One group of 22 male climbers (M_{age} = 28.3 ± 6.3 years, M_{weight} = 71.5 ± 8.0 kg, M_{height} = 177.6 ± 6.1 cm, mean lead climbing RP = 17 ± 5 on the IRCRA Scale, mean bouldering RP = 20 ± 5 on the IRCRA Scale) took part in the first phase of the study and completed maximal strength and all-out tests with and without AF (Figure 2). Another group of 9 male participants (M_{age} = 36.2 ± 9.9 years, M_{weight} = 72.1 ± 9.3 kg, M_{height} = 178.9 ± 8.7 cm, mean lead climbing RP = 21 ± 4 on the IRCRA Scale, bouldering RP = 18 ± 2 on the IRCRA Scale) took part in the second phase of the study and performed four tests (maximal strength test with AF, maximal strength test without AF, all-out test without AF, and intermittent test without AF), which were repeated on a separate occasion.

Technical characteristics of the 3D system for performance assessment in rock climbing

The 3D system for performance assessment in rock climbing is composed of: (a) a 3D force-measuring module with a place for mounting climbing holds; (b) a guidance module ensuring real-time feedback through visual and acoustic signals; (c) an object for changing the position of the force-measuring module with the climbing hold across the vertical axis, with adjustable supports for fixating the forearm and upper arm; and (d) a software package with the ability to prescribe workload, calculate mechanical parameters, and store and extract data from the computer memory.

The force-measuring module includes: (a) a microcontroller (MSP430F149, Texas Instruments, Dallas, Texas, USA), including a built-in analog-to-digital converter with an accuracy of 12 bits (0.006 N for the low significant bit) and a sample rate of 125 Hz; (b) an amplifier (Model AD623, Analog Devices, Norwood, Massachusetts, USA); (c) a radio receive/transmit station based on a Nordic semiconductor (nRF24L01, Trondheim, Norway); and (d) a 23-mm deep wooden climbing hold with a radius of 12 mm (Figure 3). The force sensor configuration was triaxial (± Fy, ± Fx, + Fz) and built on micro button-type cells, with a measuring range of 0 kN to 2.5 kN and a comprehensive accuracy of 0.5%. The climbing hold incorporated five sensors (Model F1818, Tecsis Sensor Co., Ltd., Shenzhen, China). It was not painful to hold and was the optimal depth for maximizing force application and muscular activation (Amca, Vigouroux, Aritan, & Berton, 2012; Baláš, Mrskoč, et al., 2014). Calibration was performed to measure the forces applied on the climbing hold, not at the location of the sensors. To compensate for the influence of the lever arm between the grip and y-axes and x-axes sensors, two reference loads were sequentially applied (196 N and 392 N, respectively) at the site of the grip. Thus, a calibration coefficient discrete per N was calculated using the corresponding discrete values from the analog-to-digital converter. Forces during testing were calculated by multiplying the calibration coefficient by the discrete value of the force applied with the fingers. The real-time feedback (guidance) module is composed of: a built-in 3DSAC portable 4 × 20 text display (intended for the participant), a real-time monitor for the investigator, and a program module for processing the registered data, both based on a PC compatible with Microsoft Windows XP, Windows 7, Windows 8, or Windows 10.

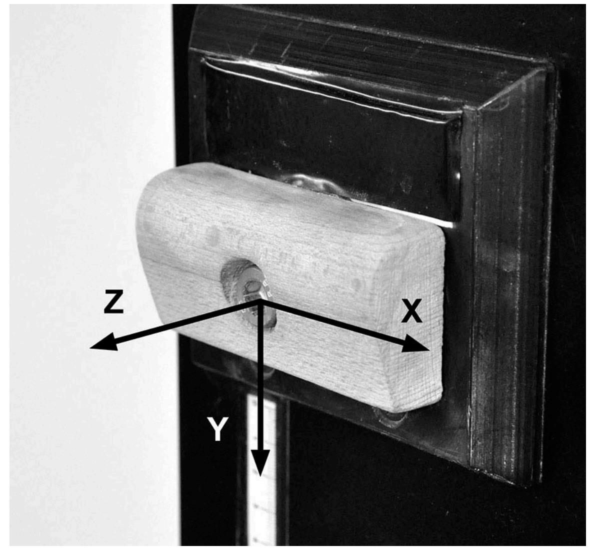

Figure 3. The climbing hold mounted on the strength-measuring module of the three-dimensional system for performance assessment in rock climbing, of which the which shape and size maximize muscular activation and reduce injury risk; y-, x-, and z-axes (arrows).

Procedures

For the purpose of investigating the effect of AF and the relationship between all-out tests and climbing ability, the group of 22 participants first completed maximal strength and then all-out testing with and without AF on the same day. The conditions with and without AF were randomly assigned. Resting time between tests included: 5 min between the maximal strength tests, 10 min between the maximal strength and all-out tests, and 20 min between the all-out tests. After completing the tests, participants were immediately asked which position was subjectively more comfortable to apply force on the hold.

In the second phase of the study, the group of nine participants came to the laboratory twice (1 week apart) and completed four tests: (a) a maximal strength test with AF, (b) a maximal strength test without AF, (c) an all-out test without AF, and (d) an intermittent test without AF. The maximal strength tests were performed in random order and before the all-out and intermittent tests. Resting time between tests was: 5 min between the maximal strength tests, 10 min between the second maximal strength test and the first endurance test, and 20 min between the intermittent and all-out tests.

On each testing day, prior to any measurements, participants warmed up following a procedure similar to that described by Baláš et al. (2016): 5 min of stair walking; 5 min of intermittent hanging on a fingerboard using 30-mm and 23-mm deep rungs; and eight contractions of 5 s on the 3DSAC, while applying force of 30% body mass and alternated by 5-s rest intervals. Participants started testing after 10 min of passive rest.

Arm fixation and grip position

During testing with AF, the participants were tested while standing and facing the 3DSAC with their right fingers on the 23-mm deep climbing hold mounted on the force-measuring module (Figure 2 and Figure 3). They used an open-finger grip position (Figure 4). The supports were adjusted so the upper arm and forearm were fixed at 90°. The shoulder was flexed at 90° and abducted at 30° (Figure 2). During testing without AF, participants loaded the climbing hold using their body mass and the same hand and finger-grip position, while their arm was placed at 180° shoulder flexion and full elbow extension (Figure 2).

Maximal strength, all-out, and intermittent tests

The maximal strength tests included three maximal voluntary finger flexor contractions separated by 1-min rest intervals. Maximal strength was determined as the highest force value from both trials. During the maximal strength test with AF, participants were instructed to produce maximal force as fast as possible to analyze the rate of force development. In the all-out tests, climbers had to develop maximal force at the beginning of the muscle contraction and maintain maximal effort for 30 s. The intermittent test was performed without AF at an intensity of 60% MVC until climbers were not able to maintain force in the target zone. The target zone was set at ± 10% of the target force. The contraction and relaxation intervals during the intermittent test were 8 s and 2 s, respectively. Previously, researchers used an intensity of 40% MVC and longer contraction and relaxation intervals (10 s and 3 s, respectively; Macleod et al., 2007). Nevertheless, finger endurance tests with 40% MVC may have a very long duration, and an endurance effort would depend more strongly on psychological factors. Sixty percent MVC and shorter contraction

Figure 4. Finger grip position used during the performance of the tests.

and relaxation intervals were used in the present study because they are more representative of modern competitive climbing (Baláš et al., 2016). Furthermore, muscle contraction at 60% MVC results in total intramuscular occlusion of the finger flexors (Barnes, 1980). Therefore, this intensity can assess peripheral factors such as oxygen delivery at a local muscle level (measuring muscle oxygenation during relaxation intervals in intermittent testing) and oxygen extraction by the mitochondria (measuring oxygenation during isometric contractions; Baláš et al., 2016; Kodejška, Michailov, & Baláš, 2015).

Analyzed parameters

Maximal force (F_m) was analyzed for maximal strength testing with and without AF. Parameters for rate of force development were used for maximal strength testing with AF. These parameters were the rate of force development in the first part of the force curve (GS) and explosive strength index (I_{es}). GS represented the ratio between F_m and the time to achieve 0.5 F_m ($T_{0.5Fm}$):

$$GS = 0.5\ F_m /\ T_{0.5Fm} \tag{1}$$

I_{es} represented the ratio between F_m and the time to achieve F_m (T_{Fm}):

$$I_{es} =\ F_m /\ T_{Fm} \tag{2}$$

Average force (F_{avg}) and fatigue index ($I_{fatigue}$) were taken into consideration for all-out testing. $I_{fatigue}$ was calculated using the following equation:

$$\left(F_m - F_{end-of-test}\right)/F_m.100 \tag{3}$$

For intermittent testing, number of repetitions, time in the force target zone, and FTI were analyzed.

Statistical analyses

Descriptives (mean ± s) were used to characterize the level of strength for all participants. To assess statistical differences between the conditions with and without AF, a one-way analysis of variance (ANOVA) with repeated measures was used. Statistical significance was set at $p < .05$. Partial omega squared ($\omega_p{}^2$) was computed to estimate effect size. The relationships between test parameters and sport climbing and bouldering ability were assessed by Pearson correlation coefficients. Intraclass correlation coefficients (ICC) and limits of agreement were calculated to assess test–retest reliability. Intraclass correlation coefficients were computed from the following equation:

$$ICC = \frac{MSB - MSE}{MSB + (k-1)MSE}, \tag{4}$$

where MSB and MSE correspond to mean squares between subjects and mean squares error from repeated measure ANOVA, respectively, and k is the number of trials. This ICC corresponds to the type $ICC_{3,1}$ according to the nomenclature proposed by Shrout and Fleiss (1979). Systematic bias was investigated via one-way ANOVA with repeated measures. To assess internal consistency of maximal strength tests (reliability between trials within the testing), $ICC_{3,1}$ was calculated. All calculations were completed in Microsoft Excel and IBM Statistical Package for the Social Sciences (SPSS) for Windows (Version 22, Chicago, IL).

Results

The impact of AF is shown in Table 1. Climbers achieved greater maximal strength without AF for both maximal finger strength and all-out tests. Moreover, finger strength was more related to bouldering and sport climbing ability without AF (Table 2). Interestingly, the condition without AF showed different relationships to sport climbing (r^2 = .48) and bouldering ability (r^2 = .66) than did the condition with AF (r^2 = .42 and r^2 = .42 for sport climbing and bouldering ability, respectively). Similar to intersession reliability (Table 3), the intrasession reliability was greater for maximal strength measurement with AF (ICC = .94 and ICC = .88, respectively). Participants' subjective preferences for arm position were greater for a straight arm without AF (n = 13 for the maximal strength test and n = 17 for the all-out test) than for a bent arm with AF (n = 6 for the maximal strength test and n = 3 for the all-out test; 3 and 2 votes were without preference).

The all-out test scores for maximal and average strength were strongly correlated with climbing ability. However, $I_{fatigue}$ did not show any relationship with climbing ability.

Table 1. Comparison of the maximal strength and all-out tests with and without arm fixation (n = 22).

		With AF	Without AF		
Test	Parameter	Mean ± SD	Mean ± SD	p	$\omega_p{}^2$
Maximal strength test	F_m (N)	484 ± 112	546 ± 132	< .001	.398
30-s all-out test	F_m (N)	459 ± 123	500 ± 116	< .001	.376
	F_{avg} (N)	369 ± 100	392 ± 94	.042	.151

Note. F_m = maximal force; F_{avg} = average force; AF = arm fixation.

Table 2. Correlation coefficients representing the relationship between the maximal strength and all-out tests and climbing ability in sport climbing and bouldering (n = 22).

		Arm position	Sport climbing	Bouldering
Maximal strength test	F_m (N)	With AF	.458*	.448*
		Without AF	.611*	.735*
	F_m (N/kg)	With AF	.648*	.649*
		Without AF	.690*	.815*
30-s all-out test	F_m (N)	With AF	.495*	.527*
		Without AF	.555*	.661*
	F_{avg} (N)	With AF	.654*	.723*
		Without AF	.655*	.764*
	$I_{fatigue}$ (%)	With AF	.185	.132
		Without AF	−.166	−.184

Note. F_m = maximal force; F_{avg} = average force; $I_{fatigue}$ = fatigue index; AF = arm fixation.
*p < .05.

Table 3. Mean (± *SD*) values for the maximal strength, all-out, and intermittent tests in test–retest conditions, statistical differences between trials (*p*), limits of agreement (LOA), and intra-class correlation coefficients (ICC; *n* = 9).

Test	Parameter	Mean test score ± *SD*	Mean retest score ± *SD*	*p*	95% LOA	ICC
Maximal strength test without AF	F_m (N)	563 ± 100	574 ± 111	.549	102.40	.878
Maximal strength test with AF	F_m (N)	518 ± 101	537 ± 121	.163	75.06	.941
	GS (N/s)	2,024 ± 1,124	1,480 ± 796	.218	2,395.69	.213
	I_{es} (N/s)	390 ± 202	276 ± 151	.062	309.70	.607
30-s all-out test	F_m (N)	512 ± 96	517 ± 92	.797	96.16	.864
	F_{avg} (N)	408 ± 92	416 ± 83	.474	68.26	.921
	$I_{fatigue}$ (%)	24.67 ± 10.32	28.63 ± 9.46	.237	15.54	.701
Intermittent test	Number of repetitions	13 ± 3.10	13 ± 2.69	.842	3.17	.845
	$T_{target\ zone}$ (s)	85.64 ± 22.07	87.91 ± 20.27	.519	19.77	.887
	FTI (N.s)	24,596 ± 5,431	26,402 ± 5,366	.048	4,558.49	.907

Note. F_m = maximal force; I_{es} = rate of force development, explosive strength index; GS = rate of force development in the early phase of contraction, S-gradient; F_{avg} = average force; $I_{fatigue}$ = fatigue index; $T_{target\ zone}$ = time in the force target zone; FTI = force-time integral; AF = arm fixation.

Table 3 provides the test–retest reliability for the maximal strength, all-out, and intermittent tests. High reliability was observed for the maximal strength test with the ICC slightly higher in the AF condition. However, low-to-moderate reliability was found for all parameters of rate of force development in the AF position. The endurance intermittent test provided high test–retest reliability with the highest ICC values being for time in the target zone and FTI. The reliability of the all-out test for F_m and F_{avg} was high. The $I_{fatigue}$ showed moderate reliability.

Discussion

The current study proposed the use of a 30-s all-out test to assess anaerobic power and capacity of forearm flexors in sport climbers. Moreover, it provided information about the intrasession and intersession reliability of fingertip grip strength and endurance measurements in rock climbing. To our knowledge, this study is the first evaluating intersession reliability for climbing-specific endurance tests. This study also determined the effect of AF on reliability and criterion validity in strength and endurance tests. The results showed that most of the parameters were highly reliable and that of the two testing positions, the one without AF is preferred.

Maximal and average forces from the maximal strength test and the all-out test as well as the number of repetitions and time of the intermittent test were parameters that reflected the actual state of the measured abilities. Maximal strength achieved in the fixated arm position had the maximal relative reliability (ICC). This intersession reliability was very similar to the intrasession reliability of the strength measured by Watts and Jensen (2003) and Baláš, Mrskoc, et al. (2014). However, rate of force development from this latter test and the $I_{fatigue}$ from the all-out test demonstrated moderate and low reliability, respectively. Therefore, they should be analyzed with caution, and participants should endeavor to perform the tests correctly. Also, caution should be exercised with the FTI from the intermittent test. The FTI has high relative reliability, but during the second trial, it was significantly higher. This finding could be explained by the learning effect, which might have contributed to participants entering the target force zone quicker and to be more accurate when maintaining that force.

Although the ICC for F_m in the testing position with AF was the highest, the position without AF appeared to be more useful because the scores were more related to climbing ability (Table 2) compared with the position with AF. Furthermore, higher force could be developed during the position without AF. There was a systematic bias of 62 N between positions. Unlike the condition with AF, a higher correlation between maximal strength without AF and bouldering ability was observed compared with sport climbing ability. Most likely, this finding was due to insufficient specificity of the muscle action. In bouldering, very powerful moves are performed where climbers move their center of body mass very fast and their fingers have to resist higher external forces to maintain grip. In this process, before the finger flexors start to act isometrically, they first act eccentrically. During the position with AF, extension at the interphalangeal joints is reduced to a minimum.

The newly applied all-out test was highly reliable when F_{avg} was taken into consideration, and it was closely related to climbing ability (r^2 = .58). This finding suggests a practical use of this parameter when evaluating anaerobic power in climbers. However, $I_{fatigue}$, which should represent an indicator of anaerobic capacity, did not correlate with climbing ability. Anaerobic power and capacity of the forearm muscles play an important role during short strenuous climbing. Nevertheless, climbing demands complex development of motor abilities and skills (Michailov, 2014). It is likely that a high level of climbing ability can still be achieved by compensating for insufficient anaerobic capacity with a higher level of other sport-specific abilities. Further construct validation and local physiological responses are needed to better understand the role of different parameters in all-out testing.

The 3DSAC cannot be validated with another apparatus as there is no climbing-specific strength-measuring device considered to be a "gold standard." Nevertheless, the strong relationship of maximal strength and endurance test scores with climbing ability and the high reliability of most parameters suggest that the 3DSAC is a suitable and reliable tool for performance assessment in rock climbers. Compared with other devices for finger flexor strength and endurance assessment (Grant et al., 1996; Philippe et al., 2012; Vigouroux et al., 2006), the 3DSAC has enhanced software. Also, in addition to contraction time, it precisely calculates the time and impulse of endurance tests using only values from the target force zone. The system's options allow for the assessment of different physical abilities (i.e., maximal strength, rate of force development, and muscular endurance of different types). Calculation of several parameters from each test provides detailed information about the climber's training status. Thus, percentages between levels of decisive abilities can be defined, which is a precondition for optimizing training.

To the best of our knowledge, the fixation mechanism of the 3DSAC is a new approach. Arm supports reduced the involvement of the upper arm and shoulder girdle muscles, as these would be otherwise activated to pull and prevent the forearm from moving against the direction of the applied force and to change the finger grip position. Nevertheless, when tests are performed using the fixation mechanism, very strong climbers may experience discomfort and pain because of the reaction forces at the elbow joint.

Training intensity during climbing cannot be controlled (Michailov, 2014). Using devices such as the 3DSAC for training purposes enables a targeted working regime and the achievement of desired physiological and training effects.

Where the force-measuring module is mounted on a climbing wall, climbing efficiency can also be assessed. As described by Fuss and Niegl (2008), more experienced climbers registered smaller forces, shorter contact times (contact between hand and hold), smaller impulse, smoother signals, higher tangential-to-normal force ratio, and more continuous movement of the center of pressure. The last two parameters are not available in the 3DSAC as its main purpose is to test sport-specific work capacity evaluation. Moreover, instrumented climbing holds with the ability to measure moment and center of pressure are costly and are not warranted for devices for strength and endurance assessment. Nevertheless, the ratio between z-axis and y-axis forces could be used for comparative analysis similar to the tangential-to-normal force ratio.

Conclusion

The proposed all-out test as well as the maximal strength and intermittent endurance test performed on the 3DSAC had sufficiently high construct validity evidence and reliability. Test parameters (F_m and F_{avg}, test time, and FTI) were highly reliable with the exception of the rate of force development from the maximal strength test and the $I_{fatigue}$ from the all-out test. Therefore, climbers should endeavor to perform these tests correctly. It was observed that AF during finger flexor testing provides slightly higher test–retest reliability. However, climbing specificity was compromised and testing without AF is recommended.

What does this article add?

The all-out test is a new version of the Wingate anaerobic test, which enriches sport-specific performance evaluation in rock climbing. For the first time, reliability of climbing-specific finger flexor muscle endurance tests and reliability of rate of force development were measured to provide researchers with support for data interpretation. Detailed evaluations and the ability to control training loads using the 3DSAC could serve to optimize the training process of climbers, which may further the development of rock climbing. Future experiments with measuring systems such as the 3DSAC are warranted to develop a sport-specific test battery, to further estimate construct validity of the finger strength and endurance measurements in climbers, and to develop training protocols to optimize grip training for different outcomes (i.e., strength and aerobic and anaerobic forearm capacity).

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