NATIONAL SPORTS ACADEMY "VASSIL LEVSKI"

Department "Theory of Sports Training"

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INVESTIGATION THE INFORMATIVENESS OF TESTS OF SHOULDER GIRDLE MUSCLE STRENGTH IN SPORTS CLIMBING

ABSTRACT

Supervisor:

Prof. Michail Michailov, Dc.s.

SOFIA, 2024

The dissertation has been discussed and is aimed at an official defense by the Department of Theory of Sport Training.

It is laid out on 152 standard pages. Includes 52 tables and 47 figures. 104 bibliographic sources were used, of which 22 are in Cyrillic, 81 are in Latin, and one is on a website.

The numbering of the tables and figures in the abstract matches that of the dissertation.

The public defense of the dissertation will take place on September 20, 2024, at 13 a.m. in the A3 Hall of the National Sports Academy "Vassil Levski" (Studentski Grad, Sofia) at a meeting of a specialized scientific jury. The materials for the defense of the dissertation are available in the library of the National Sports Academy.

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ABSTRACT

of a dissertation work for the award of an educational and scientific degree “Doctor” in the professional field 7.6. Sport, doctoral program “Theory and Methodology of Sport Science

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INTRODUCTION

Climbing is a method of moving a person on a slab or vertical, steep, or overhanging terrain. It involves the upper limbs, which distinguishes it from the ascent, which is being done only with the support of the legs. In other words, the climber used its entire body. Motor activity is the result of simultaneous and successive contractions of the muscles of the upper and lower limbs that move the body along the rock (or climbing wall); thus, the climber overcomes its own weight.

The muscle group that plays the largest part in the activity is the muscle group of the finger flexors. Among others, taking a part are the elbow flexors and the trunk, whose strength and endurance are less studied. The muscles of the arms, as well as the trunk flexors, as part of the climber's upper body that he uses during climbing, overcoming gravitational forces, play a significant role in sporting achievements. The practice shows that, in his aim to climb a certain route while solving the complexity of the relief and most often the reverse slope of the surface, the climber intensively uses the shoulder girdle and center of gravity, constantly moving the body in a direction to the wall to overcome the gravitational forces. The climber intensively uses the trunk musculature, flexors in the elbow joint, and musculature of the shoulder girdle.

Among the motor abilities that are conditioning factors of achievement in sports climbing are the muscle group of the flexor of the forearm and secondarily, of the flexors of the shoulder girdle.

There is a wealth of research evidence on the factors of high sports performance in sports climbing, which can accurately determine the morph anthropometric and motor characteristics of sports climbers. It can be assumed that elite sports climbers have a low percentage of subcutaneous fat, a high degree of maximum strength of the muscles of the upper limbs and upper body, weight-related, highly dynamic and isometric strength endurance, positive monkey index, high level of specific aerobic and anaerobic capabilities, flexibility in the hip joints (Baláš et al. 2014; Grant et al. 1996, Michailov et al. 2009; Philippe et al. 2012; Vigouroux and Quaine, 2006; Fryer et al. 2015; Grant et al. 1996; Mermier et al. 2000; Draper et al. 2008; Mihailov 2006, 2014; Mihailov et al. 2011).

Researches indicates that the four main qualities of high performance in sports climbing are: 1**). grip strength** (measured by means of a standard manual dynamometer) (Berrostegieta L., 2006; Laffaye G, 2014; López-Rivera E., 2014; Michailov ML, 2014), followed by 2). **the maximum specific strength of the flexors of forearm** (Grant S, 2001, Grant S et al, 1996, Laffae G, 2014, Schweizer A. , 2001 Watts P.B. (2004), Watts, 1996, Michailov M., 2006, Laffaye G, 2014, Lopez-Rivera E., et al, 2012, Macdonald JH. , 2011; Michailov ML, 2014); 3**.) Shoulder girdle durability, measured by bent arm hang** (Baláš J., 2012, Grant, S, 2001, nt S, 2001, Mermier C, J, 2000, Mermier C, 1997, Michailov, ML, 1997, Wall, SB, 2004, Watts, 2004, Watts PB, 2008, Watts PB, 1996); 4) **explosive power of the upper limbs** (Berrostegieta, 2006; Laffaye, 2014; Michailov, 2014); and 5.) **Body mass** (Giles LV, 2006, Mermier C, 2000): Activities involving overcoming through body mass of gravitational forces, excess weight, have a negative impact. Mandatory condition for the achievement of high sports level is the low percentage of subcutaneous fat and balanced muscle mass; **6.) endurance of flexors of the body** (Laffaye G, 2014, Muehlbauer T, 2012) – not yet established relationship between the endurance of this muscle group and sporting achievement; **7.) maximal flexor strength of the trunk - the maximum strength of the flexors of the trunk is also an important factor of sports achievement; 8.) flexibility of hip joints** (Grant 2001; Mermier 1997;

Michailov 2006; Michailov 2014). The described factors in climbing are not quite clear in science. Found that the achievement in this sport depends on a complex of factors that change in depending on the conditions. A number of authors confirm the fact that climbers opportunities also depend on the strength qualities of the musculature the shoulder girdle (Baláš et al. 2012; Berrostegieta 2006; Draper at al. 2011; Grant at al. 1996; Kodejska, Baláš, 2016; Laffaye at al. 014; Michailov at al. 2017; Wall et al. 2004). It is said that the maximum number of recruitments (Baláš et al. 2012), the duration of the hang with bent arms (Grant S, 2001, Grant S, 2008, Mermier C, 2000) and one-arm pull-up strength (Wall, CB, 2004) correlate with sporting achievement and climbing skills. A characteristic feature of motor activity in climbing is, that climbers are subjected to continuous physical tension, as during climbing alternate isometrics intermittent contractions with dynamic movements and short rest intervals that cause a reduced supply of oxygen in the muscles. Hence, the type of endurance that is shown an important factor after maximum finger strength in sports, is strength endurance. With input intensity between 40% - 100% of maximal voluntary contraction has been found in climbers last longer than non-climbers and therefore they cope better with specific rhythmic contractions long time. They also show longer voltage retention to exhaustion (Baláš et al. 2012, Vigouroux, Quaine 2006; Philippe et al. al. 2012; Michailov 2005; MacLeod et al. 2007; Michailov 2014; Philippe et al. 2012; Vigouroux, Quaine 2006; Fryer et al. 2015). Other features of motor activity on which it depends the sporting achievement in climbing are the explosive power of the above limbs or more specifically the force gradient of the flexors of fingers (Berrostegieta J I., 2015, Koestermeyer G., 2000, Michailov, 2014) - the specific explosive force of the flexors of the upper limb (Berrostegieta J I. , 2015, Laffaye G, 2014, Michailov, 2014), 4 the durability of the shoulder girdle (Baláš J. 2012, Grant S, 1996, Macdonald JH., 2011; Michailov, 2014), the power endurance of spinal flexors (Muehlbauer T at al, 2012), flexibility (generally in the hip joints (Michailov, 2006; Michailov et al. 2009; Baláš et al. 2009, Michailov 2006, Michailov, 2014). Interesting is the fact that climbers' strength, measured with a hand-held dynamometer, not particularly large compared to the general population. Relative force measured by hand dynamometer and the specific force of however, the fingers have significantly higher values and are hallmarks mainly of the elite climber. To achieve a high level in sport climbing is required great strength of the finger flexors and of the muscles of the shoulder girdle, great mobility in the hip joint - significantly higher levels for elite climbers compared to amateurs and control groups. The strength and endurance of finger flexors in a specific grip determine in a large degree of sporting achievement. The relative strength of the fingers determines sports performance between 50% and 60%, and strength durability measured by dynamometric tests at one and the same relative intensity expressed as a percentage of the maximum voluntary contraction, determines the sports achievement 30% (at intermittent tests), 48% (at intermittent tests) or about 70% (at edge hangs due to that the result in this test depends not only on endurance, but also on power) (Michailov 2022). The strength of the musculature of shoulder girdle is also one of the highly significant factors for predicting excellent sports performance among climbers. Also thus, elite climbers have greater shoulder endurance belt ($r2 = 0.49$) (Baláš et al. 2012). They have more durability of the upper part of the body (measured during the ”bent arm hang” and pull-up) and specific finger strength compared to recreational climbers. Muscular endurance of the shoulder girth, measured at the height of the bent arms, was a quality shown in the study by Draper et al. (2021). In 2011, the same author verifies the validity of the explosive power test (Power slap) that it is with excellent reliability. It only makes it clear that hang time is more important than the number of pull-ups. Another study by Wall et al. (2004) found that relative and maximum shoulder girdle strength correlates with climbing performance in female climbers. It is also known that sport climbing requires a high level of endurance of the flexor muscles in the elbow joint during high-intensity muscle contractions, but increasing it excessively will most likely not lead to a significant improvement in the level of climbing (Michailov et al. 2017). More specifically, climbers differ significantly from non-climbing populations on the relative force pulse at a relative intensity of 70% and 50% MVC with isolated involvement of the flexors in the elbow joint). Based on the available data, it can be assumed that the maximum strength and muscular endurance of the musculature of the shoulder girdle and finger flexors have similar importance for achievement in sport climbing, as maximum strength is the dominant factor. The explosive power of the musculature of the upper body part is a factor in climbing achievement, but it is more important in bouldering than in sports climbing (discipline difficulty). The power generated during dynamic pull-ups seems to depend more on the maximum strength potential of climbers than their explosiveness (their ability to quickly activate more muscle fibers to develop strength at a high rate). There is not much research related to the importance of the musculature of the shoulder girdle and armpits for climbing performance, as well as the reliability and validity of the tests for their measurement and evaluation. Muscle strength and endurance of the musculature of the shoulder girdle should be studied both through the traditionally used exercise-pull-up with or without weights, as well as through a lock-off test. To establish the level of explosive power of that muscle group, it is appropriate to use power slap and speed pull-up tests. Additional evidence is needed to clarify how credible these claims are and how much they are informative. The literature devoted to climbing as a motor activity has a minimal amount of standardized tests that would be suitable for this specific activity, and most studies address some specific aspects of climbing or are performed without the presence of specialized equipment.

The main part of the content of this dissertation is the results of the studies conducted to establish the informativeness of the previously existing and newly introduced ones by us tests to evaluate the strength qualities and durability of flexor muscles in the elbow joint and shoulder girdle in athletes. Participants performed a series of tests on the maximal and explosive strength of the upper limbs, as well as for strength endurance when counteracting their own weight or at the same relative intensity set as a percentage of the maximum force. It is established and verified that the relevant tests are sufficiently reliable and valid, as is the strength of their dependence on sports achievement, as well as the degree to which the parameters that these tests measure are suitable for application in this sport.

1. WORKING HYPOTHESIS

The above justifies the necessity of conducting the present study and defines its working hypothesis: We hypothesize that the lock-off, power slap, and speed pull-up tests are reliable, valid, and suitable for use in sport climbing as a prerequisite for their application in the practice of training process control in sport climbing.

2. OBJECTIVES, TASKS AND METHODOLOGY OF THE RESEARCH

2.1. OBJECTIVE OF THE RESEARCH

The purpose of the study is to improve the control of the training process in sport climbing by establishing the reliability and validity of tests for measuring muscle strength and endurance of the shoulder girdle.

2.2. TASKS OF THE RESEARCH

1) To characterize sport climbing as a specific motor activity and to present the main factors of sports achievement in this sport. 2) To systematize data from scientific publications on muscle strength and endurance as main factors in sport climbing, as well as on the tests used to measure and evaluate them. 3) To investigate the reliability of mechanical parameters reported using three strength tests and a dynamometer specialized for climbers. 4) To provide evidence of criterion validity related to the extent to which various tests and their parameters determine athletic performance. 5) To provide construct validity data related to which given parameter informs about which latent trait, as well as congruence and interchangeability of cognates. 6) To develop regression models for evaluating the results of the studied tests.

2.3. OBJECT AND SUBJECT OF THE RESEARCH

2.3.1 Object of Research

The object of research is muscle strength and endurance in sport climbing as the main factors of sports achievement.

2.3.2. Subject of research

The subject of research is the informativeness of tests for maximal strength, explosive strength, and muscular endurance of the musculature of the arms and shoulder girdle, as well as the importance of these qualities for achievement in sport climbing.

2.4. METHODOLOGY

2.4.1 Participants

The study involved 15 climbers with Redpoint levels from 7a to 9a, an average 7b+, and bouldering (from 6c to 8c+, an average 7c+). Sports achievements are reported in a category of difficulty according to the French scale. To enable their statistical processing and the determination of the climbers' qualifications, the metric scale of the International Rock Climbing Research Association (IRCRA), developed by Draper et al., was used. (2015), according to which climbers can be classified by sport performance as "beginner," "intermediate," "advanced," "elite" and "world class".

2.4.2. A research approach to the problem

The present work includes the theoretical and experimental research necessary for a large part of scientific developments.

2.4.3. Research methods Study of information sources

The dissertation contains 151 pages, 25 figures, 18 tables, and 103 references, of which 22 are in Cyrillic, 81 are in English, and one is a website reference. Information available in scientific publications is related to the nature of the load and the physiological reactions during climbing, as well as the requirements determined by them for the physical capabilities of sports climbers. The experiment of the present work is controlled research of a finding nature, in which all the tests used are performed once. To establish the reliability of the tests, some of them are duplicated or repeated (retests). The study conditions were modeled to determine the strength and endurance status of the elbow flexor muscles of the study participants. The data also serve to establish the importance of the studied motor qualities in sport climbing, as well as to determine the reliability and validity of various types of tests and the mechanical indicators registered through them and through modern equipment, serving to evaluate and conduct an in-depth analysis of the condition of the climbers. For this purpose, the research participants performed a total of nine tests. Four of the tests measure maximal strength (three for the shoulder girdle and one for the finger flexors); three of the tests are for muscular endurance (two for the shoulder girdle and one for the finger flexors) and the remaining two tests are for explosive strength of the upper limbs. Most tests were performed on a specific dynamometer (Climbro, Sofia, Bulgaria). Therefore, through each test, several mechanical parameters were registered, as well as a number of derivative indicators were calculated. The total number of indicators registered with these tests is over 60. Mathematical and statistical methods part of the data collected through the research represents force characteristics directly registered by the researcher or automatically calculated by the software of the measuring equipment. This applies to maximal strength and muscular endurance tests. The data collected through the explosive force tests represent force discretes over time. Therefore, they are subjected to extensive initial mathematical processing in order to calculate mechanical parameters that serve to determine the achievements in these tests. We have established the reliability and validity of the tests, and objectivity, as another criterion of informativeness, was not investigated since an instrument was used and thus the intervention of the researcher was minimized. As standardity is also an important criterion for informativeness, the uniformity of conditions during tests is ensured. They are performed in laboratory conditions, and their performance is controlled according to the requirements described in the corresponding chapter (Brogli, Ya., 1979).

2.4.4. Methodology

The experimental work to achieve the aim and tasks of the present work includes a number of measurements in which specialized equipment is used to register mechanical parameters. The basic anthropometric characteristics of the examined persons are measured, and their sports achievements, age, and sports experience are recorded. Hardware for most tests, specialized equipment called "Climbro" was used—a combination of built-in force measuring sensors with a sampling frequency of 100 Hz and a mobile application. The mobile application provides instructions and real-time feedback on the magnitude of applied force, timing of muscle contractions, and relaxation phases. Procedures and tests Study participants complete the following tests: 1. Test for specific maximum strength of the finger flexors; 2. Specific test for maximal strength with one arm (with 90% flexion of the elbow joint) - "Lock-off"; 3. Maximum strength test by two-arm pull-up with maximum weight; 4. One-arm maximum strength test with minimal counterweight; 5. Specific test for muscle endurance of the finger flexors; 6. Lock-off test for muscle endurance of the flexor muscles of the shoulder girdle; 7. Bent arm hang; 8. Test “Power Slap"; 9. Explosive Strength Test;

3. RESULTS AND ANALYSIS

3.1. RELIABILITY OF THE PARAMETERS FROM THE DYNAMOMETRICAL TESTS

RESULTS

The extent to which the quantitative test results reflect the actual state of the measured traits is demonstrated by several reliability statistics in Table 11 of the dissertation. There were no significant differences between any of the parameters measured at the test and retest. Reliability was assessed as excellent at ICC > 0.9, good at ICC between 0.75 and 0.9, moderate at ICC between 0.5 and 0.75, and low at ICC < 0.5. According to these criteria, the maximum strength of the finger flexors and of the shoulder girdle musculature is a parameter with excellent reliability (Table 11). Other tests for which there is evidence of reliability are the explosive power slap and fast pull-up tests. The parameters with excellent and good reliability in the power slap test are the distance reached (the standard error of the measurement is only 1.8 cm), the average force, and the time of the test. The remaining parameters are of moderate reliability. These are peak strength and rate of strength development metrics. The parameters with excellent and good reliability in the fast pull-up test are the peak and average force, as well as the theoretically established test time (standard error of measurement = 0.03 s). Of moderate reliability are the test time and rate of force development at Fpeak and 95% Fpeak. The remaining indicators of rate of force development have low reliability. Analysis of the obtained results The analysis of the reliability of the tests and their parameters shows that the maximum strength tests reflect the actual state of this quality, both in terms of the flexor muscles of the fingers and the musculature of the shoulder girdle. The high reliability of the finger flexor strength test used in a specific grip has already been established by previous research (Baláš et al., 2015; Michailov et al., 2018). However, for the lock-off test, these are the second reliability reports, after the published results on this problem by Michailov and Baláš (2023). It appears that it can also be reasonably applied due to the excellent ICC values (0.947). The present study reports for the first time the reliability of the rapid pull-up-up test. The high levels of reliability of maximal and average strength achieved in this test, as well as its performance time, confirm its utility. However, it should be considered that the theoretically calculated test time is reproduced by the climbers to a greater extent than the time to the beginning of the relief phase, which is observed at the end of the recruitment. It is likely that climbers are not adapted to develop much force per unit time at the beginning of the recruitment and therefore cannot reproduce average or below-average values of their force for a short time (e.g., 100 or 200 ms). The same is suggested by the lower levels of reliability of the indicators of the rate of force development compared to the other parameters in the power slap test. The rate of force development is an indicator of explosiveness, on which the speed of muscle contraction depends. However, it is known that the height of the rebound is mostly determined by the impulse of the force (McBride et al. 2010) and not by the explosiveness of the effort. The same height and impulses can be achieved with both shorter and more explosive efforts and less explosive but relatively longer efforts (for this reason, the average force will be greater in the shorter efforts and vice versa). This is evidenced by the very high reliability (in second place after the achieved distance) of the mean force (ICC = 0.864).

Table 11. *Reliability indicators of the results of the tests for the maximum strength of the flexors of the fingers and the musculature of the shoulder girdle*

Test	Parametar	Mean values Attempt 1± SD	Mean values Attempt 2 ± SD	p	95% LOA	SEM	ICC
Maximum strength of the flexors of the fingers	F_{max} (N)	583 ± 81	586 ± 74	0.651	-57 – 50	21	0.927
Test lock-off for maximum strength the muscles of the shoulder girdle	F_{max} (N)	744 ± 92	742 ± 88	0.799	-55 – 59	20	0.947

Fmax: maximum force LOA: limits of agreement; SEM: standard error of measurement; ICC: intraclass correlation coefficient

3.2. VALIDITY OF APPLIED TESTS AND THEIR PARAMETERS.

In order to use the investigated tests and their parameters in sports practice, it is necessary that they are valid. Their validity was tested in two ways in the present study. On the one hand, their criterion validity was established by calculating the correlation coefficients between the measured parameters and sports achievements. Thus, it is determined to what extent the information they carry is related to abilities that are achievement factors in sport climbing. The second type of validity is established by determining the correspondence between different parameters and tests.

3.2.1. Relationships between sports achievements and results in motor tests

RESULTS

There are many statistically significant correlations ($p < 0.05$) between the results of the strength and muscular endurance tests and sports achievements in Red-point and On-sight styles in sport climbing (lead) and bouldering (table 14).

Table 14. Correlations between sports performance and the results of maximal strength and muscular endurance tests

Test	Parameter	Sports achievements		
		Red-point	On-sight	Boulder
Maximum strength of the flexors of the fingers	F_{max} (N)	0.486	0.465	0.644*
	$F_{max/kg}$ (N/kg)	0.763*	0.577*	0.664*
Test lock-off for maximum strength of the muscles of the shoulder girdle	F_{max} (N)	0.370	0.432	0.638*
	$F_{max/kg}$ (N/kg)	0.751**	0.561*	0.683**
Two-arm pull-up and maximum weight	F_{max} (kg)	0.525	0.741**	0.680*
	$F_{max/kg}$ (kg)	0.843**	0.794**	0.695**
One-handed pull-up and minimal counterweight	F_{max} (kg)	0.502	0.551*	0.734**
	$F_{max/kg}$ (kg)	0.685**	0.606*	0.743**
Muscular endurance of the flexors of the fingers	T (s)	0.378	0.626*	0.287
	J (N.s)	0.658*	0.786**	0.731*
	$J_{/kg}$ (N.s/kg)	0.694*	0.791**	0.729*
Lock-off for muscular endurance	T (s)	0.365	0.542	0.364
	J (N.s)	-0.021	-0.095	-0.285
	$J_{/kg}$ (N.s/kg)	0.623*	0.709**	0.519
Bent arm hang	Hanging time (s)	0.683*	0.454	0.582*

Red-point: climbing style after pre-reconnaissance; On-sight: style of climbing a route without prior reconnaissance; F max: maximum force; Fmax/kg: maximum force, related to body mass (relative force); T: time within the set intensity limits of muscle contractions; J: impulse of force; J/kg: impulse of force, relative to body mass; significant correlations at p < 0.05; ** significant correlations at p < 0.01.*

Table 15 Correlations between sports performance and the results of the "power slap" test

Parameter	Sport achievements		
	Red-point	**On-sight**	**Boulder**
Distance (cm)	0.307	0.217	0.534
Distance /cm	0.503	0.413	0.699*
F_{peak} (N)	0.527	0.782**	0.383
$F_{peak/kg}$ (N/kg)	0.721**	0.805**	0.512
$F_{peak\text{-}net}$ (N)	0.706*	0.857**	0.517
$F_{peak\text{-}net/kg}$ (N/kg)	0.721**	0.805**	0.512
F_{avg} (N)	0.483	0.737**	0.431
$F_{avg/kg}$ (N/kg)	0.842**	0.908**	0.708**
$F_{avg\text{-}net}$ (N)	0.818**	0.939**	0.701*
$F_{avg\text{-}net/kg}$ (N/kg)	0.843**	0.908**	0.708**
$T_{unweight}$ (s)	-0.794**	-0.865**	-0.668*
RFD_{Fpeak} (N/s)	0.608*	0.781**	0.313
$RFD_{95\%Fpeak}$ (N/s)	0.631*	0.796**	0.337
$RFD_{50\%Fpeak}$ (N/s)	0.745**	0.826**	0.538
RFD_{100ms} (N/s)	0.743**	0.800**	0.516
RFD_{200ms} (N/s)	0.722**	0.854**	0.494
J (N.s)	-0.025	0.211	0.008
$J_{/kg}$ (N.s/kg)	0.560	0.496	0.468
J_{net} (N.s)	0.508	0.537	0.446
$J_{net/kg}$ (N.s/kg)	0.560	0.496	0.468
P_{weight} (W)	0.748**	0.890**	0.768**
$P_{weight/kg}$ (W/kg)	0.817**	0.898**	0.819**
P_{force} (W)	0.734**	0.949**	0.628*
$P_{force/kg}$(W/kg)	0.802**	0.960**	0.676*

Red-point: route passing style after pre-reconnaissance; on-sight: style of crossing a route without prior reconnaissance; Fmax: maximum force; Fmax/kg: maximum force related to body mass (relative force); T: time within the set intensity limits of muscle contractions; J: force impulse; J/kg: force impulse relative to body mass; significant correlations at p < 0.05; ** significant correlations at p < 0.01.*

Table 16 Correlations between sports performance and results of the explosive strength test "rapid pull-up"

Параметър	**Спортни постижения**		
	Red-point	**On-sight**	**Boulder**
F_{peak} (N)	-0.071	0.007	0.287
$F_{peak/kg}$ (N/kg)	0.191	0.145	0.438
$F_{peak-net}$ (N)	0.109	0.106	0.401
$F_{peak-net/kg}$ (N/kg)	0.191	0.145	0.438
F_{avg} (N)	-0.149	-0.047	0.225
$F_{avg/kg}$ (N/kg)	0.246	0.165	0.498
$F_{avg-net}$ (N)	0.155	0.126	0.459
$F_{avg-net/kg}$ (N/kg)	0.246	0.165	0.498
$T_{unweight}$ (s)	-0.461	-0.407	-0.724**
$T_{theor-unweight}$ (s)	-0.268	-0.109	-0.226
RFD_{Fpeak} (N/s)	0.097	0.071	0.335
$RFD_{95\%Fpeak}$ (N/s)	0.103	0.071	0.334
$RFD_{50\%Fpeak}$ (N/s)	0.110	0.037	0.308
RFD_{100ms} (N/s)	0.092	0.011	0.294
RFD_{200ms} (N/s)	0.044	0.131	0.184
$T_{125\%BW}$ (s)	-0.329	-0.199	-0.404
J (N.s)	-0.301	-0.111	-0.131
$J_{/kg}$ (N.s/kg)	-0.203	-0.055	-0.076
J_{net} (N.s)	0.007	0.075	0.331
$J_{net/kg}$ (N.s/kg)	0.104	0.120	0.394
P_{weight} (W)	0.006	-0.077	0.168
$P_{weight/kg}$ (W/kg)	0.245	0.063	0.212
P_{force} (W)	0.099	0.014	0.323
$P_{force/kg}$(W/kg)	0.272	0.109	0.349

F peak: peak force; F peak/kg: F peak related to body mass; F peak-net: peak force – net (Fpeak minus own weight); F peak-net/kg: F peak-net related to body mass; Favg: medium strength; Favg/kg: average fo rce relative to body mass; F avg-net: average force - net; F avg-net/kg: Favg-net related to body mass; T un weight: time to reach the lightening phase (until the moment when the applied force is equal to the own weight and after which it becomes lower than it); Ttheor - unweight: theoretical time to reach the lightening phase (calculated by extrapolation in case of non-linearity in the final part of the curve); RFDFpeak: rate of force development to Fpeak; RFD95%Fpeak: force development rate up to 95% Fpeak: RFD50%Fpeak: force development rate up to 50% Fpeak; RFD100ms: rate of force development up to 100 ms from the start of the effort; RFD200ms: rate of force development up to 200 ms from the start of the effort; T125%BW(s): time to reach force representing 125% of body weight; J: force impulse; J/kg: J referred to body mass; Jnet: force impulse – net; Jnet/kg: Jnet related to body mass; Pweight: power calculated based on own weight; Pweight/kg: Pweight related to body mass; Pforce: power calculated based on the measured force; Pfroce/kg: Pforce relative to body mass; significant correlations at p < 0.05; ** significant correlations at p < 0.01.*

The presence of significant dependencies between the studied parameters and sports achievements testifies to the fact that the tests are criterion-valid and suitable for the control of the training process in sport climbing. The established correlation coefficients between athletic performance and strength characteristics of the explosive strength tests are new data since the researchers who applied these tests did not have specialized dynamometers to measure the force applied during the pull-up on the supports of the hands. The power parameters, times, and powers reported with the power slap test are valid in terms of sport climbing performance. It should be noted, however, that the primary outcome of this test was distance traveled, which correlated significantly only with the participants' bouldering performance. This should mean that explosive pull-ups to reach distant holds are more important for the boulderer than for sport climbing, advanced climbers. Again, the rapid pull-up test is more useful for boulderers. Correlation analysis shows that the shorter the time the climber is recruited, the more difficult boulder it is to pass. The lack of significant correlations between sports performance and the other parameters of this test is probably due to the incomplete realization of both the maximum force potential and the rate of force development. This assumption finds logic in the fact that the work done per unit of time, i.e., power, is a function of the force generated and the rate of muscle contraction, which in turn is determined by the rate of force development. It is logical to consider that since the task in the "rapid pull-up" test is for the climber to pull up in the shortest possible time, the speed of muscle contraction and, accordingly, the rate of force development are more important for the test result than the maximum power potential. In the "quick pull-up" test, the displacement is limited by the length of the upper limb, and after the pull-up, the inertial force created is not used for further movement, as during climbing or in the power slap test. In the power slap test, the participants realized to a greater extent their maximum force potential and the ability to rapidly activate muscle fibers. But the manifestation of maximal strength potential in the rapid pull-up test is limited by the weight of the climbers. This is another possible reason for the inability to reach maximum strength potential during the fast-pull. Conclusion: Grip-specific finger flexor and shoulder girdle strength, as measured by the lock-off test, are equally important for climbing success. In contrast to the study by Ozimek et al. (2016), the only one where we found foreign data on the two-arm pull-up test with weights, in the present study a high strength of dependence was found between the relative strength recorded in this test and sports performance (R reaches 0.843). In the shoulder-girdle muscle endurance lock-off test, the fact that relative force momentum correlates strongly and reliably with athletic performance is novel. Until now, it was only known that climbers differed significantly ($p < 0.05$) from non-climbing populations. There are many results of muscle endurance tests of the finger flexors at intensities set as a percentage of maximal voluntary contraction. However, the majority of these related to tests performed at an intensity of 60% MVC or lower (Baláš et al. 2016, Fryer et al. 2015, Michailov et al. 2018). The present study shows that the handstand test largely determines athletic performance (49%), as previously reported (Baláš et al. 2012).

3.2.2. Correspondence between different parameters and motor tests

Results

The degree to which one parameter determines another parameter or the result of a given test corresponds to another test provides information about the construct validity of the measured traits. I.e., the extent to which a given test or parameter conveys information about a particular latent trait, as well as the extent to which one test can substitute for another. This chapter reports on the construct validity of the distance achieved in the power slap test, the force impulse in the same test, the power and force gradients in the two explosive force tests (power slap and rapid draw), and the results of the maximal strength tests.

Correspondence between the lock-off test and two-handed pull-up'

The maximum force in the lock-off test was 363 N lower than the maximum force in the two-arm pull-up (Table 17, Fig. 13). This difference is statistically significant ($p < 0.001$), and the lower and upper limits of agreement are distant, but the relatively low standard error of estimate (SEM = 53 N) and high intraclass correlation (ICC = 0.781) indicate good agreement between the two tests. In addition, the regression model in which maximal two-arm pull-up force ($F_{max\text{-}pull\text{-}up\text{-}2arm}$) was the dependent variable and maximal lock-off test force ($F_{max\text{—}lock\text{-}off}$) was adequate. R = 0.879, R2 = 0.754, F = 40.909, $p < 0.001$. The equation expressing the dependence has the following form:

$$F_{max\text{-}pull\text{-}up\text{-}2arm}\ (N) = 23.707 + 1.446 * F_{max\text{—}lock\text{-}off}\ (N)$$

Table 17. Correlation between maximum strength from the lock off test and two-handed pull-up

Mean $F_{max\text{-}lock\text{-}off}$ ± SD (N)	Mean $F_{max\text{-}pull\text{-}up}$ ± SD (N	p	95% LOA	SEM	ICC
762 ± 87	1125 ± 144	< 0.001	-517 – -209	53	0.781

$F_{max\text{-}блок:}$: maximum force from the lock-off test; $F_{max\text{-}набиране\text{-}2ръце}$: maximum force from the pull-up of two hands; LOA: limits of:; SEM: standard error of measurement; ICC: intraclass correlation coefficient.

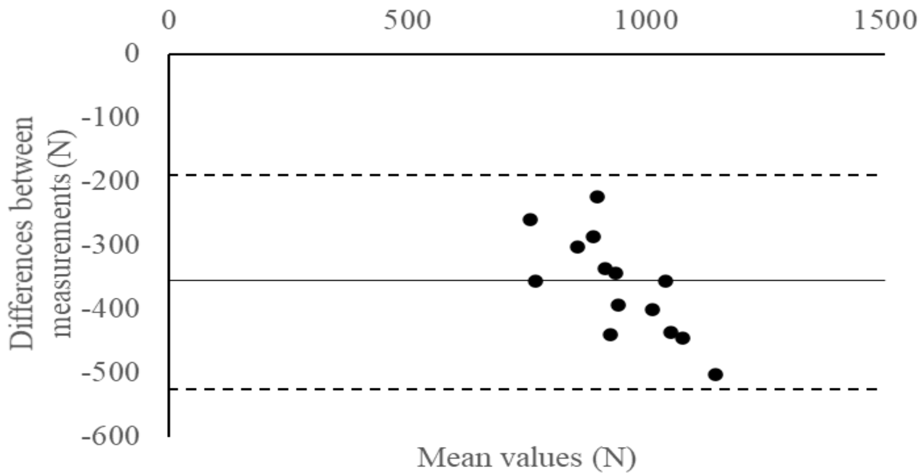

Figure 13 *Bland-Altman plot, representing the consistency between maximal strength from the lock-off and the two-arm pull-up test.*

Correspondence between the lock-off test and one-arm pull-up

The maximum force in the lock-off test was 195 N higher than the maximum force in the one-arm pull-up (Table 5, Fig. 2). This difference is statistically significant ($p < 0.001$), and the lower and upper limits of agreement are distant, but the relatively low standard error of estimate (SEM = 42 N) and high intraclass correlation (ICC = 0.810) indicate good agreement between the two tests. As in the above case, a regression model in which maximal one-arm pull-up force (Fmax-pull-1arm) was the dependent variable and Fmax-lock-off was the independent variable was adequate. R = 0.833, R2 = 0.671, F = 29.507, $p < 0.001$. The equation expressing the dependence has the following form:

$$F_{max\text{-}pull\text{-}up\text{-}1arm}\ (N) = -244.559 + 1.066 * F_{max\text{—}lock\text{-}off}\ (N)$$

Table 18 Correlation between lock-off test maximal force and one-arm **pull-up**

Mean values Fmax-lock-off ± SD (N)	Mean values Fmax-pull-up ± SD (N)	P	95% LOA	SEM	ICC
762 ± 87	567 ± 115	< 0.001	66 – 323	42	0.810

Fmax-lock-off: maximum force from the lock-off test; Fmax-recruit-1hand: maximum force from the recruitment of one hand; LOA: limits of agreement; SEM: standard error of measurement; ICC: intraclass correlation coefficient.

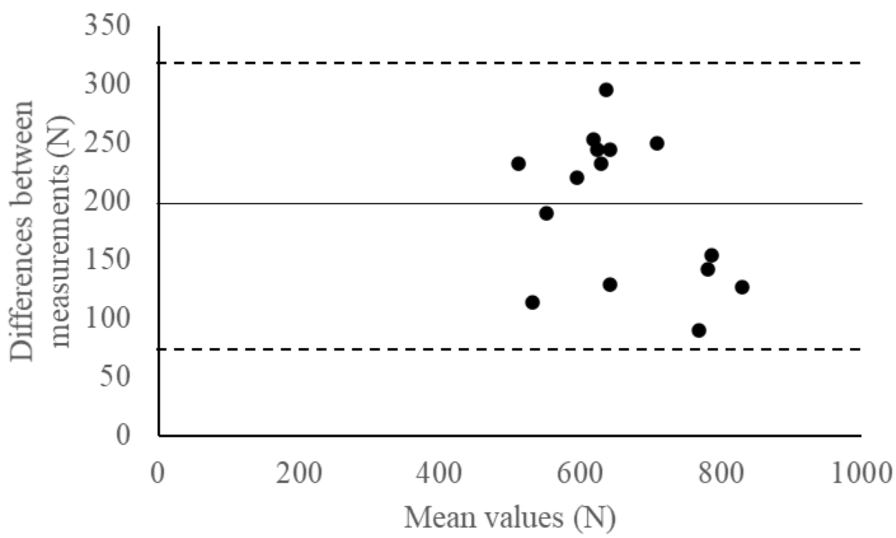

Figure 14. Bland-Altman plot representing the consistency between maximal strength from the lock-off and the one-arm pull-up test.

Correspondence between maximum pull-up force and average force in explosive tests

Multiple stepwise regression analyses showed that there was also a relationship between Fmax-pull-up-2-hands and mean net force from the power slap test (Favg-net-PS) and the fast pull-up test. A regression model in which Fmax-recruitment-2hands is the dependent variable and Favg-net-PS is the independent variable is adequate. $R = 0.925$, $R2 = 0.842$, $F = 59.608$, $p < 0.001$. The equation expressing the dependence has the following form: Fmax-pull-up-2hands = 781.839 + 2.086* Favg-net-power-slap The regression model in which Fmax-recruitment-2hands is the dependent variable and Favg-net-BN is the independent variable is adequate, but unlike the above model, in this model the coefficient of determination (R2) is not high. $R = 0.744$, $R2 = 0.479$, $F = 7.430$, $p < 0.034$. The equation expressing the dependence has the following form: Fmax-pull-up-2hands = 436.839 + 4.695* Favg-net-BN The data from the regression and correlation analyses indicate that the studied tests and their parameters are construct-valid. These data, as well as the information related to the reliability of the parameters and their relationship with sports achievements, also confirm the working hypothesis. The lock-off maximal strength test, in which a dynamometer is loaded by an isometric effort, pulling a handle while the shoulder and elbow are in 90° of flexion, is informative. It is both reliable and valid with respect to the sport's climbing performance (criterion validity) and the trait it is designed to measure (construct validity). Evidence of its reliability and criterion validity is provided in Chapters 3.2. and 3.3.1. Evidence of its construct validity is its agreement with the results of one- and two-hand recruitment, as well as the adequacy of regression models that allow the results to be predicted based on the maximum force in the lock-offtest (Tables 4 and 5, Fig. 1 and 2). This type of prediction is extremely convenient for sports practice due to the laboriousness of tests requiring weight lifting. The lock-offtest is performed in a few seconds, and the weight lifting can last over half an hour until maximum strength is established. This leads to exhaustion. Explosive strength tests are also reliable. This is confirmed by the values of the statistical indicators presented in Chapter 3.2. It is clear from this chapter that some of their parameters are structurally valid for the maximum strength potential, and another part is for the explosive power of the climbers. The parameter of this test that most strongly determines the distance reached is the force impulse, which in the present study is determined to the greatest extent by the maximal force potential and to a lesser extent by the explosive capabilities. Maximum force potential appears to determine power to a greater extent than explosive capabilities, as measured by the gradients of the same test. However, the power achieved in the "rapid pull-up" test depends most on the explosive capabilities. The data from the present study suggest that "cleaner" indicators of explosiveness are the force gradients from the "rapid pull-up" test rather than the "power slap" test. In addition, it appears that the average net force from the power slap test is more informative about maximal force capabilities than the average net force from the fast pull-up test. All of this indicates that it is most plausible to believe that during dynamic movements to reach distant grips, climbers move their bodies and generate power primarily at the expense of maximal force potential rather than rate of force development. This conclusion may not be limited to "advanced" level climbers and is consistent with the opinion of Michailov & Baláš (2023). They hypothesize that the mentioned mode of power generation is due to the lack of need for climbers to activate a large number of motor units already in the early phase of muscle contraction during a pull-up. Niegl & Fuss (2010) found that as climbers jump with two hands in the air to grab a long grip, they need to raise their center of gravity about 10 cm higher so as to avoid large peak reaction forces of the support and to provide more time to "master" the grip, i.e., to counteract the momentum of the falling body. From chapter

3.3.1, it became clear that power and other parameters from the power slap test, carrying mixed information, correlated strongly with athletic performance. This shows that this test is valid with respect to the specificity of the load in climbing.

3.3. EVALUATION OF MOTOR TEST RESULTS

Statistical indicators of reliability and validity testify that the studied tests are informative and suitable for application to climbers. However, the results of these tests would be more useful for the optimization of the training process in sport climbing if they were evaluated. In this way, it will be possible to get an idea of how satisfactory the personal achievements of individual climbers are in the specific tests. Unlike primary test scores, score points allow comparison of the status of traits that are measured using different units of measurement. This makes it possible to establish the profile of the climber, i.e., to reveal possible strengths and weaknesses, which will show how balanced the climber's preparation is. This chapter presents equations to convert test parameters that correlate strongly with athletic performance into regression estimates. The estimates are called regression because their determination is based on regression analysis. Thanks to it, the strength and form of the relationship between a given test result (dependent variable) and sports performance in the red-point or boulder style (independent variables) were determined, as well as the values of the parameters of the equations used for evaluation. In practice, it happens as the test results are converted into a category of difficulty. These kinds of points are a prediction of sports performance and show what the climber's potential is. I.e., what category of difficulty the climber is likely to overcome based on the current level of the measured latent trait. Below are equations for estimating the results of maximal and explosive strength tests, as well as statistical measures of adequacy and predictive value.

3.1. Evaluation of maximal strength and muscular endurance test results

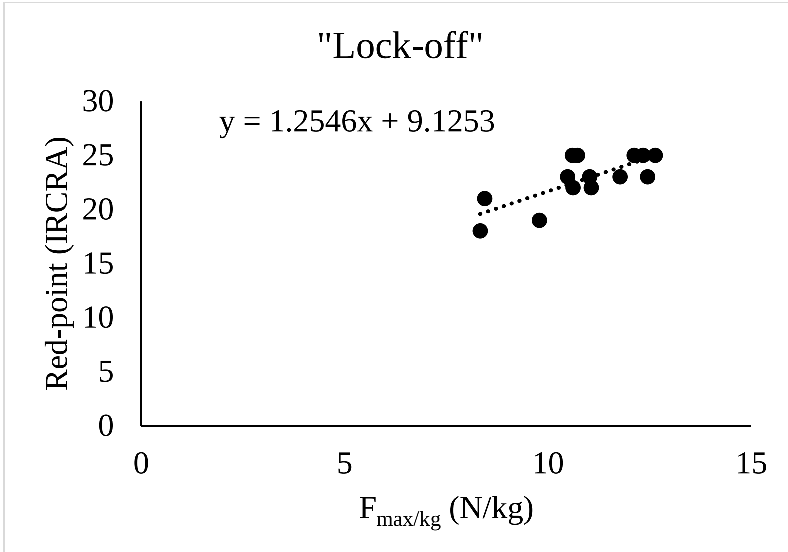

Fig. 16 Regression model for estimating the relative strength (Fmax/kg) of the shoulder girdle musculature determined by the lock-off test

Adequacy of the model for estimating relative finger strength:

R = 0.751, R2 = 0.527, F = 15.499, p = 0.002.

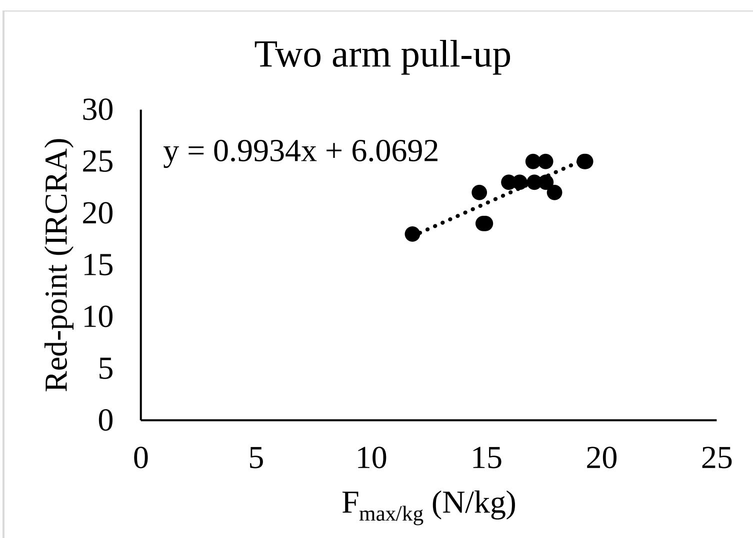

Figure 17 Regression model for estimating the relative strength (Fmax/kg) of the shoulder girdle musculature as determined by the two-arm pull-up

Adequacy of the model for estimating relative finger strength: $R = 0.843$, $R2 = 0.684$, $F = 27.029$, $p < 0.001$.

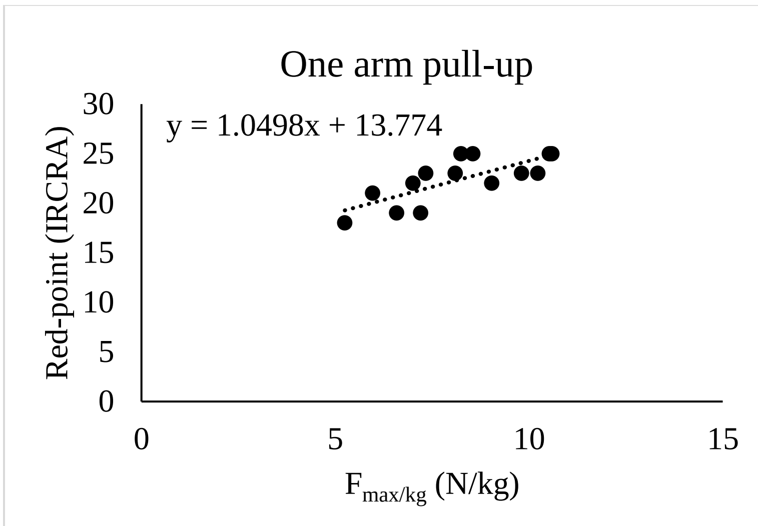

Fig. 18 Regression model for estimating the relative strength (Fmax/kg) of the shoulder girdle musculature as determined by the one-arm pull-up

Adequacy of the model for estimating relative finger strength: $R = 0.685$: $R2 = 0.429$, $F = 11.502$, $p = 0.005$.

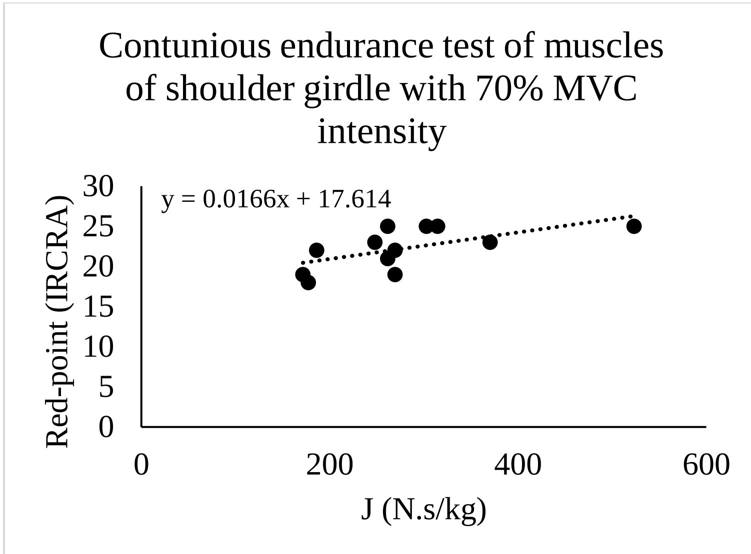

Fig. 20 Regression model for estimating shoulder girdle musculature endurance represented by force impulse (J) achieved at target force 70% Fmax

Adequacy of the model for estimating shoulder girdle musculature endurance: R = 0.623, R2 = 0.327, F = 6.343, p = 0.030.

3.3.2. Evaluation of explosive force test results

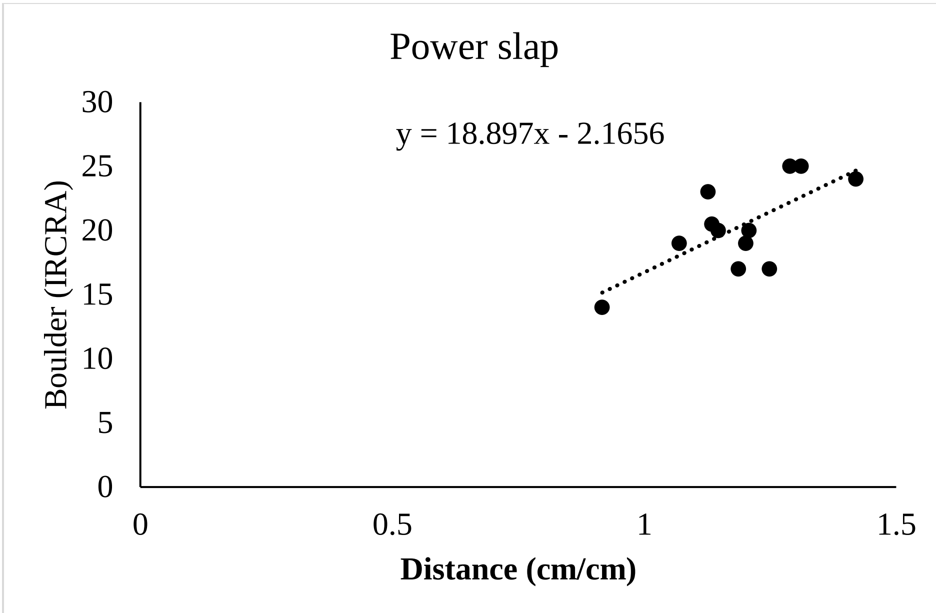

Fig. 21 Regression model for estimating the explosive power of the shoulder girdle musculature, represented by the distance achieved in the "power slap" test, related to the length of the upper limb

Adequacy of the model for estimating the explosive power of the shoulder girdle musculature by predicting bouldering performance based on the distance achieved in the power slap test relative to the length of the upper limb: R = 0.699, R2 = 0.438, F = 9.580, p = 0.011.

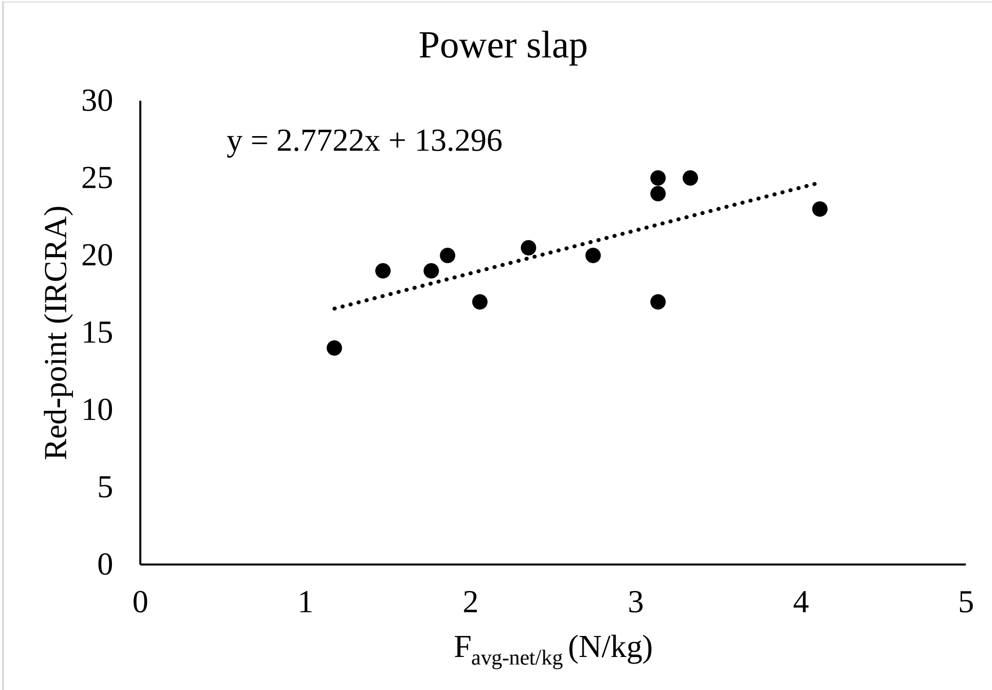

Fig. 22 Regression model for estimating the explosive power of the shoulder girdle musculature by mean net force (Favg-net/kg) related to body mass and achieved in the "power slap" test

Adequacy of the model (as determined by multiple stepwise regression) for estimating shoulder girdle musculature explosive strength by predicting red-point athletic performance based on mean net strength (Favg-net/kg) weighted to body mass and achieved in the test "power slap": R = 0.843, R2 = 0.681, F = 24.460, p = 0.001.

Conclusion:

Based on the statistical and logical analysis of the results, it can be concluded that the motor tests used are reliable and valid, as well as suitable for the control of the training process in sport climbing. The tests also provide detailed and wide-ranging information on the state of climbers' specific muscle strength and endurance due to the multiple parameters measured, which are valid for different abilities. In addition, the present study adds to the available knowledge on the problem under consideration since some of the collected data are new and have not been published by other authors. Other important contributions are the establishment of the importance of the strength qualities of the shoulder girdle musculature and the possibility to apply in practice the derived equations for the assessment of test performance. All this finds a more concrete expression in the next two chapters.

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS:

1. Both the specific grip finger flexor maximal strength test and the shoulder girdle maximal strength lock-off test have an excellent level of reliability (ICC > 0.9).
2. The high reliability levels of pull-up time and maximum and average net force achieved in the rapid pull-up test confirm its utility value.
3. In the “power slap” test, the distance reached, the average net force, and the time of the test have the highest levels of reliability.
4. The existence of significant dependencies between the studied parameters and sports achievements testifies to the applicability of the same in sport climbing.
5. For advanced climbers, explosive pull-ups to reach distant holds are more important to the boulderer than the "difficulty" discipline of sport climbing.
6. The maximum strength of the fingers and of the shoulder girdle have equal values. The endurance of the two muscle groups is of similar importance but is a lesser factor in the achievement of maximal strength.
7. The lock-off test corresponds to and can replace one- and/or two-arm pull-ups.
8. During dynamic movements to reach more distant grips, climbers move their bodies and generate power at the expense of maximal force potential rather than the rate of force development. 9) Rates of force development are more informative of climbers' explosive capabilities when determined by the "rapid pull-up" test.

RECOMMENDATIONS:

1) The lock-off test needs to gain popularity and widespread use, as it is highly informative and does not take much time and energy to perform compared to weightlifting. In addition, the results of the lock-off test can predict the maximum force that can be achieved during the one- or two-handed pull-up.

2) Climbers and their coaches would do well to apply the explosive strength tests presented in this paper and be well versed in the issues addressed in this study. Only based on detailed information about the state of key factors for climbing achievement is it possible to successfully optimize the training process.

3) Modern training and competition activities require the use of specialized dynamometers that allow the determination of parameters such as rate of force development, power, time for explosive recruitment, and others. These parameters cannot be established without the use of instrumentation.

4) Coaches should also focus their efforts on developing maximal strength, explosive power, and muscular endurance of the shoulder girdle, as the present study shows that the strength and endurance of both muscle groups are of similar importance to athletic performance in climbing.

5) The ability to reach a far-reaching grip through a dynamic pull-up can be assessed by the power slap test, but explosive power should be measured by the absolute and relative indicators of rate of force development (force gradients) measured by the speed pull-up test.

CONTRIBUTIONS:

1) The present study provides, for the first time, information on the reliability of an explosive strength test in which the goal is for climbers to pull up with both hands in the shortest possible time (the "rapid pull-up" test).

2) For the first time, the power slap and speed pull-up tests are performed with the force applied to the device taken into account.

3) By calculating a number of mechanical parameters (including rate of force development, force impulse, average force, and peak force), new and very detailed information related to the performance of both tests was provided.

4) By determining the reliability and validity of a large set of climbing-specific tests, their applicability as well as the significance of the latent traits they measure have been verified. This can help professionals structure the training process for climbing more effectively.

5) Regression models were created to evaluate the results of the studied tests, which facilitates the optimization of training loads.

6) An opportunity has been provided for a wider introduction into sports practice of the so-called lock-off test. It reliably predicts the strength that can be achieved when pulling with one or two hands. Time-consuming and labor-intensive tests to organize can be avoided.

Publications related to the topic of the dissertation:

1. Michailov M, Lambreva S, Deneva D, Andonov H. Importance of elbow flexor muscle strength and endurance in sport climbing. Journal of Applied Sports Sciences 2017; 1:3-12.

2. Michailov M, Andonov H, Deneva D, Lambreva S, Groshev O, Yordanov P. Duration of isometric efforts at a given intensity in different types of sports. Sports and Science 2017; Special Issue 1: 179-192.

3. Lambreva, St. Validity of the "Lock-off" test for maximal shoulder girdle muscle strength in climbers. "Sports and Science", 2024