NATIONAL SPORTS ACADEMY “VASIL LEVSKI”

DEPARTMENT „THEORY OF SPORT“

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A COMPLEX SYSTEM FOR SPORT-SPECIFIC PHYSICAL FITNESS ASSESSMENT IN ROCK CLIMBING

SHORT EXPOSITION OF
A THESIS FOR RECEIVING THE DEGREE “DOCTOR OF SCIENCES“

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The dissertation contains 269 standard pages and is illustrated with 34 tables and 53 figures. The references are 143.

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INTRODUCTION

Among the important conditions that determine the effectiveness of the training process is the application of sport-specific exercises and methods as well as their proper distribution over time. However, the motor potential of the athlete can be more fully realized through a scientifically based training. For this purpose, objective feedback is needed on the essential components of sport-specific physical fitness, which enables to improve the training programs.

The creation of a complex system for controlling sport-specific work capacity will be of benefit particularly in rock climbing. It is still rarely applied by specialists in the field, and the tests commonly used by sport researchers carry little information that can serve to optimize training and improve performance of climbers. For example, elite climbers do not differ significantly from lower-skilled climbers in maximal strength measured through the traditionally used hand dynamometry. The results of maximal incremental cycle or running ergometer tests do not correlate with climbing performance.

A system for the assessment of climbing specific physical fitness is obvious due to the fact that this fascinating activity has become extremely popular in recent years. In addition, sport climbing will make its Olympic debut at the Summer Olympics. This places higher demands upon sport climbers' preparation and will surely require monitoring and evaluating climbing performance-limiting factors to optimize training.

The system for the assessment of climbing specific physical fitness should be composed of suitable tests. For this purpose, it is necessary to be well acquainted with the workload characteristics, physiological responses and specific abilities that determine sport performance in rock climbing. This allows the development of climbing specific tests according to the ability they are intended to assess. Thus, the tests would be designed in a way that assures high validity with respect to the measured sport-specific latent variable and the test results would correlate with climbing ability.

1. ROCK CLIMBING AS A SPECIFIC PHYSICAL ACTIVITY

1.1. MAIN CHARACTERISTICS

Rock climbing is a term that refers to climbing routes in order to reach either the top of the rock formation, or only to the highest point of the route. Most often, "rock climbing" means climbing rocks, which are free of snow and ice. Nowadays rock climbing is not just a form of training for alpinists, but a specific recreational and physical activity (Watts 2004) and an extremely popular sport that includes various disciplines: sport climbing (lead climbing), bouldering, traditional climbing and alpine climbing. Sport climbing and bouldering are the most popular disciplines. Sport climbing is practiced outdoors or on artificial climbing walls, usually on well-protected 10 – 30 m routes were the progress is made by using the natural forms of the rock (the equipment serves only as protection in case of a fall). Bouldering is the most powerful discipline, which is practiced close to the ground and without rope on boulders or artificial structures, which makes possible to land by avoiding injuries. It is typical to climbers to climb at the limit of their individual capabilities even when not participating in a competition. The International Federation of Sport Climbing (ISCF) has introduced sport climbing as a term that can be used as a synonym for competitive climbing, which includes three disciplines: "lead climbing" (leading a sport route using a rope), "boulder" and "speed".

1.2. CHARACTERISTICS OF THE WORKLOAD IN ROCK CLIMBING

Rock climbing is neither only a strength nor an endurance sport but a physical activity with a variable character of the workload, demanding a complex development of the motor abilities, various and at the same time stable skills and mixed energy supply with dominant participation (in most types of climbing) of the aerobic and anaerobic alactic energy systems. An important feature of rock climbing is that it requires intermittent isometric contractions of the finger flexor muscles with contraction phases, which are longer than the relaxation phases. The ratio was measured to be 4:1 in sport climbing (Schadle-Schardt 1998) and 13:1 in bouldering (White, Olsen 2010). In addition, more than 1/3 of the time on the route is spent in immobilized positions (Billat et al. 1995). The muscles with the largest relative contribution during climbing are the finger flexors, followed by the elbow flexors and the muscles of the torso (Koukoubis et al. 1995; Deyhle et al. 2015). Therefore, fatigue during climbing is predominantly local in nature and mostly affects the forearms. These characteristics of climbing as a physical activity have a restrictive effect on the peripheral blood circulation and the supply of oxygen and energy, and largely explain the peculiarities of the physiological responses induced by climbing.

1.3. PHYSIOLOGICAL ASPECTS

The pattern of the increases in the physiological variables induced during climbing is non-standard. Heart rate (HR) increases disproportionately to oxygen consumption (VO_2) and the relationship between the two parameters appears not to be linear (Mermier 1997; Sheel 2003; Sheel et al. 2006; Watts 1998). The peak value of VO_2 during climbing is low compared to the maximal VO_2 values from maximal cycling or treadmill ergometric tests. A similar phenomenon was observed with regard to the concentration of blood lactate (La). In the presence of relatively high HR values, post-climbing La is relatively low (~ 6.8 mmol / l) (Mermier et al. 1997; Watts 2004). However, both VO_2 and La values for climbing and HR are lower than the same values in the traditionally used incremental ergometric tests: 79.3, 56.9 and 88.8% of the maximal running values, respectively (De Geus et al. 2006). Thus, physiological parameters recorded during climbing do not reflect energy expenditure, the type of metabolism and training zone in the same way as in other sports.

1.4. PHYSICAL QUALITIES - FACTORS OF SPORT PERFORMANCE IN ROCK CLIMBING

The nature of the workload and physiological exertion raise specific demands on the physical capabilities of climbers. The muscles of the upper body are most important. The strength related to body mass during a climbing specific grip and the muscular endurance of the finger flexors are key performance factor (Baláš et al. 2012; Baláš et al. 2014a; Grant et al. 1996; Michailov, Mladenov, Schoeffl, 2009; MacLeod et al. 2007; Michailov 2014; Philippe et al. 2012; Vigouroux, Quaine 2006a, b; Fryer et al. 2015a, b). The data of a number of authors confirm that climbing abilities also depend on the strength qualities of the shoulder girdle muscles (Baláš et al. 2012; Draper et al. 2011; Grant et al. 1996; Laffaye et al. 2014; Michailov et al. 2017). ; Wall et al. 2004). Hip mobility is also a factor of climbing ability but it determines the success on the route to a lesser extend (Grant et al. 1996; Mermier et al. 2000; Draper et al. 2009; Mihailov 2006). Although general work capacity should be at a very good level (Michailov 2014; Wall et al. 2004), climbing achievements depend mainly on the specific physical abilities. Therefore, training and testing for monitoring and evaluating climbers' fitness should reflect in detail the characteristics of rock climbing as an activity.

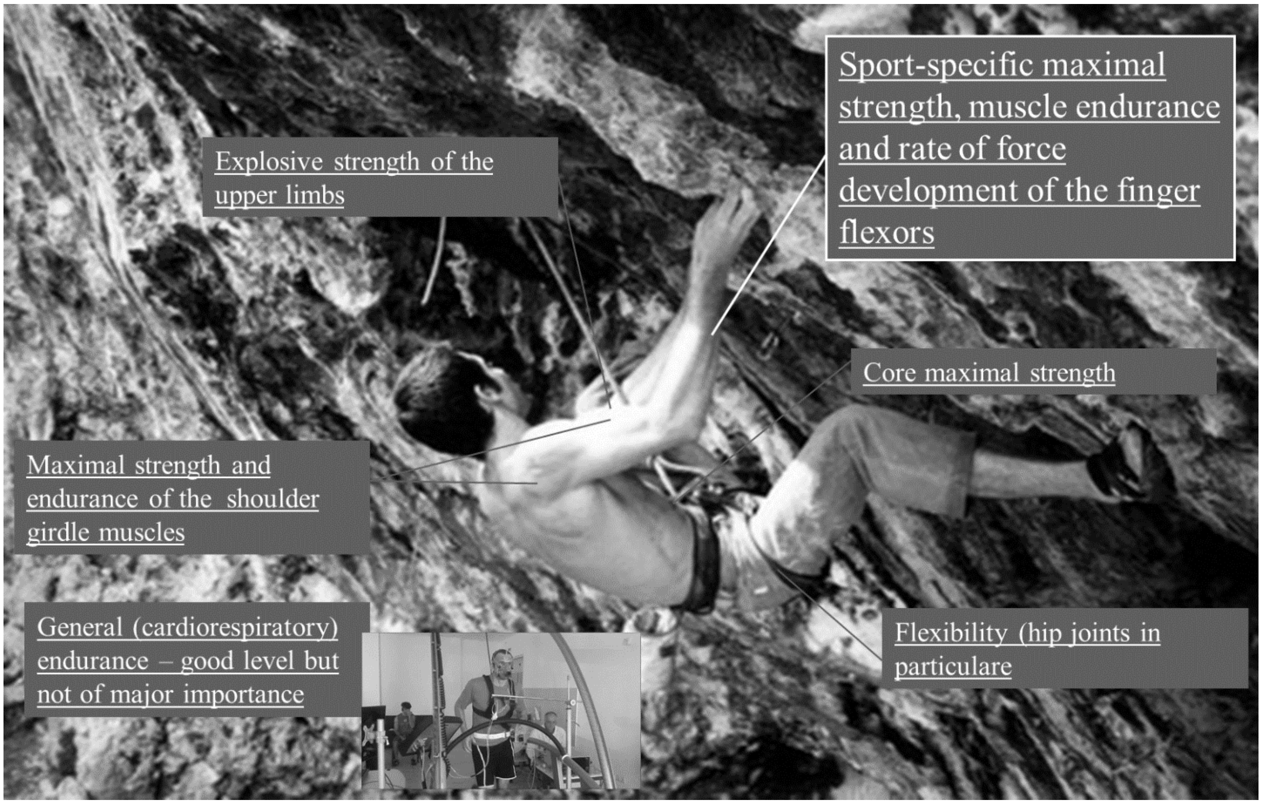

Figure 1 Physical abilities for which there is scientific evidence that they are of major importance in rock climbing

1.5. PROBLEM STATEMENT

Despite the availability of many data on the factors of sport performance in rock climbing and on the tests for the assessment of climbers' training state, there is a great need for new research, which should serve to create an effective system for the assessment of sport-specific physical fitness in rock climbers.

For this purpose, an advanced specific force measuring system must be developed first. To date, the researchers in the field have adapted dynamometers that were not specifically designed for measurements in climbers (Vigouroux, Quaine 2006 a, b; Philippe et al. 2012). The dynamometers used so far are limited in terms of: a) providing real-time feedback; b) assisting subjects in controlling the intensity and duration of muscle contractions; c) allowing correct performance of the tests by standardizing the posture, upper limb position; and d) objective criteria for test termination (when the prescribed intensity and duration of the efforts can no longer be maintained).

This type of research equipment should initially serve to select a testing position. This will show: a) to what extent the standardization of the position of the upper limb by supports for fixation of the upper arm and forearm can increase the reliability of the measurements; and b) whether this will reduce the specificity of the tests and lead to loss of meaningfulness of results. As a second step, it is important to take into consideration all the related scientific knowledge and develop new tests or variants of existing tests that would be most suitable for assessing climbers' training state. The reliability and validity of these tests should be established in order to select the most appropriate ones.

So far, there is more complete data on the informativeness of the maximal finger strength measurements (Baláš et al. 2014a, b). There is still no suitable test to assess the aerobic capacity at the systemic level in rock climbing. The workload model in such a test should induce peak values of oxygen consumption that correlate with climbing performance and allow the determination of submaximal physiological markers (inflection points / thresholds). The existing tests do not meet these important conditions for performance evaluation.

The known facts in the specialized literature and our experience determine the main *methodological concept of the present work:*

The assessment of climbing specific physical fitness and functional diagnostics at systemic and peripheral level in rock climbers as a new approach for effective management of the training process.

The research of the present work is performed taking into account the following important facts: 1) physical fitness assessment and monitoring are more useful for optimizing training if both physical abilities and physiological functions are evaluated; 2) in rock climbing, performance is limited rather by the strength, aerobic and anaerobic capacity of the muscles than by central factors related to the capabilities of the cardiorespiratory system and blood circulation.

The need to create a system for controlling the training state in rock climbers, which should include specialized, reliable and valid tests that provide detailed information, determines both the principle approach and the specific methodology of present dissertation.

2. RESEARCH PURPOSE, TASKS AND METHODS

2.1. PURPOSE

The purpose of the research was to develop a complex system for sport-specific physical fitness assessment as an essential factor for increasing the efficiency of sport training in rock climbing.

2.2. RESEARCH TASKS

1) To characterize rock climbing as a specific physical activity.

2) To lay out the basics of general theoretical knowledge on the workload during physical activity, training state of the athlete and methodology of controlling the training process, which will serve as a model to build an effective system for assessing and managing sport-specific fitness in rock climbing.

3) To systematize the data from the scientific literature on workload characteristics, physiological aspects and factors of sport performance in rock climbing.

4) To analyze the advantages and disadvantages of the tests used so far for measuring and evaluating the specific physical abilities of climbers.

5) To conduct studies for selecting a suitable test for assessing climbers' work and aerobic capacity at systemic level.

6) To develop an advanced system for measuring climbing specific strength and muscle endurance.

7) To estimate the reliability of the mechanical parameters measured during the performance of the tests for the assessment of climbing specific strength and muscle endurance of the finger flexors, as well as to calculate the correlations between these parameters and climbing performance.

8) To develop and approve a methodology for local muscle aerobic capacity evaluation.

9) To determine the validity of the investigated tests and test parameters registered through them with respect to sport-specific finger strength and endurance and the local muscle aerobic and anaerobic capacity.

10) To create scales and normative values for evaluating climbing specific strength and endurance, as well as functional capabilities at peripheral level.

2.3. RESEARCH METHODS

Literature review

The guidelines for the empirical part of the research related with the present dissertation were outlined on the basis of a review of scientific articles (121), textbooks, monographs and books (21 in total). Some of these publications were concerning the general theoretical foundations of sport training management and others physiology and performance in rock climbing.

Experiments

The experimental part of the research included several procedures for conducting eight separate studies, which were implemented in three stages. The exercise tests were performed using equipment for recording both mechanical and physiological parameters. Anthropometric characteristics of the participants were also measured.

The following equipment was used: treadmill; cycle ergometer; rowing ergometer adapted to be used for a sport-specific incremental upper-body test; climbing walls and holds; newly developed sport-specific dynamometer; traditional hand dynamometer; caliper; stadiometer; electronic scales; heart rate monitors; gas analyzing and blood sampling equipment..

More information about the experimental approach to the problem and the activities during the three stages of the experimental part of the research are shown in Figure 2.

Mathematical and statistical methods

The data collected by the conducted studies were processed by the following statistical methods: descriptive statistics; hypothesis testing (analysis of variance); correlation, regression and factor analysis. Mathematical methods have also been used to determine derivative force parameters and anthropometric characteristics as well as to calculate relative energy system contribution during the performance of the muscle endurance tests. SPSS statistical software (version 19, IBM, New York, USA) was used for all statistical analyses.

2.4. PARTICIPANTS

85 male climbers took part in the research. They were divided into 7 groups. Some of the groups participated in more than one study. To extract more information, the data from some studies was used to complete more than one of the tasks of the present work.

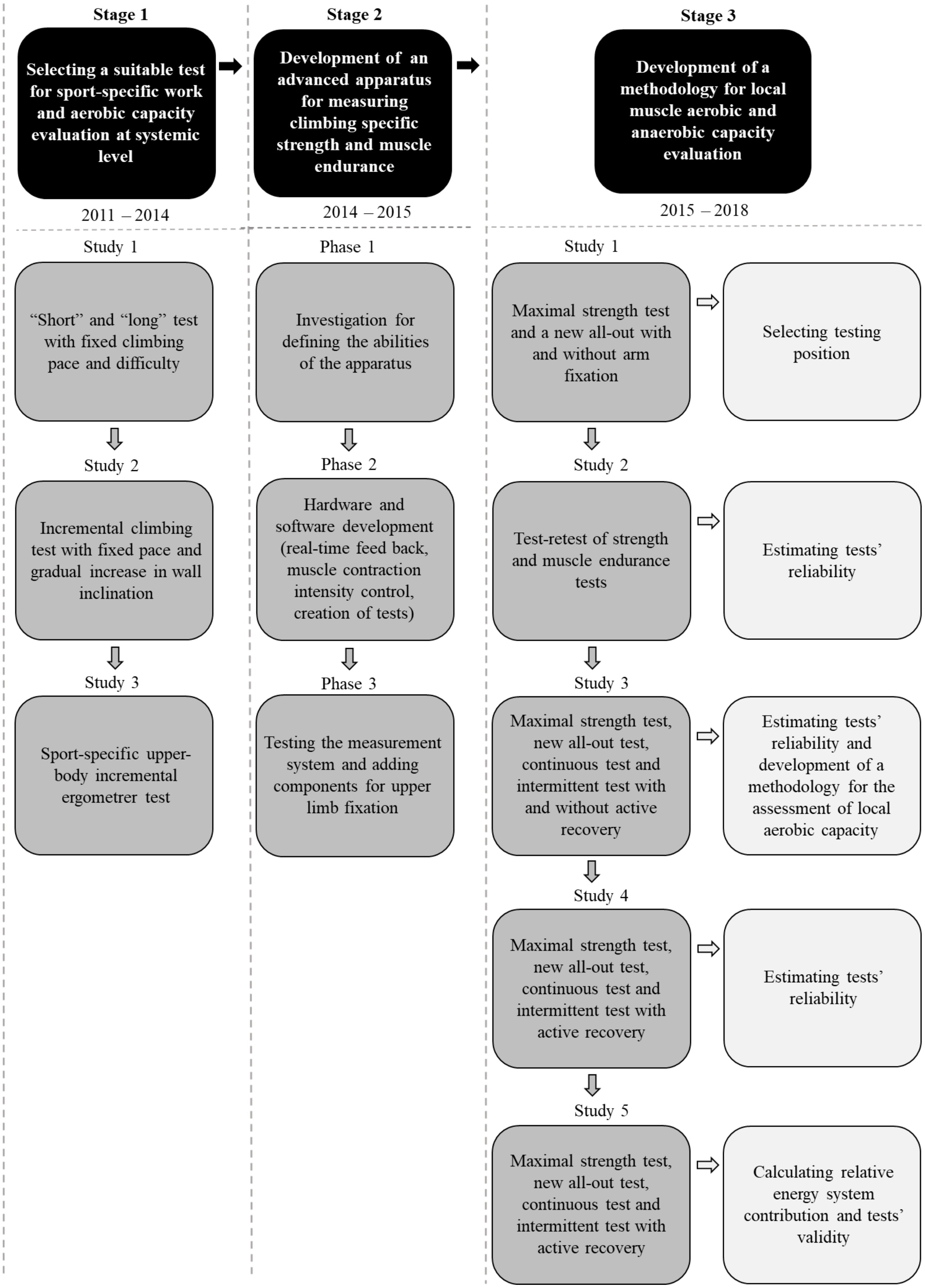

Figure 2 Scheme of the research activities

Characteristics of the groups of subjects:

- Group 1 consisted of 8 elite climbers (redpoint 8a - 9a), age 31 ± 8.5 years, who participated in stage 1, study 1.
- Group 2 consisted of 6 advanced climbers (redpoint 7a + - 8b), age 36 ± 8 years, who participated in stage 1, study 2.
- Group 3 consisted of 11 elite climbers (redpoint 7b + - 8c +), age 30.07 ± 6.4 years, who participated in stage 1, study 3.
- Group 4 consisted of 22 climbers (wide range of climbing ability: redpoint 4 - 8b; boulder 6a - 8c), age 28.3 ± 6.3, who participated in stage 3, studies 1 and 3.
- Group 5 consisted of 9 advanced climbers (redpoint 6c + - 8b; boulder 7b - 7c), age 36.2 ± 9.9, who participated in stage 3, study 2.
- Group 6 consisted of 16 climbers (wide range of climbing ability: redpoint 6a - 9a; boulder 6c - 8c +), age 33.3 ± 9.7, participated in stage 3, study 4.
- Group 7 consisted of 13 advanced and elite climbers (redpoint 7a - 9a; boulder 7a - 8a), age 29.4 ± 7.9, who participated in stage 3, study 4 and 5.

2.5. METHODOLOGY

2.5.1. Procedures during study 1 of stage 1

Tests

The aim of this study was to understand the extent to which steady paced (2 hand moves per 5 s) climbing tests until failure can be used for sport-specific work capacity evaluation. Participants performed two versions of constant in difficulty of the single moves strength endurance climbing tests, which differed only in hold type (difficult versus easy to hold). This led to different durations of the two trials. Participants traversed near the ground (changing left and right directions) on a slightly overhanging climbing wall (inclination: 12° from vertical). The difficulty of the single moves w Test 1 was designed with greater difficulty and shorter duration compared to Test 2. The technical difficulties in both tests were reduced to a minimum.

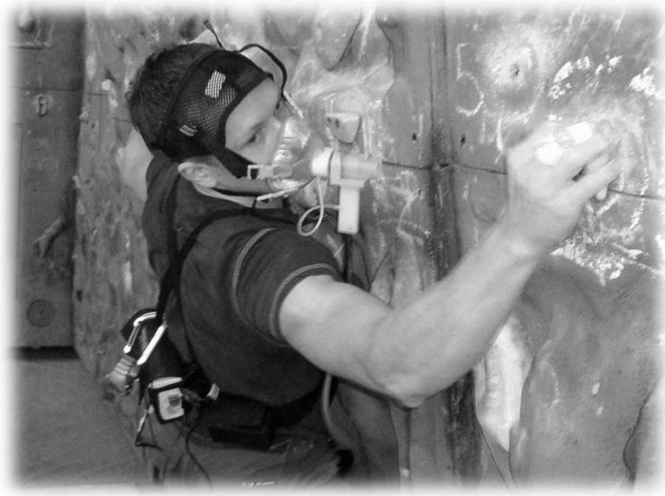

Figure 3 Performing a steady paced test where participants traversed changing left and right direction until failure

Analyzed variables

The following parameters were analyzed: time to failure, mean and peak values of heart rate (HR) and oxygen consumption (VO_2) both related to body mass (HR_{avg}, HR_{pea}k, VO_{2avg} and VO_{2peak}, respectively), mean pulmunary ventilation (VE) and respiratory exchange ratio (RER) and mean values of blood lactate concentration (La) and La clearance at the10th ($La_{clearance10min}$) and 20th minute ($La_{clearance20min}$). A second set of indicators for lactate clearance were $La_{clearance10min}$ and $La_{clearance20min}$, expressed as a percentage of the La increase (% $La_{clearance10min}$ and % $La_{clearance20min}$).

Statistical analysis

Differences between the variables from both climbing trials were analyzed through repeated measures analysis of variance. Shapiro–Wilk test was used to check for normal distribution. Spearman's correlation coefficients between estimated parameters and sport achievement in the red-point and on-sight styles were calculated to identify applicable performance indicators. Pearson's correlation coefficients were calculated between the two tests' durations and VO_2 parameters, handgrip strength, sport-specific finger strength and climbing performance in redpoint and on-sight styles.

2.5.2. Procedures during study 2 of stage 1

Tests

This study was organized in an effort to analyze the cardiorespiratory responses during an incremental climbing test. Therefore, the participants also performed a traditional maximal incremental cycle ergometer test to compare the results and to find out whether extent this type of a climbing test can lead to a maximal load at system level.

Participants performed the sport specific test (Figure 4) climbing up and down until they were no longer able to hold on and stay on the artificial wall. The climbing pace was steady (two hand moves per 5 s) and the holds type and distances between them were identical. The holds were large (for the distal, middle and partially for the proximal phalanges). However, the climbing difficulty was gradually increased by gradually increasing the wall inclination. Climbers started while the wall was inclined at 5° (from vertical to overhanging position) and after every 90 s the overhang was increased by 5°.

The cycle ergometer test was performed according to the protocol of Iliev et al. (1982). The initial power was 60 W. After each stage (90 s) the intensity was increased by 30 W until exhaustion.

Analyzed variables

The following parameters from both tests were taken into account: VO_2 related to body mass, VE, oxygen pulse (O_2/HR), metabolic equivalent (MET) and time to exhaustion.

Statistical analysis

Mean values, standard deviations and confidence intervals of the peak values of the physiological parameters and tests' duration were calculated. VO_2, HR, oxygen pulse and VE kinetics were analyzed. Paired Student's t-test was used to compare the peak values of the two tests. Regression analysis was performed to examine the VO_2-HR relationship.

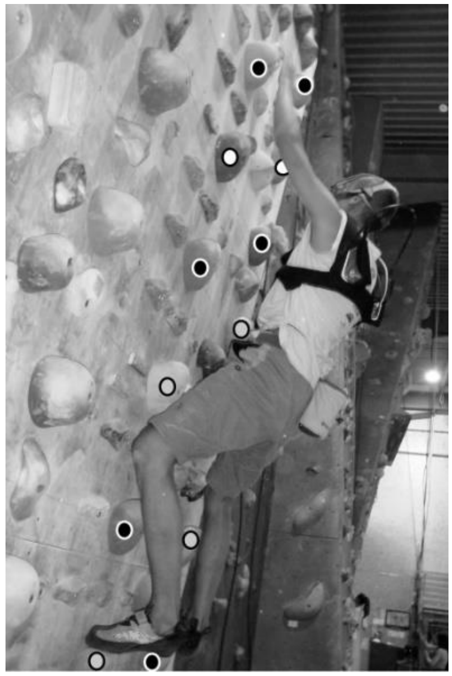

Figure 4 Performing the incremental climbing test with increasing wall inclination

2.5.3. Procedures during study 3 of stage 1

Tests

This study sought to compare the cardiorespiratory and work-load results of elite sport climbers who performed a sport-specific UBT with a traditional treadmill test (TMT) to exhaustion and to assess which set of measured variables was significantly correlated and had specificity to the training status and climbing grade ability of these elite climbers.

The UBT was performed while standing using an isokinetic rowing ergometer mounted vertically on a wall (Figure 5). Each consecutive work interval lasted 95 seconds (80-s working phase plus 15 s relaxation). Submaximal La samples were collected during each relaxation phase and at the end ($La_{end\text{-}of\text{-}test}$). The work rate for the first interval was 20 W, which increased by 15 W for each consecutive work interval until exhaustion.

The TMT followed the testing protocol validated by Iliev18. The inclination was constant (2.5%) and the initial velocity was 6 km/h. After each 90-second interval the velocity was increased by 1.2 km/h until exhaustion.

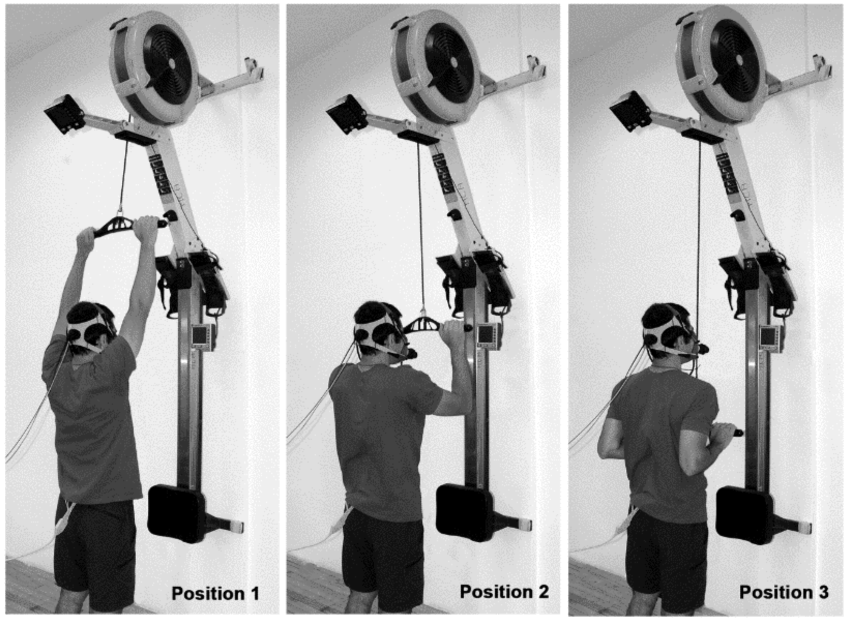

Figure. 5 Performing the new upper-body maximal incremental test. Starting, middle and end positions are presented

Analyzed variables

From the 2 maximal tests the following parameters were taken into consideration for analysis: upper-body (UB) peak power output (PPO), PPO relative to body mass, treadmill (TM) maximal velocity, maximal aerobic power relative to body mass (VO_{2peak}), time to exhaustion, peak heart rate (HRpeak), Laend-of-test, and respiratory compensation point (RCP). RCPs were expressed through the corresponding percentages of PPO, HR, and VO_2 values, as well as through La values in the UBT. HR, VO_2, and La values at respiratory-exchange ratio stabilized above 1.00 (RER_1) were also analyzed. In addition, the duration of the 2 exercises after reaching RER_1 was calculated.

Statistical analysis

The selected variables were subjected to descriptive statistics. The comparable variables from both tests were normally distributed after the Shapiro-Wilk test. An exception was TM HR at RER_1. Differences between variables were checked by paired t-test. Spearman correlation coefficients between the measured variables and sport achievements were calculated. The VO_{2peak} values from both tests were subjected to regression analysis and F test to find proof for the new test's validity in rock climbing.

2.5.4. Characteristics of the innovative system for performance assessment in rock climbing (3DSAC)

Technical characteristics of 3DSAC

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 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; (c) a radio receive/transmit station for wireless data transfer; and (d) a 23-mm deep wooden climbing hold with a radius of 12 mm (Figure 6). The force sensor configuration is triaxial (± Fy, ± Fx, + Fz), with a measuring range of 0 kN to 2.5 kN and a comprehensive accuracy of 0.5%.

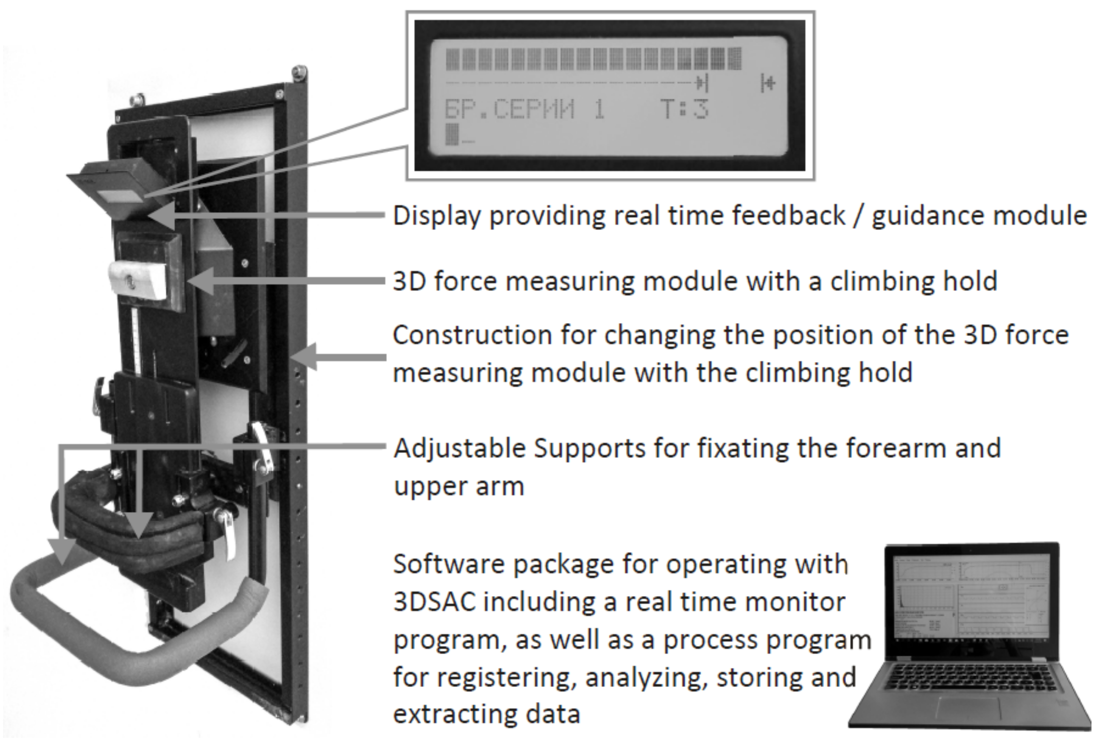

Figure 6 The innovative system for performance assessment in rock climbing (3DSAC)

Abilities of 3DSAC

3DSAC can be mounted vertically on a wall. A large number of mechanical parameters can be calculated after performing maximal strength tests, all-out tests or variants of continuous and intermittent tests at constant intensity. The assistance module allows participants to control the intensity of muscle contractions when performing continuous or intermittent tests, showing the upper and lower limits of the target force zone and graphs of the applied force in real time. The 3DSAC up or down sliding construction and forearm and upper arm fixation supports are fully adjustable to fix the upper limb of climbers with different anthropometric characteristics. This ensures a standardized test execution. Eight different types of tests are preprogrammed. Test variants of the same test type can be created by changing the load parameters. To facilitate statistical analysis, the data is separately extracted for each test in tabular form.

2.5.5. Description of the tests applied during stage 3

During the third stage of the research, the informativeness of four types of tests was investigated. These tests were: a maximal strength test, an all-out (anaerobic) test and continuous and intermittent tests at constant intensity.

Arm and grip position

The participants performed the tests standing and facing the 3DSAC. In most cases, this was done without arm fixation (AF) with the shoulder flexed at 180° and elbows fully extended (Figure 7a). During the first study of stage 3, the maximal strength and anaerobic tests were performed in two variants: with and without AF. During the AF condition, the elbow and shoulder were flexed at 90° and the shoulder was abducted at 30° (figure 7b). The intermittent test was performed in two variants: with and without hand shaking for active recovery.

All participants used a combination of the open and crimp grip (Figure 8) described by Schweizer (2011). During testing without AF, they had to load the hold of 3DSAC using their own weight without pulling through flexing their arms. For this purpose, participants bended their knees and raised their heels while holding the grip and keeping contact with the floor. The two variants of the intermittent tests differed during the relaxation phases. The exercising hand either remained up without applying pressure on the hold or was shaken down next to the body.

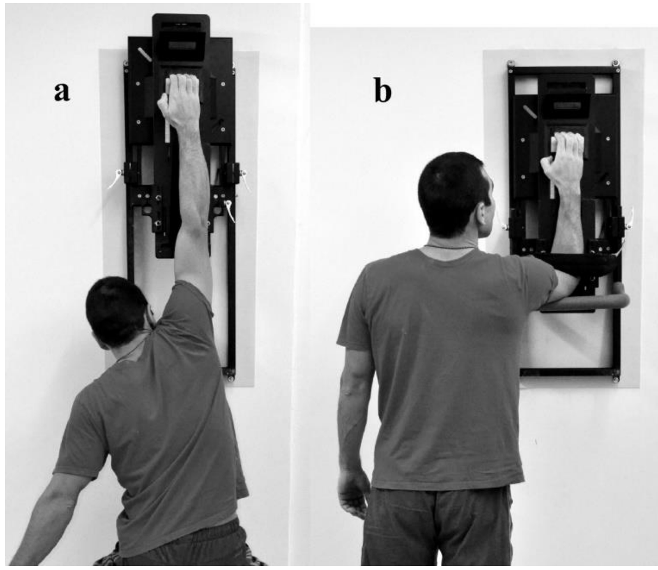

Figure 7 Performing a test with fixation (variant "a") and without arm fixation (variant "b")

Figure 8 A half-crimped (hybrid) finger grip position was used in all finger strength and endurance tests

Tests

Maximal strength tests. During the maximal strength tests, the participants performed three maximal voluntary contractions (MVC), separated by rest intervals of 1 min. Maximal strength was determined by the highest force value from the three attempts.

All-out tests. During the all-out tests the participants had to develop maximal force at the beginning of the muscle contraction and exert maximally for 30 s.

Continuous tests. Participants performed the continuous tests without AF, at muscle contraction intensity of 60% MVC until they fail to maintain the force in the target zone (± 10% target force).

Intermittent tests. The variants of the intermittent tests (with and without shaking) were also performed without AF and at intensity of 60% MVC until failure. The contraction and relaxation phases were: 8 s and 2 s, respectively. Continuous and intermittent tests were automatically stopped when the force dropped below the lower limit of the target zone for more than 1 second.

2.5.6. Procedures during stage 3

Procedures for selecting a suitable testing position

The participants in this study performed four tests on 3DSAC: a maximal strength test with and without AF and then an all-out test with and without AF. The with and without AF conditions were randomized.

Analyzed parameters. From the maximal strength test, the maximal (F_m) and relative force ($F_{m\text{-}rel}$) were analyzed. The rate of force development (RFD) parameters in the maximal strength test with AF were also taken into consideration. From the all-out tests, average force (F_{avg}) and fatigue index ($I_{fatigue}$) were analyzed.

Statistical analysis. One way ANOVA with repeated measures method was used To determine the level of significance (p) of the differences between the two conditions (with and without AF). Effect sizes were calculated to determine the effect of AF. Pearson correlation coefficient were calculated to determine the relationship between the test parameters and sport performance in sport climbing and bouldering.

Procedures for estimating tests' reliability

The participants in this study visited the laboratory twice (with an interval of 1 week between visits). On both days, they performed the same tests: 1) maximal strength test with AF, 2) maximal strength test without AF, 3) anaerobic test without AF, and 4) intermittent test without AF. Maximal strength tests (with and without AF) were performed in random order before the all-out and intermittent tests, which were also randomized.

Analyzed parameters. From the maximal strength tests, the F_m, $F_{m\text{-}rel}$. RFD parameters from the maximal strength test with AF were also analyzed. F_{avg} and fatigue index $I_{fatigue}$ were taken into account in anaerobic tests. The intermittent test's parameters were: the number of repetitions, the time in the target zone (T_{tz}), the impulse or force-time integral (J) and J related to body mass (J_{rel}).

Statistical methods. To determine the reliability of the measurements, intraclass correlation coefficients (ICC) were calculated between the test and retest scores (inter-session reliability) and the limits of agreement were determined by the of Blant and Altman method (1986). The systemic error was tested with one way ANOVA for repeated measurements.

Procedures for the development of a methodology for local aerobic capacity diagnostics

This study examined whether local muscle aerobic capacity can be assessed without the use of a device for measuring skeletal muscle oxygenation through near-infrared spectroscopy (NIRS). The participants in this study performed a maximal strength test, a continuous test, and two intermittent tests (with and without shaking) for. The maximal strength test was used to set the intensity of the muscular effort (60% MVC) during the intermittent and continuous tests. The continuous and the intermittent tests with and without shaking were randomized. The rests between tests was at least 20 minutes. The different duration of the intermittent and continuous tests is due to reperfusion and active contribution of the aerobic metabolism during the relaxation intervals in the intermittent test. The greater this difference, the higher should be the level of local aerobic capacity. Therefore, both tests' T_{tz} were used to calculate a new index called "aerobic index" (I_a). To validate I_a, muscle tissue oxygenation was registered along with the mechanical parameters. To determine the importance of local aerobic capacity, prticipants were divided into two groups: lead climbers and boulderers.

Figure 9 Performing a muscle endurance test with a NIRS device to assess muscle tissue oxygenation.

Analyzed parameters. From the maximal strength test, F_m and F_m F_{m-rel} were analyzed. From the continuous test and both variants of the intermittent test, the number of repetitions, T_{tz}, J and J_{rel} were taken into consideration. I_a, representing the ratio between T_{tz} from the intermittent test and T_{tz} from the continuous test, was also calculated. Muscle oxygenation (SmO_2) during the two endurance tests, the percentage of its decrease (deoxygenation) during the contraction intervals and the increase (reoxygenation) during the relaxation intervals of the intermittent test were also analyzed. Therefore, a NIRS device was placed over the belly of the flexor digitorum profundus.

Statistical analysis. One way ANOVA was used to check for significant differences between lead climbers and boulderers. ANOVA repeated measurements method was used to determine the effect of shaking as an active recovery factor. Effect sizes were calculated for both cases. Pearson's correlation coefficients were also calculated to determine the relationships between I_a and muscle oxygenation parameters.

Test procedures for estimating tests' validity

To determine the validity of the maximal strength test, all-out, continuous and intermittent (without shaking) tests, data from measurements without AF was used and test scores of 51 climbers was analyzed (group 4,n = 22; group 6, n = 16; and group 7, n = 13). As in the previous studies, a maximal strength test was performed and the muscle endurance tests (anaerobic, continuous and intermittent) were randomized.

Analyzed parameters. The parameters analyzed in this study were the parameters used in the previous study as well as F_{avg} and $I_{fatigue}$ from the all-out test.

Statistical analysis. Principle component analysis (PCA) was performed for providing construct validity evidence of the tests and test parameters. A stepwise multiple regression analysis was used to understand the dependence of lead climbing and bouldering achievements on the derived performance components. Pearson correlation coefficients reflecting the strength of the relationship between the various parameters and the lead climbing and bouldering performance were calculated. This was done to determine the extent to which the test parameters measure climbing specific abilities (criterion validity).

Procedures for calculating the relative energy system contribution during the performance of the tests

In this study, the maximal strength test, the all-out test, the continuous test and the intermittent test (with shaking and without AF) were performed in the same order as in the previous study on the tests' validity. Before (5 min), during and after the end (10 min) of the three muscle endurance tests (all-out, continuous and intermittent), VO_2 and RER were continuously measured, and the data was recorded breath by breath (Figure 10). La samples were taken at rest. One baseline sample was taken from each participant prior the first test, and 9 more post exercise samples were taken after each of the three endurance tests (at the first, second, and third minutes after the end of the tests).

Analyzed parameters. The relative energy system contribution is reported in $J \cdot kg^{-1}$ and as a percentage of total energy consumption. The test scores were presented through the mechanical parameters of each test, which were used during the previous studies.

Calculation of the aerobic, lactic and alactic energy. The energy delivered by the three energy systems during the muscle endurance tests was determined through the method described by Beneke et al. (2002, 2004) Aerobic contribution (net) was calculated from oxygen uptake above rest during the tests and the energy equivalent of O_2 being assumed from 19.6 to 21.1 kJ·L-1 (depending on RER). To estimate anaerobic lactic contribution, the value of 1 mmol·L-1 ΔLac was considered to be equivalent to 3 $mlO_2 \cdot kg^{-1}$ (di Prampero and Ferretti,1999). The contribution of the anaerobic alactic system was considered to be the fast component of excess post-exercise oxygen consumption (EPOC) (Beneke et al. 2004).

Statistical analysis. Regression analysis was used for calculating the energy delivered by the anaerobic lactic system. Post exercise VO_2 kinetics was interpolated using the biexponential equation:

$$VO_2(t) = a\, e^{-t/\tau a} + b\, e^{-t/\tau b} + c,$$

where VO_2 (t) is the oxygen consumption at time *t*, *a* and *b* are the amplitudes of the fast and slow components of EPOC, respectively, τ_a and τ_b are the corresponding time constants, and *c* is VO_2 at rest.

Figure 10 Registration of gas exchange indicators during a finger flexor muscle endurance test execution

Scales and normative values for the assessment of finger strength and endurance and peripheral functional capabilities

The findings of the research during stage 3 are the basis for the creation of a methodology for in-depth analysis of the climbers' physical condition, including sport-specific physical qualities and functional capabilities at peripheral level. To enable comparison of the state of the different key performance abilities measured through the tests and to determine how satisfactory are the test results, the rough scores were transformed into Z- and T-scores. Normative values that determine the limits for converting Z- and T-scores into qualitative verbal assessments were also set. The regression method for evaluating test performance was used for the indicators, which strongly correlated with climbing ability. For allowing regression evaluations, the parameters of the linear function shown below were calculated:

$$Y = a + bX,$$

where X is the test rough score and Y is the predicted climbing achievement in the redpoint style presented in climbing grade (IRCRA). After completing all tests, an overall evaluation score can be obtained on the basis of the stepwise regression analysis, which was performed for the purposes of the present research. This determined the parameters of an equation of the following type:

$$Y = a + b1\ X1 + b2\ X2 + bn\ Xn$$

3. RESULTS AND ANALYSIS

3.1. RESULTS FROM THE STUDIES CONDUCTED DURING STAGE 1

3.1.1. Physiological responses during the two steady paced climbing tests

Results

The mean values and standard deviations (SD) of the physiological variables and the duration of the two climbing tests are presented in Table 1. $La_{clearance10min}$ and $La_{clearance20min}$ were 1.4 ± 0.5 mmol/l and 2.8 ± 0.6 mmol/l, respectively. La clearance as a percentage of the La increase after 10 and 20 min recovery was 37.2 ± 12.3% and 74.7 ± 7.9%, respectively. $\%La_{clearance20min}$ correlated significantly with outdoor performance ($r = 0.75$, $p = 0.033$ for red point and $r = 0.82$, $p = 0.012$ for on-sight). Handgrip and sport-specific finger strength were: 53.63 ± 16.86 kg and 54.26 ± 6.68 kg, respectively. Handgrip and sport-specific finger strength related to body mass were 0.795 and 0.805, respectively. These results did not correlate significantly with test duration. Nevertheless, sport-specific finger strength related to body mass correlated moderately with duration of test 1. Correlation coefficients between test durations as dependent variables and VO_2 parameters, handgrip strength, sport-specific finger strength and climbing ability are presented in Table 2.

Table 1 Comparison of physiological variables between tests (n = 8).

Variable	Test 1	Test 2	Difference		p	Partial η^2
	Mean ± SD	Mean ± SD	Mean ± SD	Confidence interval		
HR_{avg} (bpm)	154 ± 15	156 ± 14	1 ± 6	-4 – 6	0.528	0.059
HR_{peak} (bpm)	166 ± 16	171 ± 13	6 ± 9	-2 – 13	0.093[a]	0.353[b]
VO_{2avg} (ml/min/kg)	28.2 ± 2.7	29.2 ± 2.1	1 ± 2.1	-0.7 – 2.8	0.202	0.220
VO_{2peak} (ml/min/kg)	34.1 ± 4.8	37 ± 2.1	2.9 ± 3.5	0.0 – 5.8	0.051	0.442
VE (l/min) *	47.7 ± 9.2	54.8 ± 6.7	7.1 ± 4.2	3.5 – 10.6	0.002	0.761
RER *	0.89 ± 0.10	0.95 ± 0.07	0.06 ± 0.07	0.00 – 0.12	0.048	0.450
La_{3min} (mmol/l)	5.7 ± 0.8	6 ± 0.7	0.4 ± 1.1	-0.6 – 1.3	0.397	0.104
Climbing duration (s) **	111 ± 54	255 ± 127	144 ± 102	59 – 229	0.005	0.694

HR_{avg}: average heart rate; HR_{peak}: peak heart rate; VO_{2avg}: average oxygen uptake; VO_{2peak}: peak oxygen uptake; VE: average pulmonary ventilation; RER: average respiratory exchange ratio; * significant difference between test 1 and test 2 ($p < 0.05$); ** significant difference between test 1 and test 2 ($p < 0.01$).

Table 2 Correlation coefficients between test scores.

	VO_2 of test 1		VO_2 of test 2		Relative finger strength	Relative handgrip strength	Redpoint	On-sight
	VO_{2avg} (ml/kg/min)	VO_{2peak} (ml/kg/min)	VO_{2avg} (ml/kg/min)	VO_{2peak} (ml/kg/min)				
Climbing duration of test 1	0.54 (p = 0.171)	0.8* (p = 0.017)			0.482 (p = 0.226)	-0.001 (p = 0.998)	0.94** (p = 0.001)	0.8* (p = 0.016)
Climbing duration of test 2			0.85** (p = 0.008)	0.33 (p = 0.432)	-0.042 (p = 0.920)	-0.208 (p = 0.621)	0.6 (p = 0.114)	0.52 (p = 0.191)

VO_2: oxygen uptake; VO_{2avg}: average oxygen uptake; VO_{2peak}: peak oxygen uptake; * significant correlation ($p < 0.05$); ** significant correlation ($p < 0.01$).

Discussion

A new finding of the present study is that % $La_{clearance20min}$ correlated strongly with climbing performance and was an important indicator of the training state of climbers. Higher values of % $La_{clearance20min}$ were associated with the ability to reach higher specific VO_2 values, which determined a longer climbing duration. Despite VO_{2peak} and VO_{2avg} do not correlate with sport performance in rock climbing, it appears that VO_2 is an important physiological indicator for assessing sport-specific performance in rock climbing. The results of this study show that the model of the strength endurance tests is applicable. However, test 1 as a measure of short-term endurance, which depends more on the strength component, appears to be more useful because it correlates more strongly with sport performance than the duration of test 2, which evaluates the ability to sustain longer routes with easier moves.

The impact of hold type was greater on peak compared to average HR and VO_2 values where peak values were higher in the longer duration test. However, La_{3min}, VO_{2avg} and HR_{avg} may not differ between different combinations of hold types and tests duration. These average values more readily reflect the magnitude of the exercise effort rather than momentary exertion. Therefore, these variables could be used for performance evaluation but should not be utilized as intensity indicators during sport climbing training.

3.1.2. Cardiorespiratory responses during the incremental climbing test

VO_2, HR, VO_2/HR, VE and MET peak values as well as time to exhaustion are listed in Table 3. VO_2, VO_2/HR and VE peak values were significantly lower in the climbing test ($p < 0.01$). Nevertheless, VO2 climbing peak (VO_2peak-climb) represented 82 % of the $VO_{2peak\text{-}cycling}$ and the differences between HR_{peak} values were small (3 bpm) and insignificant ($p = 0.136$).

Table 3 Peak values, standard deviations and confidence intervals of physiological parameters and time to exhaustion in the climbing and cycle incremental tests

Variables	Incremental climbing test		Incremental cycle ergometer test		p
	Mean ± SD	Confidence interval	Mean ± SD	Confidence interval	
VO_{2peak} (ml/min/kg) **	41.7 ± 2.4	39.1 – 44.2	50.7 ± 5.2	45.2 – 56.1	0.004
HR_{peak} (bpm)	181 ± 7	174 - 189	184 ± 5	179 – 189	0.136
VO_2/HR_{peak} **	17.2 ± 2.1	14.9 – 19.4	20.3 ± 2.3	18.0 – 22.7	0.006
VE_{peak} (l/min) **	101.4 ± 12.7	88.1 – 114.8	149.4 ± 22.2	126.1 – 172.7	0.000
MET **	11.9 ± 0.7	11.2 – 12.6	14.5 ± 1.5	12.9 – 16.0	0.004
Time to exhaustion (s) **	505 ± 113	386 – 623	793 ± 86	703 – 882	0.003

VO_{2peak}: peak oxygen uptake; HR_{peak}: peak heart rate; VO_2/HR_{peak}: peak oxygen puls; VE_{peak}: peak pulmonary ventilation; MET: peak value of metabolic rate of task; ** significant difference between tests ($p < 0.01$).

VO_2, HR, VO_2/HR and VE kinetics are shown in Figure 11 and 12 These figures illustrate the existing differences between the two tests. The parameters varied more in the climbing test. The general trend of climbing VO_2 kinetics was characterized by: reduced increases at the middle of the test and sharp increases at the end (Figure 13). VO2-HR relationship appeared to be linear in both tests (Figure 14). Nevertheless, during the climbing test HR increases were disproportionally higher compared to VO_2 increases.

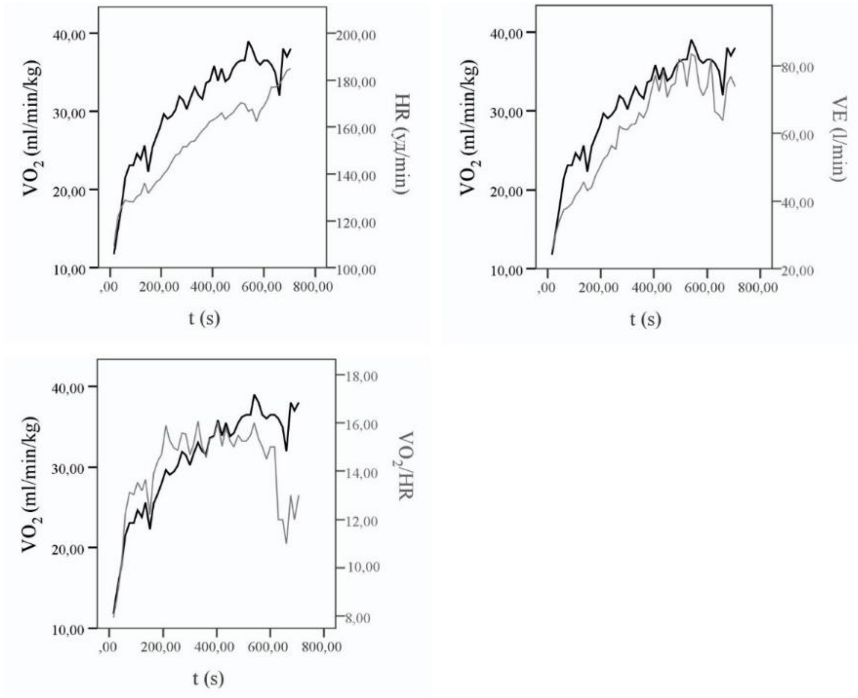

Figure 11 Oxygen consumption (VO_2), heart rate (HR), pulmonary ventilation (VE) and oxygen puls (VO_2/HR) kinetics in the incremental climbing test. Subjects number during the stages: first 450 sec (n = 6), 450-540 sec (n = 3), 540-630 sec (n = 2), > 630 sec (n = 1).

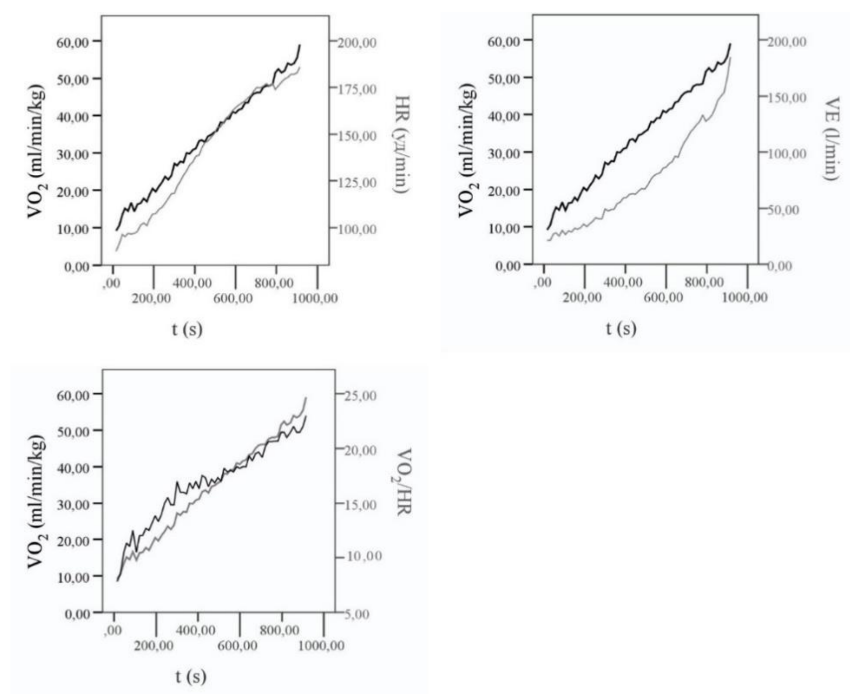

Figure 12 Oxygen consumption (VO_2), heart rate (HR), pulmonary ventilation (VE) and oxygen puls (VO_2/HR) kinetics in the cycle ergometer test. Subjects number during the stages: first 810 s (n = 6), 810-900 s (n = 5), > 900 s (n = 2)

Note that due to the smaller subjects' number at the last three stages the last parts of the curves are less representative

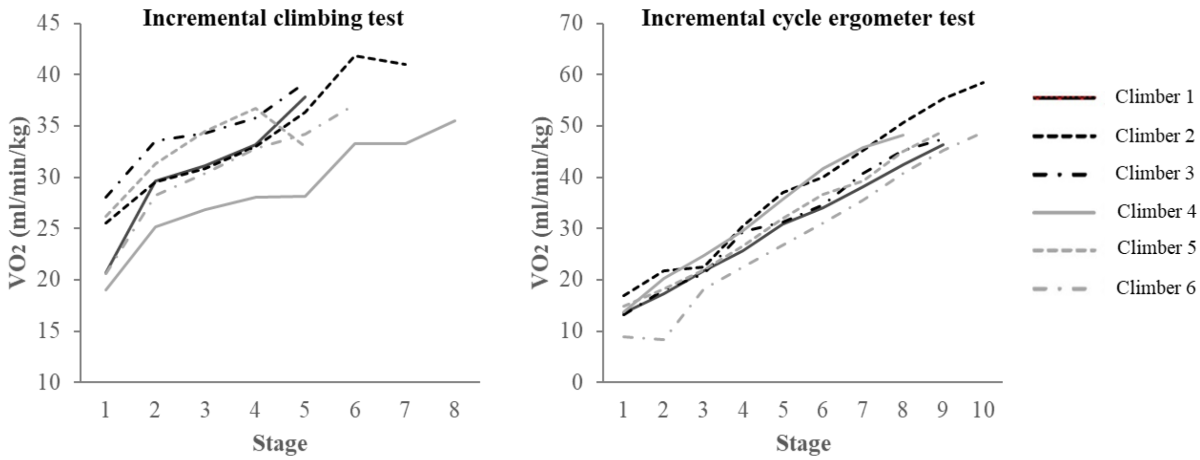

Figure 13 Oxygen consumption (VO_2) kinetics. The curves are created using averaged data points corresponding to each stage of the climbing and cycling incremental test

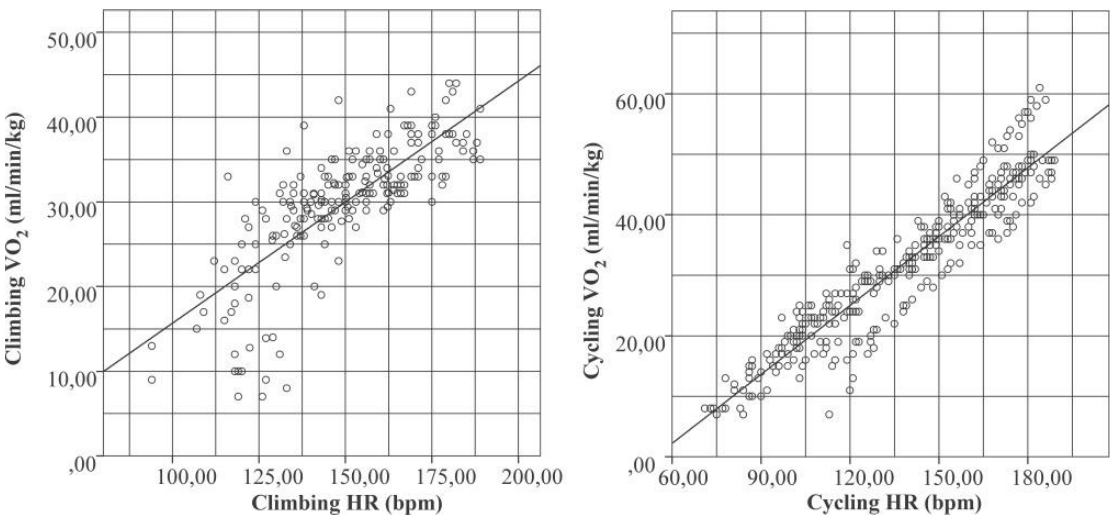

Figure 14 Scatter plots of VO_2 and HR values from the climbing and cycling incremental tests. An F-test suggested that the linear regression model is adequate for the climbing ($R^2 = 0.63$, $F = 339$, $p < 0.01$) and cycling ($R^2 = 0.88$, $F = 2343$, $p < 0.01$) tests

Discussion

Climbing to exhaustion using big holds, which does not involve prolonged immobilized positions, can lead to exhaustion at systemic level. $VO_{2peak\text{-}climb}$ represented a very high portion of $VO_{2peak\text{-}cycle}$. This suggests that aerobic metabolism may play an important role in this otherwise strength demanding sport. VO_2-HR relationship may be linear in some climbing situations. This new finding can be applied in the sport practice, for example when controlling the training workload during in rock climbing. However, the lack of correlation between $VO_{2peak-climbing}$ and sport performance requires a more appropriate test for assessing climbers' aerobic and work capacity.

3.1.3. A new sport-specific upper-body ergometer test for evaluating aerobic and work capacity in rock climbers

Results

Table 4 lists the submaximal and maximal physiological and the performance results for the UBT and TMT. The mean peak values and mean values at RER_1 and at RCP of HR, VO_2, and La from the 2 maximal tests are shown in Figure 15. Subjects' climbing ability was significantly correlated with variables from the UBT (Table 5). UBT VO_{2peak} correlated significantly with redpoint and on-sight achievements ($P < 0.05$). TMT VO_{2peak} was not correlated with either sport performance ($P > 0.05$) or UBT VO_{2peak} ($r = –0.06$, $P = 0.854$). With respect to UB and TM VO_{2peak} values, an F test suggested that the linear-regression model is inadequate ($R^2 = 0.04$, $F = 0.33$, $P = 0.58$). UBT PPO per kilogram body mass was correlated significantly with the current redpoint and on-sight achievements ($P < 0.01$).

No significant difference was found between percentages of PPO in the UBT and the percentages of maximal velocity in the TMT at RCP ($p = 0.295$). HR, VO2, and La differences between values at RER_1 and RCP in the UBT were 26.1 beats/min ($p < 0.001$), 4.7 ml/min/kg ($P < 0.001$), and 3 mmol/L ($p < 0.001$), respectively. HR and VO_2 differences between values at RER_1 and at RCP in the TMT were not significant: 3 beats/min ($p = 0.096$) and 1.7 ml/min/kg ($p = 0.177$), respectively. After reaching RER1 the climbers were able to continue exercising 366.4 ± 83.5 seconds in the UBT and 152.7 ± 75.3 seconds in the TMT.

Table 4 Physical work parameters and physiological variables from the upper-body and treadmill maximal incremental tests (n = 11)

Test	Variable	Mean	SD	Min	Max
Upper-body ergometer test	Peak power output (W)	135.0	26.7	103.0	185.0
	Peak power output relative to body mass (kg)	2.0	0.2	1.6	2.4
	Time to exhaustion (s)	694.5	142.1	520.0	960.0
	VO_{2peak} (ml/min/kg)	34.1	4.1	26.9	41.2
	HR_{peak} (уд./min)	184.5	7.8	173.0	193.0
	$La_{end\ of\ test}$ (mmol/l)	11.9	1.7	9.1	14.2
	RCP expressed as percentage of peak power output (%)	80.6	0.9	79.2	82.5
Treadmill ergometer test	Maximal velocity (km/h)	14.1	1.0	12.3	15.2
	Time to exhaustion (s)	717.3	58.0	580.0	780.0
	VO_{2peak} (ml/min/kg)	58.3	2.6	53.7	62.9
	HR_{peak} (уд./min)	197.1	7.6	187.0	210.0
	$La_{end\ of\ test}$ (mmol/l)	12.3	2.5	7.5	17.4
	RCP expressed as percentage of peak power output (%)	81.0	0.6	80.0	82.2

VO_{2peak}: peak oxygen consumption; HR_{peak}: peak heart rate; $La_{end\ of\ test}$: blood lactate concentration at the end of the test; RCP: respiratory-compensation point.

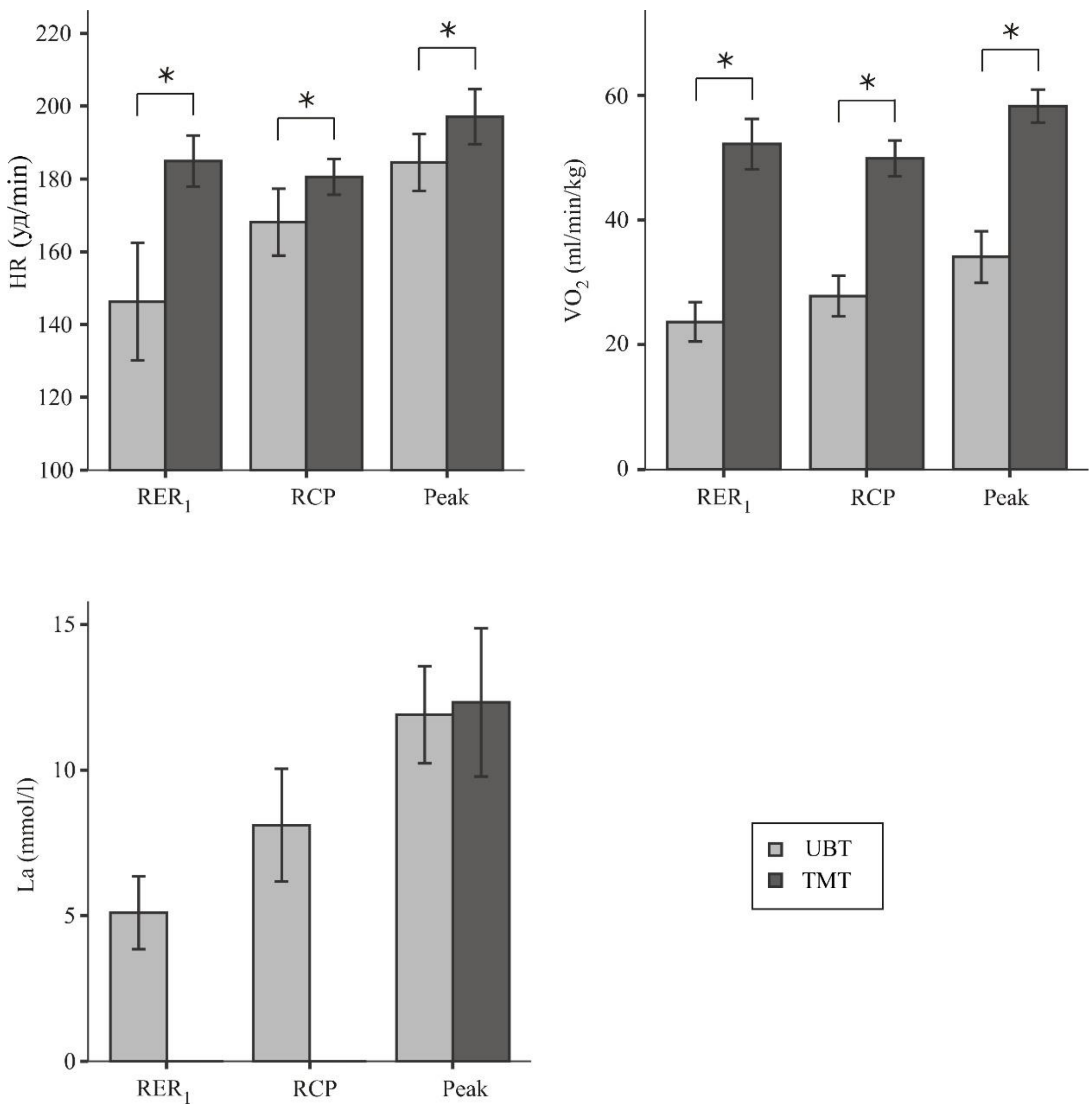

Figure 15 Physiological parameters from the upper-body and treadmill-running maximal incremental tests (n = 11), mean ± SD

HR, heart rate; VO_2, oxygen consumption; La, blood lactate concentration; RER_1, respiratory-exchange ratio at 1.00; RCP, respiratory-compensation point. Error bars: ±1 SD. *Significant differences ($p < .001$) between the sport-specific upper-body test and the treadmill test. Significant differences ($p < 0.001$) between HR at RER_1 and RCP and VO_2 at RER_1 and RCP were found only in the upper-body ergometer test; La samples were not taken during the performance of the treadmill test

Table 5 Correlation coefficients representing the relationships between some parameters from the upper-body maximal test, anthropometric variables, and climbing abilities (n = 11).

	PPO/kg	$VO_{2peak/kg}$	Body-mass index	Percentage body fat[a]
Best redpoint	0.55	0.67*	-0.65*	-0.51
	(p = 0.081)	(p = 0.025)	(p = 0.029)	(p = 0.109)
Best on-sight	0.47	0.68*	-0.46	-0.27
	(p = 0.146)	(p = 0.022)	(p = 0.160)	(p = 0.430)
Current redpoint	0.80**	0.72*	-0.63*	-0.78**
	(p = 0.003)	(p = 0.013)	(p = 0.038)	(p = 0.004)
Current on-sight	0.75**	0.85**	-0.46	-0.63*
	(p = 0.007)	(p = 0.001)	(p = 0.150)	(p = 0.039)

PPO: peak power output; VO_{2peak}: peak oxygen consumption; [a] Percentage body fat calculated through the equation of Durnin and Womersley (1974); * $p < 0.05$ correlation coefficients; ** $p < 0.01$ correlation coefficients. Note: Only indicators that correlated significantly ($p < .05$) with climbing abilities are included.

Discussion

The major finding from this study was that PPO and VO_{2peak} (both relative to body mass) in the sport-specific UBT correlated strongly with climbing performance. To the best of our knowledge, the current study also demonstrates for the first time that among a sample of elite climbers, aerobic capacity is directly related with climbing performance. The new test for maximal aerobic power focuses on the upper-body musculature with specificity to climbing exercise and fatigue and is more suitable for evaluating sport-specific work capacity than traditional incremental treadmill exercise tests. Still, climbers possess good levels of general fitness, and these latter tests should not be abandoned.

In the UBT an earlier contribution of the anaerobic energy supply was present for all subjects. RER_1 was reached at VO_2 corresponding to 70% of VO_{2peak}, and after this breakpoint the climbers were able to work for 6 minutes on average, which was more than half the total time (53%). This phenomenon was not observed in the TMT. The strenuous and intermittent character of climbing also demands bioenergetics with a reliance on both aerobic and anaerobic metabolism. The fact that the submaximal markers were different only in the UBT suggests that it had specificity to climbing exercise.

3.2. RESULTS FROM THE STUDIES CONDUCTED DURING STAGE 3

3.2.1. Suitable testing position and reliability of strength and muscle endurance measurements

Results

The impact of arm fixation is shown in Table 6. 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 7). 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 8 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 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 (Fm and Favg, test time, and FTI) were highly reliable with the exception of the rate of force development from the maximal strength test and the Ifatigue 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.

Table 6 Comparison of the maximal strength and all-out tests with and without arm fixation (n = 22).

Test	Parameter	With AF Mean ± SD	Without AF Mean ± SD	p	ω_p^2
Maximal strength test	F_m (N)	484 ± 112	546 ± 132	< 0.001	0.398
30 s all-out test	F_m (N)	459 ± 123	500 ± 116	< 0.001	0.376
	F_{avg} (N)	369 ± 100	392 ± 94	0.042	0.151

F_m: maximal force; F_{avg}: average force; AF: arm fixation

Table 7 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	0.458*	0.448*
		Without AF	0.611*	0.735*
	F_m (N/kg)	With AF	0.648*	0.649*
		Without AF	0.690*	0.815*
30-s all-out test	F_m (N)	With AF	0.495*	0.527*
		Without AF	0.555*	0.661*
	F_{avg} (N)	With AF	0.654*	0.723*
		Without AF	0.655*	0.764*
	$I_{fatigue}$ (%)	With AF	0.185	0.132
		Without AF	-0.166	-0.184

F_m: maximal force; F_{avg}: average force; $I_{fatigue}$: fatigue index; AF: arm fixation

Table 8 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 ± SD	Mean ± SD	p	95% LOA	ICC
Maximal strength test without AF	F_m (N)	563 ± 100	574 ± 111	0.549	102.40	0.878
Maximal strength test with AF	F_m (N)	518 ± 101	537 ± 121	0.163	75.06	0.941
	GS (N/s)	2024 ± 1124	1480 ± 796	0.218	2395.69	0.213
	I_{es} (N/s)	390 ± 202	276 ± 151	0.062	309.70	0.607
30-s all-out test	F_m (N)	512 ± 96	517 ± 92	0.797	96.16	0.864
	F_{avg} (N)	408 ± 92	416 ± 83	0.474	68.26	0.921
	$I_{fatigue}$ (%)	24.67 ± 10.32	28.63 ± 9.46	0.237	15.54	0.701
Intermittent test	Repetitions	13 ± 3.10	13 ± 2.69	0.842	3.17	0.845
	T_{tz} (s)	85.64 ± 22.07	87.91 ± 20.27	0.519	19.77	0.887
	FTI (N.s)	24596 ± 5431	26402 ± 5366	0.048	4558.49	0.907

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

3.2.2. Development of a methodology for local aerobic capacity diagnostics

Results

Active recovery (shaking) during the relaxation phases of the intermittent test led to in a significantly ($p < 0.05$) longer test time (↑ 22%), a greater FTI (↑ 28%) and a quicker re-oxygenation (↑ 32%) compared to the intermittent test without shaking. The time of muscle contraction was 1.80 times longer in the intermittent test than in the continuous test. This indicator, which was called "aerobic index" (I_a), was higher in sport climbers than in boulderers (1.98 versus 1.48). A significant correlation ($p < 0.05$) was found between Ia and re-oxygenation during the relaxation phases of the intermittent test ($R^2 = 0.29$, $p < 0.05$).

The results from the intermittent test with active recovery and continuous test are presented in Tables 9 and 10, respectively. Significant differences were found only for muscle oxygenation parameters. Boulderers had significantly lower values of deoxygenation during muscle contractions and re-oxygenation during relaxation phases.

Table 9 Results from the intermittent test

Parameter	Discipline	Mean ± SD	p	Partial η^2
T_{tz} (s)	Sport climbers (n 12)	60.6 ± 13.0	0.15	0.111
	Boulderers (8)	52.2 ± 11.5		
	Total (n 20)	57.3 ± 12.8		
FTI (N.s)	Sport climbers (n 12)	17487 ± 5039	0.98	< 0.001
	Boulderers (8)	17433 ± 4294		
	Total (n 20)	17466 ± 4636		
FTI (N.s/kg/s)	Sport climbers (n 12)	249 ± 74	0.98	< 0.001
	Boulderers (8)	250 ± 80		
	Total (n 20)	250 ± 74		
Oxygenation mean values (% SmO_2)	Sport climbers (n 12)	28.75 ± 7.09	0.01	0.361
	Boulderers (8)	38.93 ± 7.36		
	Total (n 20)	32.82 ± 8.68		
Oxygenation minimum values (% SmO_2)	Sport climbers (n 12)	13.47 ± 8.47	0.01	0.348
	Boulderers (8)	25.63 ± 8.17		
	Total (n 20)	18.34 ± 10.17		

T_{tz}: time in the force target zone; FTI: force-time integral; SmO_2: tissue oxygenation

Table 10 Results from the continuous test

Parameter	Discipline	Mean ± SD	p	Partial η^2
T_{tz} (s)	Sport climbers (n 12)	120.04 ± 54.54	0.06	0.182
	Boulderers (8)	77.42 ± 30.33		
	Total (n 20)	102.99 ± 50.20		
FTI (N.s)	Sport climbers (n 12)	34811 ± 17299	0.28	0.065
	Boulderers (8)	26830 ± 12383		
	Total (n 20)	31618 ± 15679		
FTIJ (N.s/kg/s)	Sport climbers (n 12)	509 ± 289	0.32	0.056
	Boulderers (8)	388 ± 194		
	Total (n 20)	460 ± 257		
Oxygenation mean values (% SmO_2)	Sport climbers (n 12)	20.07 ± 9.32	0.16	0.109
	Boulderers (8)	26.09 ± 8.18		
	Total (n 20)	22.48 ± 9.17		
Re-oxygenation (% SmO_2)	Sport climbers (n 12)	18.05 ± 5.35	0.01	0.295
	Boulderers (8)	12.10 ± 3.59		
	Total (n 20)	15.67 ± 5.50		
Deoxygenation (% SmO_2)	Sport climbers (n 12)	19.59 ± 5.25	0.06	0.179
	Boulderers (8)	15.56 ± 2.81		
	Total (n 20)	17.98 ± 4.80		

FTI: force-time integral; oxygenation: average tissue oxygenation; re-oxygenation: increase of tissue oxygenation during the relaxation phases; deoxygenation: decrease of tissue oxygenation during muscle contractions

Discussion

This study provides a new and easily applicable methodology for assessing local muscle aerobic capacity. The aerobic index can be successfully used as a local aerobic capacity indicator. The presented methodology for aerobic capacity diagnostics has the potential to widen functional diagnostics in sports due to the possibility to obtain the necessary information only on the basis of the results of a maximal strength test and two muscle endurance tests (continuous and intermittent). The new approach used in this study can be applied in all endurance disciplines with submaximal intensity.

The lack of significant correlations between the aerobic index and deoxygenation confirms that the time difference between the continuous and intermittent tests are mainly determined by the re-oxygenation during the relaxation phases in the intermittent test. Therefore, the aerobic index provides information on oxygen delivery, rather than extraction. Therefore, the aerobic index cannot completely replace NIRS. Without NIRS it is impossible to measure deoxygenation and assess the ability of the muscle to use oxygen. NIRS reflected the differences between the metabolic profiles of boulderers and sport climbers. Aerobic capacity is more important in sport climbing than bouldering. Boulderers deoxygenated and re-oxygenation significantly less their flexor digitorum profundus compared to sport climbers. However, boulderers had a higher level of maximal strength and their climbing ability was similar to that of sport climbers. This showed that climbers with different athlete profile may climb routes of the same difficulty.

3.2.3. Validity of the strength and muscle endurance tests parameters

Results

Table 11 shows the mean values, standard deviations (± SD) and confidence intervals of the parameters measured in the maximal strength and muscle endurance tests. Table 12 presents the correlations between test parameters and sport climbing and bouldering ability.

Table 11 Mean values (± SD) of test parameters registered during the maximal strength and muscle endurance tests (n = 51)

Test	Parameter	Mean ± SD	Confidence interval
Maximal strength test	F_m (N)	560 ± 111	520 – 601
	$F_{m/kg}$ (N/kg)	8.04 ± 0.19	7.26 – 8.68
30-s all-out test	F_m (N)	509 ± 107	482 – 565
	F_{avg} (N)	398 ± 81	364 – 426
	$F_{avg/kg}$ (N/kg)	5.68 ± 0.14	5.03 – 6.12
	$I_{fatigue}$ (%)	36.00 ± 12.32	31.89 – 40.10
Intermittent test	Repetitions	15.4 ± 5.51	13.8 – 17.1
	T_{tz} (s)	97.74 ± 25.87	89.11 – 106.36
	J (N.s)	30911 ± 10915	27272 – 34549
	$J_{/kg}$ (N.s/kg)	441 ± 167	385 – 497
Continuous test	T_{tz} (s)	59.36 ± 12.40	55.23 – 63.50
	J (N.s)	18605 ± 5014	16149 – 19921
	$J_{/kg}$ (N.s/kg)	267 ± 78	228 – 285
	I_a	1.66 ± 0.39	1.53 – 1.79

F_m: maximal force; $F_{m/kg}$: F_m related to body mass; F_{avg}: average force; $F_{avg/kg}$: F_{avg} related to body mass; $I_{fatigue}$: fatigue index; T_{tz}: time in target zone; FTI: force-time integral; $FTI_{/kg}$; FTI related to body mass; I_a: aerobic index

Table 12 Coefficients of correlation between the parameters of the tests and sporting achievements in sport climbing and bouldering (n = 51)

Test	Parameter	Redpoint Sport climbing	Redpoint Bouldering
Maximal strength test	F_m	0.63** ($p < 0.001$)	0.73** ($p < 0.001$)
	$F_{m/kg}$	0.74** ($p < 0.001$)	0.82** ($p < 0.001$)
30-s all-out test	F_m	0.56** ($p < 0.001$)	0.65** ($p < 0.001$)
	F_{avg}	0.60** ($p < 0.001$)	0.68** ($p < 0.001$)
	$F_{avg/kg}$	0.69** ($p < 0.001$)	0.77** ($p < 0.001$)
	$I_{fatigue}$	-0.12 ($p = 0.405$)	- 0.17 ($p = 0.296$)
Intermittent test	Repetitions	0.34* ($p = 0.017$)	0.21 ($p = 0.184$)
	T_{tz}	0.34* ($p = 0.016$)	0.22 ($p = 0.173$)
	J	0.51** ($p < 0.001$)	0.41** ($p = 0.007$)
	$J_{/kg}$	0.55** ($p < 0.001$)	0.45** ($p = 0.004$)
Continuous test	T_{tz}	0.14 ($p = 0.338$)	0.34 ($p = 0.834$)
	J	0.69** ($p < 0.001$)	0.73** ($p < 0.001$)
	$J_{/kg}$	0.77** ($p < 0.001$)	0.81** ($p < 0.001$)
	I_a	0.34* ($p < 0.015$)	0.28** ($p < 0.072$)

F_m: maximal force; $F_{m/kg}$: F_m related to body mass; F_{avg}: average force; $F_{avg/kg}$: F_{avg} related to body mass; $I_{fatigue}$: fatigue index; T_{tz}: time in target zone; FTI: force-time integral; $FTI_{/kg}$; FTI related to body mass; I_a: aerobic index; * significant correlations, $p < 0.05$; ** significant correlations, $p < 0.01$

F_m related to body mass ($F_{m/kg}$) correlated more with bouldering (r = 0.82) than with sport climbing (r = 0.74) performance. $F_{m/kg}$ correlated less with bouldering performance among boulderers of higher ability (r = 0.76 for boulderers performing < 7A; r = 0.56 for boulderers performing > 7A). The force-time integral related to body mass ($J_{/kg}$) from the intermittent test, as well as the aerobic index, correlated more with sport climbing (r = 0.55) than with bouldering (r = 0.45) performance. In both disciplines the correlations between $J_{/kg}$ from the intermittent test and climbing performance decreased with increase in qualification (from r = 0.62 to r = 0.23 in sport climbing and from r = 0.48 to r = 0.16 in bouldering). $J_{/kg}$ from the continuous test seems to be equally important in both disciplines (r = 0.77 for sport climbing; r = 0.81 for bouldering). The correlation between $J_{/kg}$ from the continuous test and climbing performance decreased with increase in qualification only in bouldering (from r = 0.72 to r = 0.49). In contrast, among boulderers with ability > 7A the fatigue index ($I_{fatigue}$) correlated significantly with bouldering performance (r = -0.45), while this was not observed in boulderers with ability < 7A and the two groups of sport climbers (ability < 7b+ and > 7b+).

The results from the principle component analysis are presented in Table 13. The parameters are seperated into three components. The first component explained 46.66% of the variance and was identified as "local aerobic capacity". The second component explained 28.01% of the variance and was identified as "strength and local anaerobic alactic capacity". The third component explained 12.41% of the variance and was identified as "local anaerobic lactic capacity". All parameters show very high values of communality with the corresponding latent variable/component (h^2 0.934 – 0.993), except for the $I_{fatigue}$ and the time in the continuous test (h^2 = 0.591 and h^2 = 0.592, respectively).

Figure 16 and 17 show the extent to which sport climbing and bouldering performance are determined by the three components.

Table 13 Principle component analysis

Test	Parameter	Компоненти Muscle endurance and local aerobic capacity	Strength and Local anaerobic alactic capacity	Muscle endurance and local anaerobic lactic capacity	h^2
Maximal strength test	F_m		0.961		0.934
30-s all-out test	F_{avg}		0.934	-0.243	0.937
	$I_{fatigue}$	-0.214		0.736	0.591
Intermittent test	Repetitions	0.992			0.984
	T_{tz}	0.996			0.993
	J	0.938	0.273		0.955
Continuous test	T_{tz}	0.529		0.556	0.592
	J	0.317	0.802	0.419	0.919
	Ia	0.949			0.931
% of total variance		46.66	28.01	12.41	
Cummulative %		46.66	74.67	87.07	

F_m: maximal force; $F_{m/kg}$: F_m related to body mass; F_{avg}: average force; $F_{avg/kg}$: F_{avg} related to body mass; $I_{fatigue}$: fatigue index; T_{tz}: time in target zone; FTI: force-time integral; $FTI_{/kg}$; FTI related to body mass; I_a: aerobic index; h^2, communality

Discussion

The significant correlations between climbing performance and test parameters indicate that the applied tests are suitable for the assessment and monitoring of sport-specific strength and muscle endurance in rock climbing. For the first time construct validity evidence was provided showing the latent variables that are measured through these tests. It was confirmed that the tests were designed in an appropriate way to register parameters that carry information on the physical or functional capabilities that the tests were intended for. In addition, the importance of the test parameters as sport-specific training state indicators was determined for sport climbers and boulderers of different ability level.

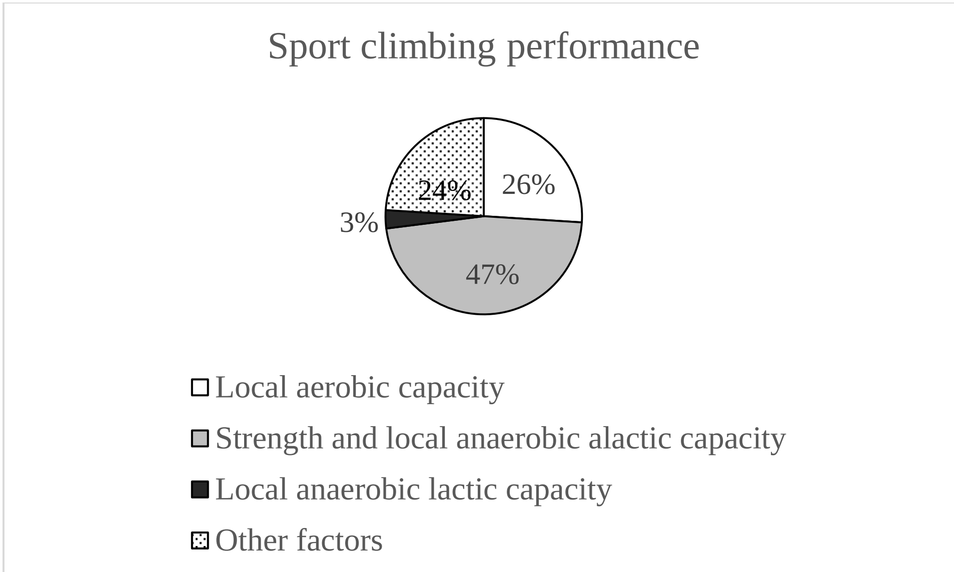

Figure 16 Dependence of bouldering performance on forearm capabilities

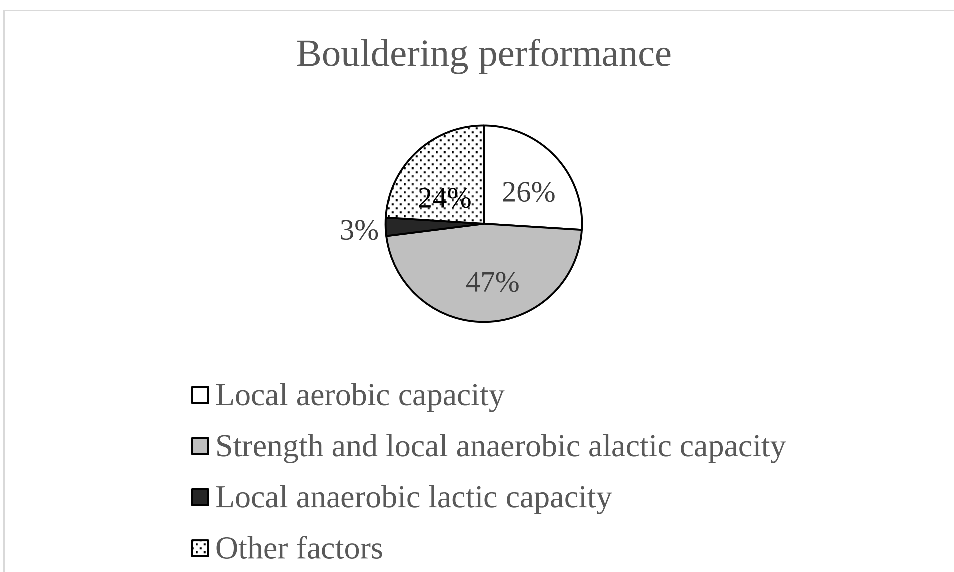

Figure17 Dependence of bouldering performance on forearm capabilities

Previous studies demonstrated that climbers perform better compared to controls during intermittent not during continuous tests. This was explained by higher aerobic capacity, including enhanced local vasodilatory capacity, muscle reoxygenation during relaxation phases, and deoxygenation during contractions (Ferguson & Brown 1997, Fryer et al. 2015[a,b], Macleod et al. 2007). Nevertheless, the present study showed that local anaerobic capacity is also a performance-limiting factor in rock climbing and can be assessed through either the all-out or the continuous test. The reasons why the present study revealed the importance of sustained muscle contraction performance and local anaerobic capacity in rock climbing should be the lower relative intensity in previous studies (40% MVC). This does not lead to total intramuscular circulatory occlusion and allows higher aerobic contribution. Moreover, among elite and higher elite climber (for whom anaerobic capacity appears to be more important) participated in the present study.

The results of this study show that the applied testing approach is suitable in rock climbing, allows in-depth analysis of climbers' training state and can expand the possibilities for functional diagnostics in sports.

3.2.4. Relative energy system contribution during the performance of the muscle endurance tests

The results presented in this chapter are focused on the relative participation of energy systems (aerobic, anaerobic lactate and anaerobic lactate) during the test with a constant maximum effort for 30 s, the continuous and intermittent test at an intensity of 60% MVC. These results further validate muscle endurance tests with physiological data on the extent to which each test provides information about the functional capabilities it is intended to measure.

Results

The relative energy system contribution during the tests is presented in Figure 18. The largest contribution of the aerobic energy was noted during the intermittent test (56.9 ± 12.0%). It was significantly higher compared to the aerobic energy contribution during the continuous (31.5 ± 15.6%, $p = 0.004$) and all-out (19.5 ± 8.1%, $p < 0.001$) tests. The continuous and all-out tests did not differ with respect to aerobic energy ($p > 0.108$). The contribution of anaerobic alactic energy was higher in the all-out test (61.7 ± 11.3%) than in the continuous (51.2 ± 18.3%) and intermittent (29.3 ± 10.0%) tests. The alactic energy in the intermittent test was significantly smaller than in the continuous ($p = 0.006$) and all-out ($p < 0.001$) tests, which did not differ with respect to alactic energy. The all-out test demanded also more anaerobic lactic energy (18.8 ± 9.9%) compared to the continuous (16.7 ± 8.9%) and intermittent (13.8 ± 6.4%) tests. Nevertheless, anaerobic lactic energy did not differ significantly between all tests ($p = 0.296$).

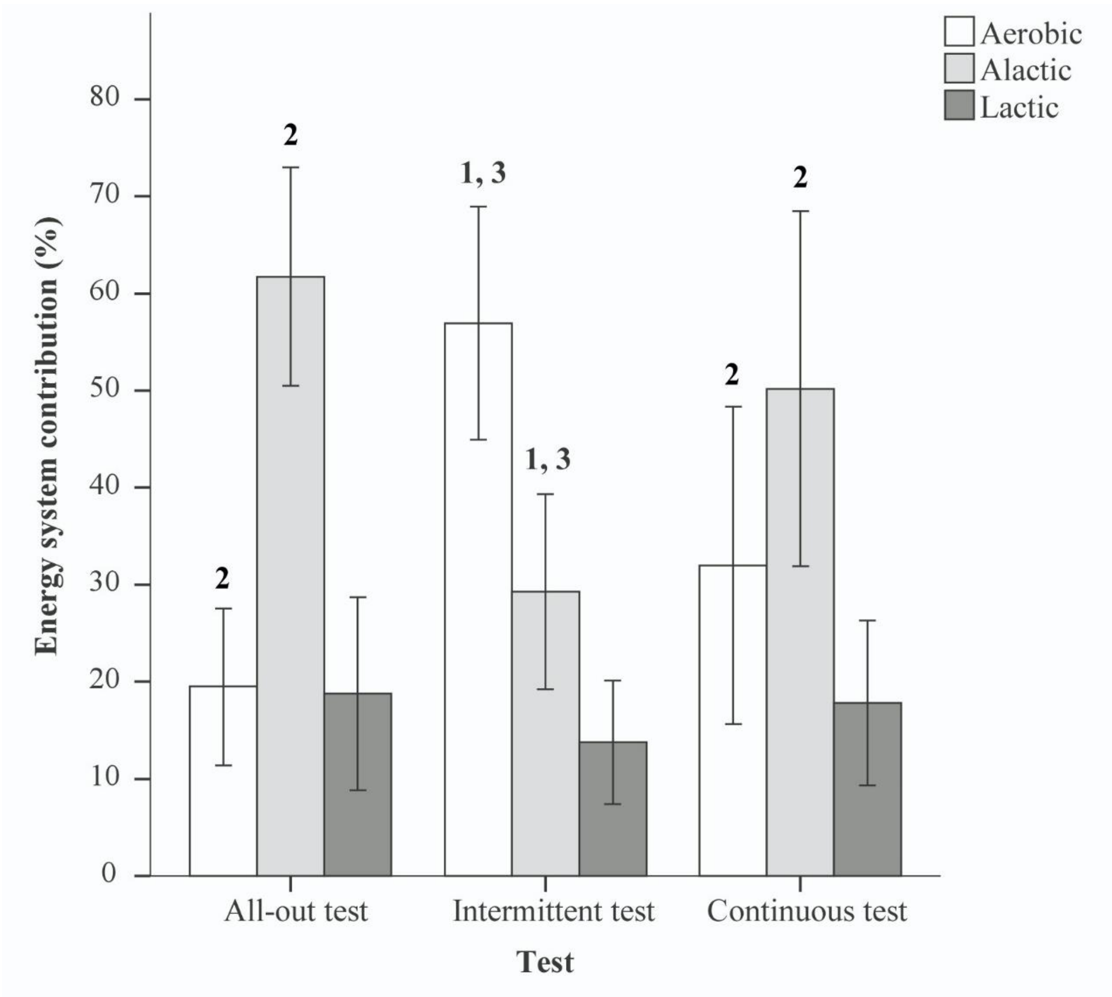

Figure18 Differences between tests for aerobic, alactic and lactic relative energy contributions (mean ± SD)

2 – when significantly different ($p < 0.05$) from the intermittent test; 1, 3 – when significantly different ($p < 0.05$) from the all-out and continuous test.

Discussion

The present study showed that the intermittent test is more informative for evaluating local aerobic capacity (59.9% aerobic and 40.1% anaerobic energy contribution), whereas the all-out (19.4% aerobic and 80.6% anaerobic) and continuous (38.1% aerobic and 71.9% anaerobic) tests are suitable for assessing local anaerobic capacity. The all-out test was predominantly anaerobic alactic and the continuous test was alactic-aerobic. The alactic and lactic energy contribution during these two tests were similar and one of them would be enough to be included in a test battery for functional diagnostics at peripheral level.

The only study so far (Bertuzzi et al. 2007), which assessed the contribution of the energy system during actual climbing, indicated that the main energy systems required in real climbing conditions are the aerobic and anaerobic alactic systems. The results of the present study indicate that the test with the greatest contribution of aerobic and anaerobic alactic systems is the intermittent test (aerobic 59.9 ± 12.0%, alactic 27.2 ± 10.0%). It seems that the most adequate test for the assessment of climbers' local aerobic capacity, and at the same time, with similar energy contribution to actual climbing, is the intermittent test.

It should be noted that the small finger flexor muscles produced low arterial blood lactate concentrations. Thus, the calculated anaerobic lactic contribution in all muscle endurance tests reflect the metabolism of the whole body, rather than the energy processes undergoing locally in the most exerting finger flexors (shoulder girdle muscles played only a stabilizing role). Nevertheless, the energy contributions during the isolated muscle endurance tests more closely reflect the local metabolic processes than calculations made during actual climbing where all muscle groups considerably expend energy.

The present study was the first to determine the energy system contribution in laboratory tests, which are designed to assess and monitor climbers' training state. The calculation of the relative energy system contribution during a sport-specific exercise test determines the bioenergetic profile of a sport discipline or an athlete. This also shows whether the exercise tests is suitable and which functional capabilities is assessed. Such data allow a more in-depth performance analysis and the application of training methods that would develop the necessary physiological functions.

3.2.5. Evaluation of sport-specific strength and muscle endurance in climbers

The tests selected for the assessment of climbers' training state are valid and reliable. However, the raw test scores alone are not useful enough to optimize training. To understand how satisfactory the quantitative measures of finger strength and endurance are, the raw test scores should be converted into evaluations (i.e. points and qualitative grades). This also allows comparison between the measured abilities, which otherwise are presented in different measurement units. This will show whether the climber has a balanced athletic profile with respect to maximal strength, muscle endurance and local aerobic and anaerobic capacity. The balanced state of these performance indicators ensures the fullest realization of climber's motor potential because rock climbing is an activity that requires complex development of motor skills and abilities.

In this dissertation, data needed for calculating two evaluation score types is presented. The so-called regression and standard deviation methods were used for the first and second type of evaluation scores, respectively. The first method was applied on the test parameters, which strongly correlated with climbing performance. In this case the evaluation scores were expressed as IRCRA climbing grades. In order to apply the regression evaluation method, linear function parameters were calculated. These functions reflected the relationship between test parameters and sport climbing performance. After completing all tests, an averall evaluation score can be given using an equation of the following type: $Y = a + bx_1 + cx_2 + dx_3$. Stepwise multiple regression analysis was used to obtain this equation for calculating averall evaluation scores.

The values of the test parameters, which do not correlate significantly with climbing ability, cannot be converted into regression scores. However, these parameters carry useful information. For example, the duration of the intermittent and continuous tests do not correlate with athletic performance, but informs about local muscle aerobic and anaerobic lactic capacity, respectively. Therefore, this dissertation presents data needed for the assessment through the "standard deviation" method.

Figure 19 and 20, as well as Tables 14 and 15 illustrate the described evaluation methods showing individual results of two climbers of different ability.

The presented performance evaluation approach provides an in-depth analysis of climbers' strength, muscle endurance and local aerobic and anaerobic capacity, which are main factors of climbing performance. Turning the test results into points allows to reveal the strengths and weaknesses in climbers' preparation. Eventual differences in predicted and actual climbing grades indirectly provide information on climbers' technical, tactical and mental preparation.

Table 14 Strength and muscular endurance test results, reference values and evaluation scores of a higher elite climber (current redpoint 8c+)

Test	Parameter	Result	"Standard deviation" scores		"Regression" scores	
			T-scores	Verbal evaluations	Partial scores (IRCRA points)	Overall score (IRCRA points)
Maximal strength test	Fm (N)	706	5.32	Very good		
	Fm/kg (N/kg)	11.7	5.95	Very good	27.92	
30-s all-out test	Favg (N)	481	5.02	Very good		
	Favg/kg (N/kg)	7.7	5.51	Very good	25.70	
	Ifat (%)	31	4.41	Average		
Intermittent test	Ttz (s)	128.0	5.17	Very good		
	J (N.s)	51417	5.88	Very good		27.87
	J/kg (N.s/kg)	824.0	6.29	Excellent	26.81	
Continuous test	Ttz (s)	57.8	3.87	Average		
	J (N.s)	23807	5.04	Very good		
	J/kg (N.s/kg)	381.5	5.47	Very good	25.94	
	Ia	2.21	5.42	Very good		

F_m: maximal force; $F_{m/kg}$: F_m related to body mass; F_{avg}: average force; $F_{avg/kg}$: F_{avg} related to body mass; $I_{fatigue}$: fatigue index; T_{tz}: time in target zone; FTI: force-time integral; $FTI_{/kg}$; FTI related to body mass; I_a: aerobic index

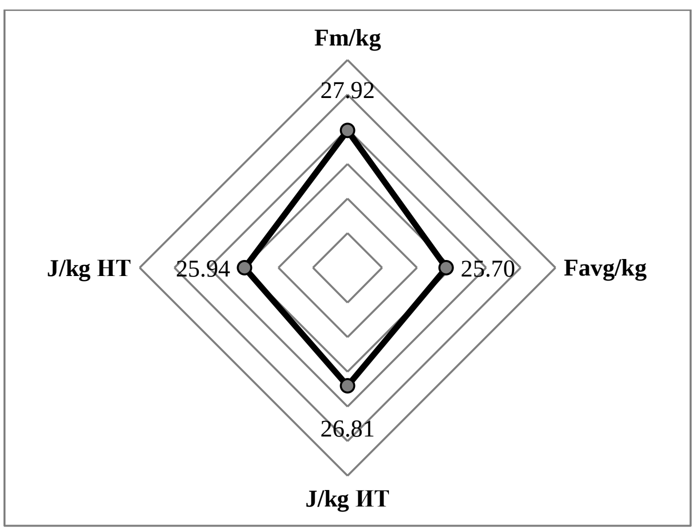

Figure 19 Regression scores (IRCRA points) of a higher elite climber (current redpoint 8c+) illustrating a relatively balanced state

Table 15 Strength and muscular endurance test results, reference values and evaluation scores of an elite climber (current redpoint 8b)

Test	Parameter	Result	"Standard deviation" scores		"Regression" scores	
			T-scores	Verbal evaluations	Partial scores (IRCRA points)	Overall score (IRCRA points)
Maximal strength test	Fm (N)	569	4.08	Average		
	Fm/kg (N/kg)	9.6	4.86	Good	23.34	
30-s all-out test	Favg (N)	382	3.81	Average		
	Favg/kg (N/kg)	6.5	4.58	Good	22.01	
	Ifat (%)	25	4.89	Good		
Intermittent test	Ttz (s)	186.6	7.44	Excellent		24.86
	J (N.s)	58406	6.52	Excellent		
	J/kg (N.s/kg)	989.9	7.29	Excellent	30.30	
Continuous test	Ttz (s)	63.1	4.30	Average		
	J (N.s)	19788	4.24	Average		
	J/kg (N.s/kg)	335.4	4.88	Good	23.34	
	Ia	2.96	7.33	Excellent		

F_m: maximal force; $F_{m/kg}$: F_m related to body mass; F_{avg}: average force; $F_{avg/kg}$: F_{avg} related to body mass; $I_{fatigue}$: fatigue index; T_{tz}: time in target zone; FTI: force-time integral; $FTI_{/kg}$; FTI related to body mass; I_a: aerobic index

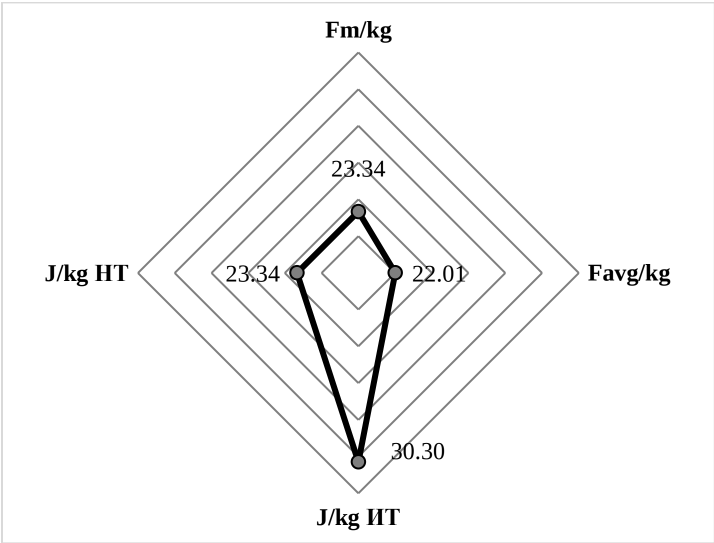

Figure 20 Regression scores (IRCRA points) of an elite climber (current redpoint 8b) illustrating existing strengths and weaknesses

CONCLUSION

The present dissertation is a theoretical and experimental study of rock climbing as a specific physical activity. The aim of this study was to create a complex system for the assessment and optimization of some of the major factors of sport performance in rock climbing. The methodological concept was directed towards the essential components of sport-specific performance, which should be measured, evaluated and improved during the different stages of the training process. Several studies were conducted. A large number of climbers participated in the studies. Participants were tested using a wide range of highly informative specialized tests.

The empirical part of the research was carried out over a period of 8 years. It included testing of elite climbers from Bulgaria, Czech Republic, Poland and Greece. The research equipment included a unique climbing specific system for the assessment of a wide range of parameters with the ability to measure in real time in a precise and objective manner.

The research results can be systematized in the following main directions:

- The descriptive statistics characterized the various components of sport-specific physical fitness in rock climbers. The results were systemized according to the climbing discipline and compared with the results of leading researchers in the field.
- The applicability of tests and physiological and ergometric indicators for the assessment of climbers' work and aerobic capacity at system level was estimated.
- The reliability and criterion validity of sport-specific strength and muscle endurance tests with and without arm fixation was determined.
- The importance of the strength and muscle endurance test parameters with respect to the climbing discipline and ability level was determined.
- The construct validity of the test parameters was revealed.
- The dependence of sport climbing (lead) and bouldering performance on the derived components of forearm physical and functional capabilities was determined.
- The relative energy contribution was calculated to further validate the muscle endurance tests and clarify the extent to which they assess local aerobic or anaerobic capacity.
- A methodology for evaluation of test results and comprehensive analysis of climber's training state was developed.

Based on the present results, the following can be recommended in summary form:

- Climbers' work and aerobic capacity at system level should preferably be assessed through specialized upper-body ergometric tests rather than traditionally used treadmill exercise tests and climbing to exhauston. These upper-body tests should not require isometric muscle contractions but dynamic efforts (i.e. pulling not rotating movements movements).
- The finger flexor muscle endurance as well as their local aerobic and anaerobic capacity can be assessed by a combination of a continuous and intermittent test at muscle contraction intensity that leads to total intramuscular circulatory occlusion.

The presented approaches for comprehensive analysis of climbers' training state significantly increase the possibilities for optimizing training.

Specific contributions:

- New facts were discovered that expand the limited application of physiological indicators in the climbers' training process management.
- A new specialized incremental upper-body ergometric test was developed and approved.
- A unique and advanced system for performance assessment in rock climbing (3DSAC) was developed.
- A methodology for strength and muscle endurance assessment as well as for functional diagnostics at peripheral level was developed.
- For the first time, a test for the assessment of local anaerobic capacity was introduced.
- Information on the metabolic profile of rock climbing and sport-specific tests was provided.

Application

The presented system for sport-specific physical fitness assessment and monitoring has been used for years by the national sport climbing teams of Bulgaria and Czech Republic. For the wider application of the present findings, a device, which with a mobile application, measures force in real time and guides climbers while training and testing, was recently created. This may further the development of rock climbing.

The results of the present work expand the knowledge on rock climbing performance and physiology as well as the general theory and practice of functional diagnostics in sports. The innovative testing approach of the present work can be used in other sports where the peripheral performance factors are of great importance.

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