BIOMECHANICAL PROFILE OF THE MUSCLES OF THE UPPER LIMBS IN SPORT CLIMBERS

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Abstract
Introduction. Studies have demonstrated an important role of muscle strength and endurance in climbing. However, little research has explored the speed parameters of the muscles of climbers. This study aimed to evaluate biomechanical indices of the functional status of the upper limbs in climbers. ***Material and methods.*** Group G1 (n = 3) were athletes who were able to climb 8c+/9a climbing routes using the red-point style and 7c+/8b routes with the on-sight style. Group G2 (n = 5) comprised climbers who were able to climb 8a/8b+ and 7b+/8a routes, respectively. Maximum muscle torques were measured in the elbow and arm flexors and extensors. Hand grip tests, dynamometric arm strength tests, and laboratory endurance tests were conducted. ***Results.*** Strength parameters in both joints were similar in the two groups of climbers. Maximum absolute values of hand grip, crimp grip, and global arm force in hanging did not differ between the groups. Furthermore, significant differences were found for relative indices (from circa 3% to circa 12%). No significant differences were recorded for the parameters of muscle speed. Furthermore, no significant effect of the subjects' skill level on the results of endurance tests was found. The results obtained in the groups of athletes (G1, G2, and G1+2) were compared with the values recorded in a control group of students (GC, n = 48). ***Conclusions.*** Elite climbers were found to have an advantage over the controls only in strength and muscular endurance. No significant differences were observed in the results of speed tests in the muscles of the athletes and students examined in the study. The climbers (G1 and G2) differed in the strength potential of their muscles, but only when relative force indices were analysed. No differences were found in the biomechanical variables of speed and muscular endurance. Conventional tests are typically not a valuable diagnostic tool for the evaluation of climbers.

Key words: biomechanics, elite rock climbers, muscle strength, speed, endurance

Introduction

Sport climbing is a new and dynamically developing sport that stems from mountain climbing. The common feature of both sports is the specific type of physical activity, which is climbing. The differences are related to physical and spatial aspects and the risk level. The environment of the activity and the risk level involved in ascending a climbing route on a glacier in the Himalayas differs fundamentally from ascending a route with fixed protection in the rocks or on an artificial climbing wall.

As in other sports, in sport climbing, it is also essential to explore the main factors that determine success. In light of the literature, it seems that an essential role is played by muscle strength and endurance, with particular focus on the level of relative force produced by the upper limbs [1, 2, 3, 4]. The studies of the effect of strength in sport climbing have used a variety of dynamometers, also in specific motor tests. In some studies [5, 6, 7], better results for relative strength were documented for elite climbers compared to non-climbers or amateur climbers.

Research has also demonstrated the importance of endurance to this sport. Sport climbing is a sport where the time of exercise ranges from several to several dozen minutes. This exercise is characterised by a specific rhythm of muscular work, that is isometric contraction of the muscles followed by a rest period. Both dynamometric and indirect tests have been employed in measurements. Tests performed in laboratory environments have demonstrated that professional climbers were able to maintain 60% of Fmax (maximum force) longer and 80% of Fmax in intermittent exercise compared to non-climbers [8, 9]. In a study by Staszkiewicz and Rokowski [3], indirect tests showed that elite climbers were able to continue the exercise for a longer time, for example during hanging on a slat to exhaustion. The problem of differences in relative force and muscle endurance in groups of athletes with insignificant (yet measurable) differences in skill level have not been explored sufficiently to date. Similarly, the rate of force development during rock climbing also needs to be evaluated unequivocally as dynamic reaches are frequently used by climbers on extremely difficult climbing routes. In such cases, the speed of catching a hold may be a factor in winning the competition.

The aim of the present study was to determine the level of biomechanical indices of strength, speed, and endurance of the upper limbs in rock climbers with elite-level skills.

We also attempted to verify which variables measured in a dynamographic laboratory setting differentiate the most between the groups of athletes compared to the results obtained on a climbing wall during competitions.

Material and methods

The tests were performed in the Department of Biomechanics at the University of Physical Education in Krakow. The study examined two groups of rock climbers (**G1** and **G2**) and a control group (**GC**) that comprised non-climbers who were students from the University of Physical Education in Krakow, aged 21-25 years (n = 48). Measurements were made only for male participants.

The first group (G1, n = 3) were athletes who were able to climb 8c+/9a routes (French scale) using the red-point (RP) style and 7c+/8b rock routes using the on-sight (OS) style. The mean age of athletes from this group was 27 years, and the mean training experience was 17 years.

The second group (G2) of athletes was comprised of climbers aged 30 years, with a mean training experience of 12 years (n = 5). The level of achievement of the athletes from this group was the difficulty of 8a/8b+ in RP style and 7b+/8a in OS style.

The division of the climbers into two groups of different skill levels resulted from the need to compare the biomechanical indices of the muscles of the upper limbs. Another argument for such an approach was the fact that, after the completion of the measurements one athlete in the G1 group climbed a 9a+ route. This exceptional achievement has been repeated only by one Polish athlete (in 2016). It should be noted that according to the guidelines of the International Rock Climbing Research Association (IRCRA), the athletes from the G1 group were at higher elite level, whereas those from G2 performed at an insignificantly lower (elite) level [10].

Due to the division of climbers into sub-groups, the number of participants in the G1 and G2 groups was small, which became an obstacle for the use of statistical tests that would allow for the evaluation of the significance of differences recorded in these groups of athletes, despite the likelihood of correlations between the skill level and the values of the variables [11]. However, initial correlation analyses, with the competitive level of athletes from both groups expressed as a countable variable, did not provide evidence for such correlations. Probably, due to varied accomplishments in both climbing styles (RP and OS), the effects of explorations of statistical correlations turned out to be difficult to be unequivocally interpreted. However, the observations allowed for the analysis of the population of all climbers as one group (G1+2), and this approach was used to evaluate the significance of differences in variables documented in athletes and the control group (GC).

Several biomechanical tests were performed to characterise the functional status of selected muscles of the upper limbs. The following tests were performed to evaluate strength:

a. Static measurements of maximum torques (Mmax) of the elbow and arm flexors and extensors.
b. Measurements of maximum hand grip force for two hand positions (F1max and F2max). A conventional dynamometric hand grip was used in the first variant, with the resistance component of the distal part of the dynamometer adjusted to the intermediate phalanges. In the second grip, only the distal phalanges of four fingers (excluding the thumb) were used, whereas the forearm was in the crimp grip position. Due to the use of a turnbuckle on the dynamometer side and fixation of the forearm (below the elbow) to the support with adjustable height, the conditions were similar to static ones. Measurements of the grip force were performed using a dedicated prototype test stand. The hand testing position is presented in Figure 1.
c. Measurement of maximum global arm force (F3max) by means of a special test on a campus board with wooden slats (2 cm in width). The participant used only the distal phalanges of one hand, hung on a slat, and attempted to lift their body. The level of resistance force was recorded using a dynamometer fixed to the ground and connected with the climbing harness the climber was wearing. The assumptions used in our study were an extension of the methodology applied in the study by Balas et al. [12]. The lengths of individual components in the measurement line were chosen so that the measurements were performed under isometric conditions. However, in some tests, a jerk would lead to a momentary increase in the force, and such tests were repeated (maximally three times). If changes in F3max were recorded several times, the analysis was based on the profile where the initial force was the closest to body weight (Q).

Figure 1. Position of the hand on the test stand during the measurement of maximum grip force (F1 – left, F2 – right)

All the strength variables were presented in absolute values (Nm and N) and calculated per body mass (Nm/kg and N/kg, respectively).

Due to the use of test stands for all the strength measurements, the rate of maximum force development was also recorded under static conditions F(t). Based on these functions, the times to attain maximum force and half maximum force (tFmax and t0.5max, respectively) and the maximum value of the derivative of force with respect to time (F'max) were developed. These variables were next used to evaluate the speed potential of the muscles. The testing procedure for this test is presented in Figure 2.

Figure 2. Maximum force development in the elbow flexors (Fl_E)

Finally, two laboratory tests evaluating the endurance of the upper limbs to exhaustion were also performed. In the first test (**EN_1**), the participant maintained the climbing crimp grip as in the above described special test with the force of 60%Fmax. The second test (**EN_2**) used the same grip, and the procedure involved maintaining the maximum contraction of the palmar and antebrachial muscles for 7 s, followed by a 3-second rest and another maximum contraction for 7 s. The number of such cycles was counted, and the duration of the whole experiment was recorded.

Results

Table 1 presents Mmax values for the flexors and extensors of the upper limb in the elbow and arm joints. It is noticeable that the variables in the groups of climbers (G1 and G2) do not differ significantly. Relative indices (Mrel) presented in Table 2 lead to similar conclusions.

Table 1. Maximum muscle torques (Mmax) in the muscles of the upper limbs in the three groups of participants (**Fl_E, Ex_E** – elbow flexors and extensors, respectively; **Fl_S, Ex_S** – shoulder flexors and extensors, respectively)

	Fl_E	Ex_E	Fl_S	Ex_S
	[Nm]	[Nm]	[Nm]	[Nm]
G1	89 ± 9.7	61 ± 9.7	113 ± 21.2	107 ± 13.6
G2	93 ± 21.2	61 ± 13.4	118 ± 29.2	108 ± 21.4
GC	84 ± 9.9	52 ± 8.0	112 ± 28	85 ± 20.1

Table 2. Relative muscle torques (Mrel) in the muscles of the upper limbs in the three groups of participants (symbols as in Table 1)

	Fl_E	Ex_E	Fl_S	Ex_S
	[Nm/kg]	[Nm/kg]	[Nm/kg]	[Nm/kg]
G1	1.37 ± 0.05	0.93 ± 0.08	1.72 ± 0.2	1.63 ± 0.2
G2	1.35 ± 0.18	0.89 ± 0.16	1.69 ± 0.35	1.57 ± 0.33
GC	1.13 ± 0.14	0.69 ± 0.10	1.50 ± 0.37	1.14 ± 0.26

An analysis of the results contained in Tables 1 and 2 reveals that the strength potential of the main muscle groups in climbers was similar, despite measurable differences in the skill level of study participants. Differences in strength indices were noticeable only for non-standard dynamometric tests. These tests were used to provide a comprehensive characterisation of strength in the muscles of the upper limbs, which are responsible for maintaining a strong grip on a climbing wall.

Table 3 contains the values of hand grip force (F1), special grip force (F2), and global arm force in hanging (F3). It can be noticed that the maximum values of the variables in absolute terms did not differ between groups G1 and G2. However, significant differentiation was found for the results obtained for relative indices. These differences were circa 3% (F1rel), circa 10% (F3rel), and circa 12% (F2rel). It should be noted that the last two of the strength tests are a valuable diagnostic tool for climbing, as discussed in the Introduction. These tests revealed the highest differences in the results, described with relative indices recorded in athletes with different skill levels.

Table 3. Mean values (x ± SD) of maximal and relative hand grip force (F1), crimp grip force (F2), and bent arm force (F3) in the three groups of participants

	F1max	F1rel	F2max	F2rel	F3max	F3rel
	[N]	[N/kg]	[N]	[N/kg]	[N]	[N/kg]
G1	687 ± 7.5	10.7 ± 0.8	436 ± 36.5	6.8 ± 1.1	558 ± 12	8.69 ± 0.23
G2	716 ± 122	10.4 ± 1.9	415 ± 114	6.0 ± 1.4	536 ± 69	7.78 ± 0.39
GC	549 ± 65	7.6 ± 0.8	272 ± 43.4	3.8 ± 0.6	427 ± 74	5.91 ± 0.29

As described in the Methodology section, the aim of the second part of the measurements was to record changes in muscle strength in static conditions F(t). The measurements concerned the elbow flexors and extensors as well as the hand muscles responsible for the grip. Two variants of the test were used in the latter case. The first one was a typical dynamometric grip, which involves the muscles of all the fingers (including the thumb). The second variant used only the distal phalanges of the second to fifth fingers.

The indices of the rate of development of muscular force in the two groups of climbers did not differ, with a similar profile of the speed potential in the same muscles observed between the athletes. As expected, this profile was much similar to the profile of speed abilities in the muscles of men from the control group and demonstrated a speed advantage of anti-gravity muscles (Fl_E) over their antagonists. The time to attain the maximum force in the groups of athletes (G1 and G2) ranged from circa 0.2 s to circa 0.3 s, whereas the time to attain half of this value was circa 0.07 s. The maximum derivative of force (F'max) was over 4,000 N/s for Fl_E and slightly over 2,500 N/s for Ex_E. However, none of the cited values that characterised muscle contraction speed differed significantly from those recorded for the GC group.

The results obtained during the evaluation of the speed potential in the muscles responsible for the grip led to two major conclusions. Firstly, the muscles of the athletes showed higher levels of the characteristics described with respect to the male subjects from the control group. Secondly, the values of the variables discussed did not differ between the groups of athletes. The results show that the rate of force development for the dynamometric hand grip (F1) was higher than the values obtained for the climbing crimp grip (F2). Time tFmax ranged from 0.2 to 0.4 s (F1) and from 0.3 to 0.5 s (F2). Furthermore, the maximum derivative of the force in these two tests was over 5,000 N/s and circa 3,000 N/s, respectively. Unfortunately, the analysis of the significance of differences did not lead to the conclusion of speed dominance of the arm and forearm muscles in climbers, and all the differences were insignificant.

As discussed before, the last stage of the study was to evaluate muscle endurance potential using two tests performed to exhaustion (EN_1, EN_2). The time of maintaining the crimp grip in the continuous test at the level of 60% of the maximum level (EN_1) in both groups exceeded 1 minute (from 62 to 71 s), whereas the differences between the results did not exceed 9 s. However, it should be emphasised that the relative value of the resistance force differed between the groups. In the group of the best climbers (G1), this value was over 260 N and was 5% higher than in G2, whereas the mean value of the grip force in the GC group was 160N. In these conditions, the longest duration of the test was found in the G2 group.

The results of the intermittent endurance test (EN_2) showed the significant dominance of the climbers over the non-climbers. From 16 (G1) to 17 (G2) ten-second cycles were recorded on average in the groups of climbers. The results were significantly higher than those obtained by the controls (9 cycles).

Table 4 shows only the variables whose mean values in the group of climbers and students differed significantly. It is can be observed (with one exception, that of the arm flexors) that the elite climbers obtained higher values of strength indices (p from 0.001 to 0.05). Although the speed characteristics of the muscles seemed to be more favourable in climbers than in the control group, none of the differences in favour of athletes was statistically significant. The data shown in Table 4 also demonstrate that the variables that describe muscle endurance (EN_1 and EN_2) were significantly higher in climbers than in the group of students (p was 0.05 and 0.01, respectively).

Table 4. Mean values of variables in the group of climbers (G1+2) and the control group (GC) and the level of significance of the differences found (p)

	G1+2	GC	p		G1+2	GC	p
Fl_E [Nm]	92.2	84.2	0.04	Fl_E [Nm/kg]	1.4	1.1	0.05
Ex_E [Nm]	61.3	51.3	0.001	Ex_E [Nm/kg]	0.91	0.7	0.001
Ex_S [Nm]	107.5	85.3	0.001	Ex_S [Nm/kg]	1.6	1.1	0.001
F1max [N]	708.1	549	0.001	F1rel [N/kg]	10.5	7.6	0.001
F2max [N]	421.1	272	0.001	F2rel [N/kg]	6.2	3.8	0.001
F3max [N]	542.2	427	0.002	F3rel [N/kg]	8.0	5.9	0.001
EN_1 [s]	69	63	0.05	EN_2 [n]	17	9	0.01

Discussion

The measurement position is considered to be one of the major factors that affect the value of the force generated by the skeletal muscles. Therefore, a comparison of the Mmax values recorded in the group of elite rock climbers is possible only if the measurements are performed using the same methodologies. With this postulate, the strength abilities of the athletes are substantially higher than those of the group of non-athletes after the completion of a progressive phase of the development of strength abilities [13]; the levels of maximum muscle torques recorded in this study were higher by circa 15 Nm (Ex_E) to circa 25 Nm (Ex_S), that is 15-30% in percentage terms. The differences in the values of relative torques were even greater and ranged from 20 to 50%. This observation is not surprising since improvement in muscle strength abilities with athletic training is indisputable. The importance of strength conditioning in climbers has been discussed in several studies (e.g. [1, 14]). Thus, it is not surprising that the maximum grip force recorded was 20% higher and the relative force was over 20% higher in climbers with respect to non-climbers.

Furthermore, an analysis of the results obtained in our study reveals that the differences would be slightly lower if a different methodology of selection for the group was chosen. This might be demonstrated by a comparison of the differences in the results of our study and the data used by Staszkiewicz [13]. In the former case, the control group was comprised of students of the University of Physical Education, whereas in the latter case, the group included individuals from a cross-sectional study in the population of Krakow. The control groups differed significantly in the level of muscle strength potential.

The present study demonstrated no significant differences in the strength of the flexors and extensors in the elbow or arm joints between the groups of climbers. Obviously, it is likely that the samples used do not sufficiently characterise the strength potential of the muscles of climbers. However, it seems that with a high level of sport achievement, what is of the highest importance is special strength, including the strength of the muscles which determine firm grip during climbing. Therefore, significant differences in the level of special muscle force were recorded between the athletes studied, especially in relative terms. The athletes from the group of climbers at the higher skill level (G1) obtained values for relative arm strength and relative grip strength that were 10 to 12% higher compared to those achieved by the climbers from group G2. These findings are likely to be caused by the fact that the movement on a climbing wall occurs against gravity, and it is necessary to improve muscle strength while maintaining the lowest possible (optimum) body mass. This analysis is entirely consistent with the data documented by Watts [4] and Ferguson and Brawn [15], who examined world elite climbers and found that the high level of relative force represents one of the main factors in achieving success in this sport.

Muscular endurance was evaluated in the present study based on the crimp grip test in two variants (continuous and intermittent test). Both experiments were performed to exhaustion, with the level of the resistance of the dynamometer set at 60% of the maximum force. The hand position was not arbitrary as it is used during climbing on extremely difficult routes with a high number of small holds [16]. Therefore, there is a tendency among climbers to use it in a variety of tests [3], also in laboratory settings [18]. The level of the resistance (60%Fmax 2) was determined based on the information provided in a study by Grant et al. [17]. These researchers approached the evaluation of muscular endurance based on tests with resistance lower than 40%Fmax sceptically. In our previous study [3], we expressed similar scepticism about the level of 50%Fmax. The intermittent endurance test with the ratio of 7 s of contraction to 3 s of rest was chosen as proposed in the study by Watts et al. [19], although it should be noted that these authors used the ratio of 10 s/3 s in a similar test. There are also items in the global literature that described the examinations of muscle endurance using intermittent tests with an even ratio, for example 5 seconds of contraction to 5 seconds of rest (e.g., [20]).

The results of endurance tests were quite surprising. Firstly, in the continuous exercise (EN_1), the time of maintaining the grip was similar in all the groups (slightly more than 1 minute). Secondly, slightly better results were obtained by G2 climbers in both endurance tests. As expected, a noticeable advantage was found in the group of climbers compared to the controls during intermittent tests (7/3). This leads to the conclusions that continuous isometric tests do not show differences between athletes and non-athletes, whereas this differentiation can be expected for intermittent exercise. Similar findings were presented in the study by Watts et al. [19]. Grant et al. [17] found that this is likely to be caused by human body adaptation to the specific exercise typical of climbing training. This explains why climbers with the highest competencies, such as the participants from groups G1 and G2 in our study, obtain similar results in endurance tests. In athletes at high skill levels, this finding does not suggest insufficient development of strength but rather the achievement of its optimum level and, consequently, shows the need for maintaining this level, since progress in climbing (and the above discussed level) depends on factors other than merely striving for continuous increase in muscular endurance.

Sport climbing is characterised by a specific rhythm. With respect to the muscles of the forearm, this means alternating phases of contraction and relaxation. When holding a small hold, the muscles of the forearm perform isometric work and are substantially contracted, which causes vasoconstriction. When reaching for another hold, temporary relaxation releases the mechanism of partial recovery based on oxygen transport [21]. In technically complex movement sequences, moving the hand from one hold to another is sometimes performed at a relatively high speed. Simultaneously, a quick contact with the rock formation occurs, combined with the high rate of force development. The essential role in the above elements of the competition is played by time, which can, to a certain degree, be linked to the rate of muscle activation. Contraction rate depends on, for example, the type of muscle tissue. However, studies that identified muscle tissue composition in climbers have not provided unequivocal information regarding this issue to date. Nevertheless, Esposito et al. [21], based on examinations by means of the EMG method, found that the muscles of advanced climbers were characterised by different strategies of recruitment of motor units compared to those of non-climbers. The difference is likely to be caused by adaptations at the muscular level (hypertrophy combined with the prevalence of type II muscle fibres) and the nervous system level (higher value and frequency of potentials). Consequently, the muscles of elite climbers are capable of recruiting new motor units with higher force compared to those of non-athletes. The results of our study are only partially consistent with these conclusions since the athletes demonstrated a higher level of speed potential of the muscles compared to male participants from the control group, but the differences were not significant. Furthermore, the variables that characterised the contraction rate did not differ between the groups of athletes.

It should be stressed that the statistical analysis led to the conclusion that the muscles of the athletes and students differed significantly only in the level of strength and endurance. These observations are likely to result from the fact that sport climbers have to increase muscle strength while maintaining substantially low (optimal) body mass. This phenomenon was already emphasised in this study while the research on world class climbers [4, 8] provides the unequivocal evidence. The advantage of climbers over non-climbers in terms of muscle endurance was previously found by Ozimek et al. [22]. These researchers explained this observation by the use of strength training to induce changes in the level of endurance.

Conclusions

1. Groups of elite climbers differ significantly in the strength potential of their muscles, but only for relative force indices. These indices were the highest in the best climbers.
2. Despite the differences in the skill level in the groups of climbers, we found no differences in biomechanical variables that characterise speed and muscular endurance.
3. Laboratory tests aimed to examine muscle potential in climbers should be designed to take into consideration the specific character of this sport since conventional tests are not a valuable diagnostic tool for the evaluation of climbers.

Literature

1. Rokowski R., Staszkiewicz R. (2010). Sport climbing: The role and importance of strength training in climbing performance. *Sport Wyczynowy* 2, 19-34. [in Polish]
2. Sheel W. (2004). Physiology of sport rock climbing. *British Journal of Sports Medicine* 38, 355-359. DOI: 10.1136/bjsm.2003.008169.
3. Staszkiewicz R., Rokowski R. (2011). Sport climbing: The role and importance of endurance training. *Sport Wyczynowy* 2, 107-119. [in Polish]
4. Watts P. (2004). Physiology of difficult rock climbing. *European Journal of Applied Physiology* 91, 361-372. DOI: 10.1007/s00421-003-1036-7.
5. Grant S., Hasler T., Davies C., Aitchison T., Wilson J., Whittaker A. (2001). A comparison of the anthropometric, strength, endurance and flexibility characteristics of female elite and recreational climbers and non-climbers. *Journal of Sports Sciences* 19, 499-505. DOI: 10.1080/026404101750238953.
6. Rokowski R., Tokarz R. (2007). The importance of energy-related motor skills in on-sight style climbing competitions. *Antropomotoryka* 40, 81-91. [in Polish]
7. Macleod D., Sutherland L., Buntin L., Whitaker A., Aitchison T. et al. (2007). Physiological determinants of climbing-specific finger endurance and sport rock climbing performance. *Journal of Sports Sciences* 25(12), 1433-1443. DOI: 10.1080/02640410600944550.
8. Michailov M., Mladenov L., Schöffl V. (2009). Anthropometric and strength characteristics of world-class boulderers. *Medicina Sportiva* 13(4), 231-238. DOI: 10.2478/v10036-009-0036-z.
9. Vigouroux L., Quaine F. (2006). Fingertip force and electromyography of finger flexor muscles during a prolonged intermittent exercise in elite climbers and sedentary individuals. *Journal of Sports Sciences* 24, 181-6. DOI: 10.1080/02640410500127785.
10. Draper N., Giles D., Schöffl V., Fuss F., Watts P., Wolf P. et al. (2016). Comparative grading scales, statistical analyses, climber descriptors and ability grouping: International Rock Climbing Research Association Position Statement. *Sports Technology* 8(3-4), 88-94. DOI: 10.1080/19346182.2015.1107081.
11. Gajewski J., Hubner-Wozniak E., Tomaszewski P., Sienkiewicz-Dianzenza E. (2009). Changes in handgrip force and blood lactate as response to simulated climbing competition. *Biology of Sport* 26(1), 13-21. DOI: 10.5604/20831862.890171.
12. Balas J., Mrskoc J., Panackova M., Draper N. (2014). Sport-specific finger flexor strength assessment using electronic scales in sport climbers. *Sports Technology* 7(3-4), 151-158. DOI: 10.1080/19346182.2015.1012082.
13. Staszkiewicz R. (2013). *Sexual dimorphism and muscle distribution in children and adolescents aged 8-18 years.* Kraków: AWF Kraków. [in Polish]
14. Grant S., Hynes V., Whittaker A., Aitchison T. (1996). Anthropometric, strength, endurance and flexibility characteristics of elite and recreational climbers. *Journal of Sport Sciences* 14, 301-309. DOI: 10.1080/02640419608727715.
15. Ferguson R.A., Brawn M. (1997). Arterial blood pressure and forearm vascular conductance responses to sustained and rhythmic isometric exercise and arterial occlusion in trained rock climbers and untrained sedentary subjects.

European Journal of Applied Physiology 76, 174-80. DOI: 10.1007/s004210050231.

16. Schoffl I., Oppelt K., Jungert J., Schweizer A., Neuhuber W., Schoffl V. (2009). The influence of the crimp and slope grip position on the finger pulley system. *Journal of Biomechanics* 42, 2183-2187. DOI: 10.1016/j.jbiomech.2009.04.049.
17. Grant S., Shields C., Fitzpatrick V., Ming Loh W., Whitaker A., Watt I. et al. (2003). Climbing-specific finger endurance: A comparative study of intermediate rock climbers, rowers and aerobically trained individuals. *Journal of Sports Sciences* 21, 621-630. DOI: 10.1080/0264041031000101953.
18. Giles L., Rhodes E., Taunton J. (2006). The physiology of rock climbing. *Sports Medicine* 36(6), 529-545. DOI: 10.2165/00007256-200636060-00006.
19. Watts P., Martin D., Durtschi S. (1993). Anthropometric profiles of elite male and female competitive sport rock climbers. *Journal of Sports Sciences* 11, 113-117. DOI: 10.1080/02640419308729974.
20. Quaine F., Viguoroux L., Martin L. (2003). Finger flexors fatigue in trained rock climbers and untrained sedentary subjects. *International Journal of Sports Medicine* 24, 424-7. DOI: 10.1055/s-2003-41174.
21. Esposito F., Limonta E., Ce E., Gobbo M., Veicsteinas A., Orizio C. (2009). Electrical and mechanical response of finger flexor muscles during voluntary isometric contractions in elite rock-climbers. *European Journal of Applied Physiology* 105, 81-92. DOI: 10.1007/s00421-008-0877-5.
22. Ozimek M., Staszkiewicz R., Rokowski R., Stanula A. (2016). Analysis of tests evaluating sport climbers' strength and isometric endurance. *Journal of Human Kinetics* 53, 249-260. DOI: 10.1515/hukin-2016-0027.

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