

Comparative biomechanical characteristics of one-arm hang in climbing for beginners and qualified athletes

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Purpose: The aim of the study was to identify the basic kinematic characteristics of the one-arm hang in climbing for beginners and qualified climbers. *Material and methods:* Technique of the one-arm hang in climbing among 20 leading climbers of the World and Ukraine and 20 beginner male amateur climbers was analyzed. A qualified athlete participated in the demonstration of various models of the one-arm hang performance. By means of Kinovea software 0.8.15, the kinematic characteristics of two models of the technique were analyzed (model 1 for beginner athletes, model 2 for qualified athletes). *Results:* The presence of significant differences ($p < 0.001$) between beginners and qualified athletes in the magnitude of the angles between the shoulder and clavicle, between the spine and the vertical axis in the phase of fixation of the one-arm hang was revealed. The dynamics of the angle between the shoulder and clavicle from the moment of capture of the climbing hold to the phase of fixation of the hang was shown. A theoretical justification for the correct climbing technique regarding to the laws of mechanics and the laws of force interaction in kinematic chain was provided. *Conclusions:* Beginner athletes carry out the one-arm hang mainly due to the ligamentous apparatus of the joints of the shoulder girdle with minimal inclusion of muscles, which is dangerous by trauma to the ligaments of the shoulder joint. Skilled athletes perform the one-arm hang with trunk and leg muscles included, which reduces the strain from the ligamentous apparatus and lowers the possibility of injury to the ligaments of the shoulder joint.

Key words: rock climbing, bouldering, technique, kinematic characteristics

1. Introduction

Climbing is a fast-growing sport and has recently been included in the Tokyo Olympic Games 2020 and the Youth Olympic Games 2018. This imposed high demands on the level of sports professionalism. The enhancement of the technical training of athletes in climbing is of particular importance [2], [3], [10], [13]. The correct technique of physical exercise is

a method of its performance, in which the motor task is solved in the most effective and efficient way [7], [8]. That is, a physical exercise involves the performance of any motor task. This motor task should be carried out in the most rational way: as quickly as possible, more precisely, efficiently, etc. [4]–[6]. First of all, the correct technique presupposes, first of all, the energy efficiency of the motion, which predetermines not only the saving energy, thereby providing the opportunity for achieving the highest athlete's results.

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Performing motions in the most rational way prevents injuries [18], [21]–[23], creating conditions for biomechanically appropriate work of the motor apparatus [23], [25], [27].

The scientific substantiation of the correct technique of motions implies its biomechanical analysis in terms of determining the optimal options for performing various motions [11], [12], [14]. This is possible when substantiating the effectiveness of the technique of various motions by relying on the laws of physics (mechanics), biomechanics, physiology, biochemistry. In the study on the technique of motions, biomechanical analysis is of great importance, because it involves the determination of various indicators of the technique of motions: speed and acceleration of the motions of individual parts of the body, the angles in the joints, etc. [7], [8]. The juxtaposition of these characteristics with physical laws enables determining the most effective performing way of various elements. Since the scientific justification of the technique for performing individual elements in climbing is just being carried out, this area is topical and timely. The analysis of the technique for performing basic elements, one of which is the one-arm hang in capture of the climbing hold after jump in climbing is of great importance [15], [27]. The technique of this element as well as other elements in climbing was formed empirically. Therefore, the scientific justification of the technique of this element may lead to the development of the principles for other elements of performance. In addition, the scientific justification of the technique of the one-arm hang in climbing may provide the basis for methods of teaching this particular technique.

The correct technique is characterized by the optimal ratio of working muscles to ensure effective motion. According to N.A. Bernstein's theory of motor control in the process of formation of motor skill, a constant correction of motion occurs in keeping with the goal of motion. N. Bernstein [1] also stated that when performing a motion at the level of the spatial field (level C), the background levels serve as the tone ones (level A) and synergies (level B). Furthermore, the higher the athlete's skill, the more perfect the inclusion of levels A and B. N. Bernstein also links traumas with the inadequacy of background levels with a leading spatial field level [1], [18]. The one-arm hang in climbing refers to motions at the level of spatial field. Therefore, its performance should be provided not only using the muscles directly involved in the motion, but also the muscles which are responsible for the synergies in this motion, that is, the muscles of the trunk and legs. The one-arm hang in climbing after

the jump is also characterized by the need for being ready to immediately perform the next motion. For this, not only arms should work, but legs and trunk as well [2], [3].

Highly qualified athletes in the process of long practice form more rational motions in comparison with novice athletes. Therefore, studying the biomechanical characteristics of highly qualified athletes' motions and comparing them with the biomechanical characteristics of novice athletes' motions may provide a deeper understanding of the correct technique mechanisms. This is necessary both for the theoretical justification of rational technique and for practical work on teaching motions. The inclusion of different muscles in the motion leads to different angles in joints. Thus, the study of the angles in the joints when performing technical elements by athletes of different qualifications will enable the trainers to justify the rational performance of techniques. In this study, the hypothesis is stated: according to Bernstein' theory [1], [18] and the theory of formation of the technique of motion [7], [8], there are differences in the technique of the one-arm hang performance in climbing among the athletes of different qualifications, which is represented in the angles between the various parts of the body.

The aim of the study was to identify the basic kinematic characteristics of the one-arm hang in climbing in beginners and qualified climbers.

2. Materials and methods

2.1. Participants

The technique of the one-arm hang performance in climbing was analyzed among 20 leading climbers of the World and Ukraine (athletes of high qualification, climbing experience – more than 5 years, masters of sports ($n = 18$) and masters of sports of international class ($n = 2$) and 20 beginner amateur climbers (experience in climbing less than 1 year). All subjects were male. Age of the athletes 22.4 ± 3.2 years, body length – 178.5 ± 12.5 cm, body weight – 72.2 ± 8.5 kg.

2.2. Experimental protocol

There were analyzed the technique of the one-arm hang performance in climbing among 20 leading climbers of the World and Ukraine and 20 beginner athletes.

Athletes stood on the floor in front of a climbing stand, performed a jump, grabbed a climbing hold and hung with one arm. This is the standard motion in bouldering. All athletes performed the jump, starting from the floor.

The main characteristics of the correct technique of the one-arm hang performance were compiled based on the analysis of technique of the one-arm hang performance by athletes.

The analysis of the technique was carried out by means of Kinovea software 0.8.15. The kinematic characteristics of two models of the technique were analyzed (model 1 – typical for beginner athletes, model 2 – typical for qualified athletes). Employing Kinovea software 0.8.15, the angles between the shoulder and clavicle, as well as between the spine from the middle of the thoracic section to the coccyx and the vertical axis, were determined. The analysis of angles was carried out from the moment of capture of the climbing hold to the stable fixation of the hang ($t = 0.5$ s, the number of frames analyzed was 10, frames were selected at regular intervals). A comparative characteristic of the measured angles from the moment of capture of the climbing hold to the stable fixation of the hang was carried out.

Via Sony FDR-X3000 camcorder a technique of the one-arm hang performance by unskilled and qualified athletes was demonstrated and fixed. To provide standard conditions for anthropometric data, the demonstration was conducted by one person. The demonstration was carried out by the author – a qualified athlete, candidate for master of sports of Ukraine, winner and prizewinner of all-Ukrainian competitions.

2.3. Statistical analysis

The measured angles at the point of stable fixation of the one-arm hang were compared based on 20 measurements for each model of technique. The following indicators were calculated: average values of angles in each of 10 frames, error of the mean, standard deviation, coefficient of variation. Data processing was carried out using computer programs – “EXCEL-2016” and “SPSS-17”.

3. Results

The analysis of the technique of the one-arm hang in climbing by athletes of different qualifications re-

vealed that there are two models of the technique for performing this motion, significantly different in basic parameters. The demonstration of these models of technique is presented in Figs. 1 and 2. In Figure 1, the first model of the one-arm hang technique in climbing is displayed. It is characterized by a large angle between the shoulder and clavicle, and almost vertical position of the lumbar part of the spine with curvature in the upper part. This type of technique is typical for unskilled athletes. In Figure 2, the second model of the one-arm hang technique in climbing is displayed. This model is characterized by a smaller angle between the shoulder and clavicle, and a large angle between the spine and the vertical axis. The first model of technique is typical for beginner amateur athletes, the second model of technique is typical for qualified athletes.



Fig. 1. An example of a videogram of one-arm hang in climbing, model 1, typical for beginner athletes (photos by author)

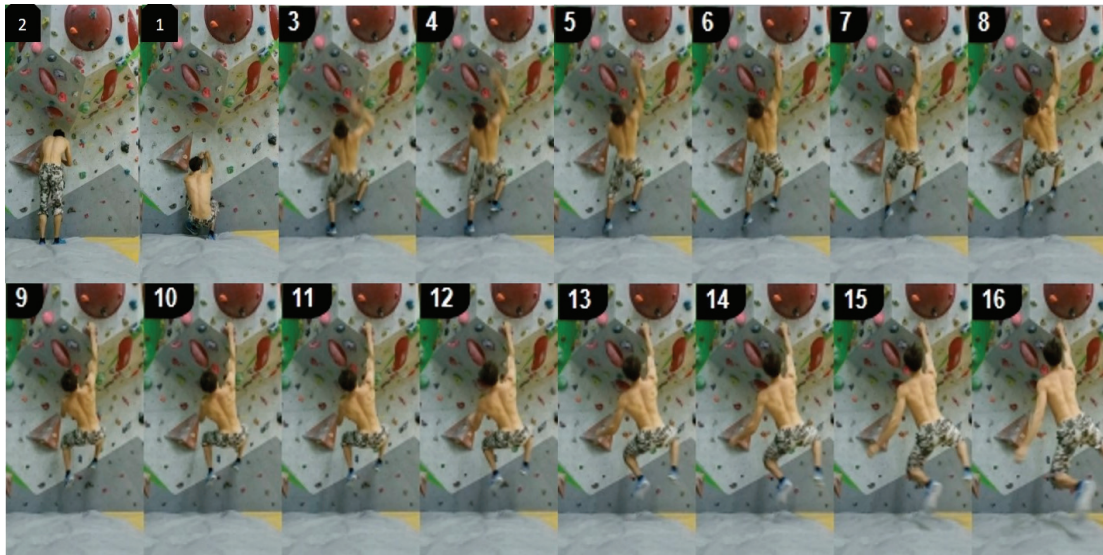


Fig. 2. An example of a videogram of hanging of One-Arm Hang in Climbing, model 2, typical for qualified athletes (photos by author)



Fig. 3A. The phase of fixing the one-arm hang in climbing, model 1, typical for beginner athletes (frame no. 7 of the videogram in Fig. 1) (photos by author); an illustration of a frame for fixing a hang



Fig. 3B. The phase of fixing the one-arm hang in climbing, model 1, typical for beginner athletes (frame no. 7 of the videogram in Fig. 1) (photos by author); biomechanical analysis of the angles between the shoulder and collarbone, between the lower spine and the vertical axis



Fig. 4A. The phase of fixing the one-arm hang in climbing, model 2, typical for qualified athletes (frame no. 14 of the videogram in Fig. 2) (photos by author); an illustration of a frame for fixing a hang

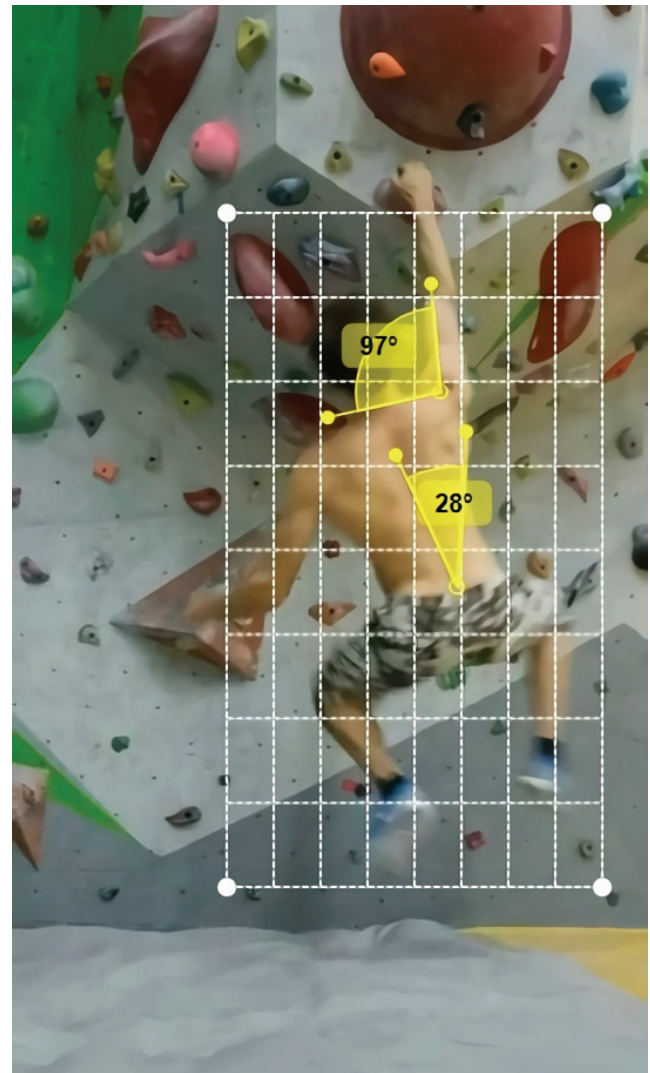


Fig. 4B. The phase of fixing the One-Arm Hang in Climbing, model 2, typical for qualified athletes (frame no. 14 of the videogram in Fig. 2) (photos by author); biomechanical analysis of the angles between the shoulder and collarbone, between the lower spine and the vertical axis

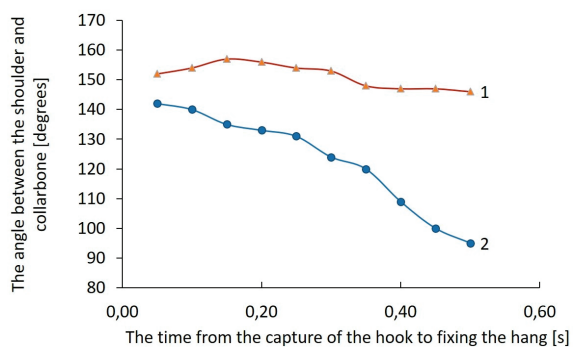


Fig. 5. The magnitude of the angles between the shoulder and collarbone of one-arm hang in climbing: 1 – model of technology 1, typical for beginner athletes, 2 – model of technology 2, typical for qualified athletes

A kinematic analysis of two models of the one-arm hang technique in climbing indicated that there are significant differences ($p < 0.001$) in the angles between the shoulder and clavicle, between the spine and the vertical axis in the phase of fixation of the one-arm hang (Table 1, Fig. 5). Thus, the angle between the shoulder and the clavicle in the first model of technique was $146^\circ \pm 16^\circ$ (Fig. 3, Table 1), in the second model of technique this angle is $97^\circ \pm 9^\circ$ (Figs. 4, 5, Table 1). In the first model, the angle between the lumbar spine and the vertical axis was $11^\circ \pm 4^\circ$ (Fig. 3, Table 1), in the second model, this angle was $28^\circ \pm 5^\circ$ (Fig. 4, Table 1).

Table 1. Comparative characteristics of the angles between the shoulder and collarbone and between the spine and the vertical axis in various models of One-Arm Hang in Climbing ($n = 20$)

Indicators	Model of technology	Statistical indicators					
		\bar{x}	S	m	CV	t	p
The angle between the shoulder and collarbone [°]	Model 1, typical for beginner athletes	146	16	3.58	10.96	11.94	<0.001
	Model 2, typical for qualified athletes	97	9	2.01	9.28		
The angle between the vertical axis and the spine [°]	Model 1, typical for beginner athletes	11	2	0.44	18.18	-14.12	<0.001
	Model 2, typical for qualified athletes	28	5	1.12	17.86		

4. Discussion

The present study discovered that the main kinematic parameters of the one-arm hang in climbing for various models of technique typical for athletes of different qualifications were identified. Unskilled athletes A type of technique with minimal tension on the muscles of the shoulder, back, a large angle between the shoulder and clavicle, and almost vertical position of the lumbar spine with curvature in the upper section is characteristic for unskilled athletes. Qualified athletes are characterized by a type of technique with tension in the muscles of the shoulder, back, a large angle between the shoulder and clavicle, and a large angle between the spine and the vertical axis. The dynamics of the angle between the shoulder and clavicle from the moment of capture of the climbing hold to the phase of fixation of the one-arm hang is presented. At the moment of capture of the climbing hold, the angle between the shoulder and clavicle is almost the same for both models of technology. In the second model of the one-arm hang technique, the angle between the shoulder and the clavicle gradually decreases from the moment of the capture of the climbing hold to the fixation phase of the one-arm hang, while in the first model this value remains the same.

The hypothesis claimed in this study was confirmed. To prevent injuries and diseases of the musculoskeletal system, the formation of biomechanically effective motor stereotypes is required. To do this, it is necessary to rely on a certain theoretical basis. As a theoretical base, we applied Bernstein's theory of motor control [1], [18] and the laws of mechanics. The correct one-arm hang technique in climbing is based on the laws of physics, in particular, on the laws of mechanics, and is based on Bernstein's theory of motor control.

In Figure 5, the dynamics of the angle between the shoulder and clavicle from the moment of capture of the climbing hold to the phase of fixation of the one-arm hang is displayed. At the moment of capture, the angle between the shoulder and clavicle was almost the same for both models of technique. However, the main interest was the position in the phase of fixation of the one-arm hang. In this position, there was a significant difference ($p < 0.001$) of the angle between the shoulder and clavicle both for the first and second models. In the second model of the one-arm hang technique, the angle between the shoulder and the clavicle gradually decreases from the moment of capture of the climbing hold to the fixation phase of the climbing hold, while in the first model this value remained the same (Fig. 5). These differences were due to more intensive work of the muscles of the trunk, legs, and shoulder in the second model compared to the first model (Figs. 1–4). Since the second model (qualified athletes) was characterized by the intensive work of muscles not only of the upper limb, but also of the trunk and legs, it can be concluded that the second model requires the development of these muscles, and cannot be applied by unskilled athletes due to insufficient development of the muscle system. In the first model, the one-arm hang was carried out mainly due to the ligamentous apparatus of the joints of the shoulder girdle with minimal inclusion of muscles, which is dangerous by trauma to the ligaments of the shoulder joint. In the second model, the one-arm hang ensures the inclusion of muscles, which reduces the strain from the ligamentous apparatus and lowers the possibility of injury to the ligaments of the shoulder joint.

This study provides new data on the kinematic parameters of various models of the one-arm technique in climbing. A correct technique implies the most efficient performance of a motion, i.e., a motion in which there is an optimal combination of expended

efforts and the achieved effect [7], [8]. Therefore, the question arises about up to what extent muscle tension is worthwhile in the second model of the one-arm technique in climbing. Usually, athletes come to this model empirically. However, the effectiveness of this model at the present time, although it has shown the effectiveness of the application, is not justified in terms of the laws of biomechanics and kinesiology. To understand the ways of improving the technique of motions in climbing, it is necessary to substantiate the basic principles of motions. One of the most common climbing motions is the one-arm hang [27]. Therefore, the justification of the correctness of this motion performance is of great importance for the climbing technique as a whole, as well as for other sports in the technique of which there are similar patterns.

Based on this, we analyzed both models of the one-arm technique in climbing in terms of the laws of physics (Fig. 6) and the specific features of the interaction of forces in kinematic chains (Fig. 7). We schematically presented the distribution of tension during the one-arm hang in the form of interconnected elements. This “structure” is attached by one link to the upper support (d), and is in a state of hang (Fig. 6). In Figure 6(1), a frame of the first model of the technique of the one-arm hang performance is shown and in Figure 6(2), a frame of the second model for the one-arm hang performance is presented. The first model of the technique of the one-arm hang performance is characterized by minimal inclusion of the muscles of the shoulder girdle, trunk, legs, and therefore the area (b) of the links connection (a, c) is relatively small. The second model of the one-arm hang in climbing is characterized by a larger area (b) of the links connection (a, c) with each other due to the inclusion of more muscles of the shoulder girdle, trunk, legs.

From the point of view of the balance of forces acting on the body [16], [25], these models are the same: in both cases, the body weight, which is the product of body mass (m) and gravitational acceleration (g), is kept in the hang by the force of fastening on the support, which is equal to the reaction force of the support F_p :

$$mg + F_p = 0, \quad (1)$$

where:

m – the body weight,

g – gravitational acceleration,

F_p – the force of fastening on the support, is equal to the reaction force of the support.

However, if we consider these models in terms of the laws governing the conservation of the tensile structure, these models have significant differences. These differ-

ences are due to the laws of mechanics, in particular, the resistance of materials to tension or compression [20].

According to the basic law of the strength condition, under tension or compression deformation, normal stresses σ arise in the sections of the bar. The longitudinal force N is related to the normal stress σ by the following dependence (Eq. (2)):

$$\sigma = \frac{N}{A}, \quad (2)$$

where:

σ – the normal stress,

N – the longitudinal force in the cross section of the bar,

A – the cross-sectional area of the bar.

According to this formula, the stress that occurs in the one-arm hang in climbing (σ) depends on the longitudinal force, that is, on the body weight (N), and on the cross-sectional area (A), that is, on the muscles and ligaments of the shoulder girdle that ensure the execution of the hang. Body weight (N) is the same in the first and second models, but the cross-sectional area (A) in the second model is larger. Accordingly, the stress (σ) is greater in the first model compared to the second, because, according to Eq. (2):

$$A_1 < A_2, \quad N_1 = N_2, \quad \text{consequently } \sigma_1 > \sigma_2.$$

The higher efficiency of model 2 (typical for qualified athletes) can also be explained in terms of the addition of forces in a kinematic chain. A kinematic chain is a connection of a series of relatively moving kinematic pairs (arm, leg, or the entire body of an athlete). Depending on the connections imposed on the body, three main types of kinematic chain are distinguished, which are important for understanding the technique of sports motion. An open or open kinematic chain (with fixation of one of its ends in positions such as handstand, leg stand, hang stand, as well as with motions of the free limb – swing with a hand, foot, etc.). A closed kinematic chain (positions with fixed both ends of the kinematic chain, for example, with simultaneous support with arms and legs) [18], [23]. In a closed chain, isolated motion is impossible, i.e., motion in a single joint. So, bending and straightening the legs in a lunge, we can make sure that the motion in any joint will certainly cause a motion in others.

If we consider the set of the individual parts of the body when doing the one-arm hang, this position can be described as an open kinematic chain. In modern kinesiology [9], [17], [24], the links of the kinematic chain are understood to mean bones connected by joints, as well as muscles attached to bones. When

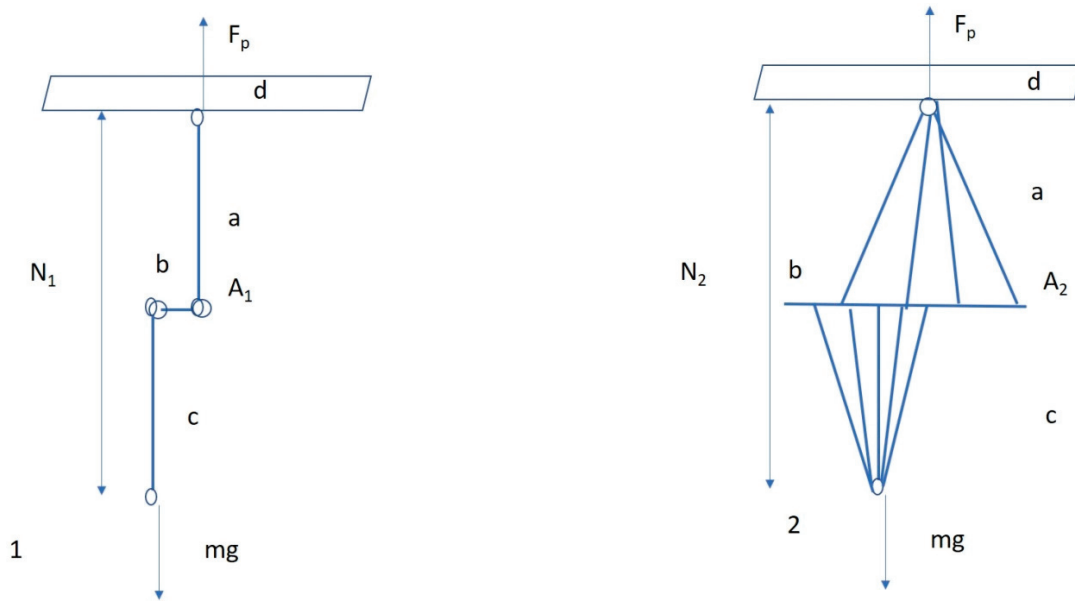


Fig. 6. Schemes of models of stress distribution during the execution of one-arm hang in climbing: 1 – model 1 (the wrong technique, typical for beginner athletes); 2 – model 2 (the correct technique, typical for qualified athletes); a – upper part of the chain (upper limb); b – connection of the upper and lower parts of the chain; c – the lower part of the chain (trunk); d – support (climbing stand) N – the longitudinal force in the cross section of the rod; A – the cross-sectional area of the rod (muscles and ligaments in the joint of the shoulder and trunk)

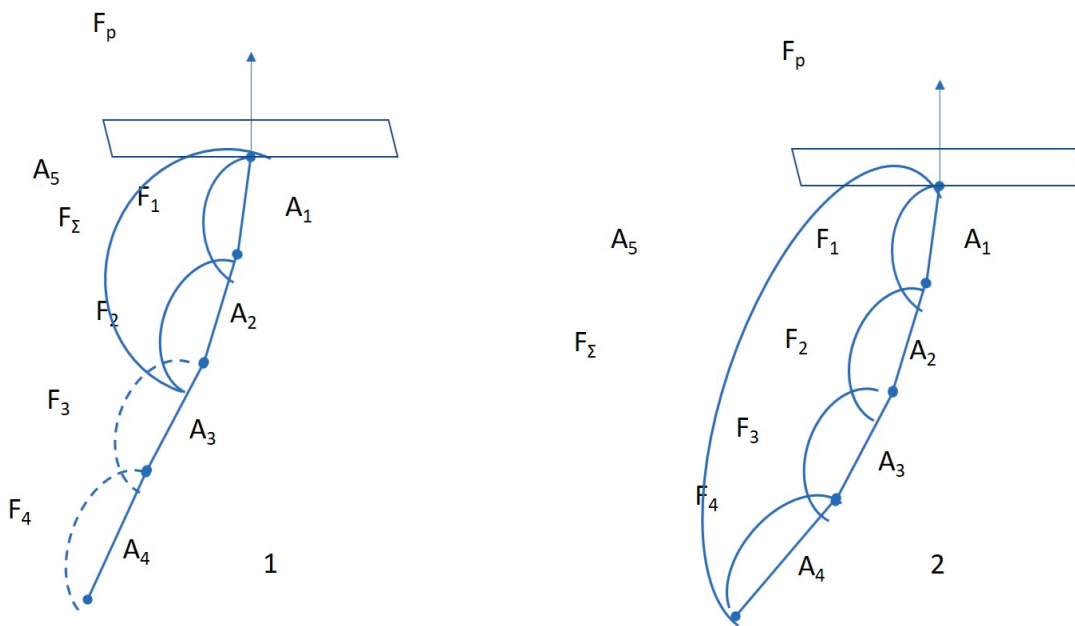


Fig. 7. Scheme of a kinematic chain in various models of one-arm hang in climbing: 1 – model 1 (wrong technique); 2 – model 2 (the correct technique); F_p – force; the force of fastening on the support is equal to the reaction force of the support; F_Σ – the force that holds the body on a support in the hang; F_1, F_2, F_3, F_4 – forces arising as a result of tension of individual muscles; A_1, A_2, A_3, A_4, A_5 – links of the kinematic chain (A_5 – the link arising as a result of tension of mutually transitioning muscles of the kinematic chain); Model 1 – a kinematic chain is formed by a small number of links; the force holding the body in the suspension (F_Σ) is due to the force of F_1 and F_2 : $F_\Sigma = F_1 + F_2$; Model 2 – a kinematic chain is formed by a large number of links; the force holding the body in the hang (F_Σ) is due to the strength of the links A_1, A_2, A_3, A_4 : $F_\Sigma = F_1 + F_2 + F_3 + F_4$

tensioned, these muscles form a single structure. In Figure 7(1), a variant of a kinematic chain formed in the first model of a technique of the one-arm hang

performance is shown. In this case, only two links of the kinematic chain (A_1 and A_2) are involved in supporting the entire body in the hang. The working mus-

cles cause the forces F_1 and F_2 to form a connected structure, and form another link in the A_5 kinematic chain. As a result, the total force that ensures the one-arm hang performance is equal to the sum of the forces F_1 and F_2 .

Similarly, the addition of forces occurs in the second model of the technique of the one-arm hang in climbing. However, in this case, the number of chain links involved in the motion is greater. In this case, all the links of the kinematic chain (A_1 and A_2) are involved in supporting the entire body in the hang. The working muscles cause the action of the forces F_1, F_2, F_3, F_4 , form a connected structure, and form another link in the kinematic chain A_5 . As a result, the total force that ensures the one-arm hang performance is equal to the sum of the forces F_1, F_2, F_3, F_4 .

In general, the addition of forces in the presented kinematic chains can be represented in the form of a formula (Eq. (3)):

$$F_{\Sigma} = \Sigma F_i, \quad (3)$$

where:

F_{Σ} – the force that holds the body in the hang,

F_i – force due to the inclusion of individual interconnected links of a kinematic chain,

F_p – the reaction force of the support.

In the second model, the total force providing the position of the hang is significantly greater than this force in the first model. This means that in the second model, not only the muscles of the upper limb (as in the first model), but also the muscles of the trunk and legs participate in supporting the position of the one-arm hang in climbing, creating another link in the kinematic chain. Accordingly, the upper limb has less load in comparison with the first model of technology. This determines the effectiveness of the second model of technique and provides a theoretical basis for the formation of the most effective climbing technique, which ensures the achievement of a sports result and prevents injuries. However, experimental verification of these data requires additional research.

Thus, in this study, the main kinematic parameters of the one-arm hang in climbing were identified for various models of the technique which are typical for athletes of different qualifications. These data were theoretically justified relying on the laws of mechanics and the laws of interaction of forces in the kinematic chain, which is new data. The data [17], [24] were confirmed regarding the formation of kinematic chains when the interconnected muscles included in the work.

5. Conclusions

1. The main kinematic parameters of the one-arm hang in climbing for various models of the technique which is typical for athletes of different qualifications were identified. Unskilled athletes are characterized by a type of technique with minimal tension in the muscles of the shoulder, back, a large angle between the shoulder and clavicle, and the almost vertical position of the lumbar spine with curvature in the upper section. Qualified athletes are characterized by a type of technique with tension in the muscles of the shoulder, back, a large angle between the shoulder and clavicle, and a large angle between the spine and the vertical axis.
2. The presence of significant differences ($p < 0.001$) in the angles between the shoulder and clavicle, between the spine and the vertical axis in the phase of fixation of the hang is provided. So, the angle between the shoulder and clavicle in the first model of the technique was 146° , in the second model of technique this angle is 97° . The angle between the lumbar spine and the vertical axis in the first model was 11° , in the second model this angle was 28° .
3. The dynamics of the angle between the shoulder and clavicle from the moment of capture of the climbing hold to the phase of fixation of the one-arm hang is presented. At the moment of capture of the climbing hold, the angle between the shoulder and clavicle is almost the same for both models of the technique. In the second model of the one-arm hang technique, the angle between the shoulder and clavicle gradually decreases from the moment of the capture of the climbing hold to the fixation phase of the one-arm hang, while in the first model this value remains the same.
4. It is shown that in the first model, the one-arm hang in climbing is carried out mainly due to the ligamentous apparatus of the joints of the shoulder girdle with minimal inclusion of muscles, which is dangerous by trauma to the ligaments of the shoulder joint. In the second model, the one-arm hang in climbing ensures the inclusion of muscles, which reduces the strain from the ligamentous apparatus and lowers the possibility of injury to the ligaments of the shoulder joint. The theoretical substantiation of the correct technique of the one-arm hang in climbing is provided in terms of the laws of mechanics and the laws of the interaction of forces in the kinematic chain.

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Conflict of interest

Authors state that there is no conflict of interest.

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