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EFFECT OF LOCAL MUSCLE FATIGUE ON BIOMECHANICAL AND VISCOELASTIC PROPERTIES OF SKELETAL MUSCLES

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Abstract. The work is devoted to the study of the effect of local muscle fatigue on the biomechanical and viscoelastic properties of skeletal muscles. A device for non-invasive digital palpation MyotonPRO was used to carry out myotonometric measurements. The study involved 13 males and females (6 males and 7 females) aged 32.5 ± 10.6 years. Each volunteer completed two series of exercises that induce local muscle fatigue of the hand muscles. The exercises were performed with a hand grip with a resistance of 20 kg. The first series of exercises was performed until the volunteer developed a subjective fatigue, the second - until his/her refusal to continue due to excessive fatigue of the hand muscles. Testing had 3 stages: before starting strength exercises, after exertion, before subjective fatigue, and after loading with maximal exertion. Local muscle fatigue was objectively confirmed by dynamometry in accordance with the physiology standards. Myotonometry was performed on the cubital and radial flexors of the carpus, and on the abductor thumb muscle. As a result of the statistical analysis of data, it was shown that the myotonometry can be used to diagnose muscle fatigue. A change in active muscles myotometric indicators can be registered even when a subjective fatigue occurs, while local muscle fatigue does not affect the change in the tone of inactive muscles. It was also shown that the location of the measurement point of myotonometric characteristics on the muscle belly of the cubital flexor of the carpus does not affect the results with the condition that the place of application of the device is within the range of ± 2 cm from the center of the muscle belly.

Key words: local muscle fatigue, myotonometry, dynamometry, biomechanical properties of skeletal muscles.

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INTRODUCTION

Muscle fatigue is the main factor that limits the human motor activity. In addition to the general positive effect of preventing the exhaustion of body systems under the influence of physical exertion exceeding its physiological capabilities, muscle fatigue can negatively affect the level of work performance [22, 29], as it leads to an increase in physiological cost of work and a decrease in physiological reserves of the body [16]. Insufficient restoration of body's resources during periods of rest can cause serious consequences such as overstrain and overwork. These conditions are difficult to correct and they can cause the development of diseases [29].

Muscle fatigue is accompanied by a decrease in the contractility of muscles, changes in their biomechanical properties and bioelectric activity [14]. The occurrence of muscle fatigue is evidenced by changes in the composition of blood and the dynamics of indicators of the state of cardiovascular and respiratory systems [4]. Assessment in the early stages of the above-mentioned changes can help prevent its further development into fatigue and overstrain. But cardiovascular and respiratory systems status monitoring is not always informative and objective, and the analysis of the dynamics of biochemical markers of intense muscle activity requires invasive manipulations under the supervision of medical personnel, which is a significant limitation for the widespread use of this method. Taking this into account, procedures related to registration of changes in the characteristics of skeletal muscles can be diagnostically effective.

Manual testing (palpation determination of muscle tone), dynamometry (determination of muscle strength and endurance) and electromyography (EMG) (determination of the bioelectrical activity of muscles) are most common methods for assessing the state of skeletal muscles [17]. In addition, tensomyography, myotonometry and ultrasound methods have begun to be used recently for assessing the state of skeletal muscles [1, 8, 11]. At the moment, research is being conducted to determine the possibility of their extensive use, and specific methods are being developed to solve problems in various fields of medicine. The use of ultrasonic methods is often difficult due to overall characteristics of the equipment and impossibility of conducting research in "field" conditions. Tensomyography provides for electrical stimulation of muscles, which in practice is not always acceptable. Consequently, most accessible method is myotonometry – a method of studying the functional state of muscles by measuring muscle tone [19].

The latest device allowing to conduct myotonometric measurements is a device for non-invasive digital palpation “MyotonPRO” (Myoton AS, Estonia). The principle of determining muscle tone parameters with this device is based on the functional muscle model proposed by Vine in 1990 [27]. In addition to determining the muscle tone, the instrument provides information on biomechanical and viscoelastic properties of skeletal muscle [26].

The available theoretical data [26, 27] about informative values of biomechanical and viscoelastic properties of the muscle during fatigue are confirmed by experimental research on the properties of muscles after physical exertion in athletes [4, 5, 7–10, 12, 13, 21]. A minimum of 9 publications with results on the reliability of myotonometry with “MyotonPRO” were produced in the last year [2, 6, 8, 11, 18, 23–25, 28]. At the same time, despite the fact that number of such works is increasing and number and profile of specialists using myotonometry are increasing, it has not yet been proven that this method can be used to diagnose muscle fatigue at local loads.

The aim of this study is to determine changes in tone, biomechanical and viscoelastic characteristics of skeletal muscles in local muscle fatigue.

MATERIALS AND METHODS

The study involved 13 healthy volunteers without musculoskeletal disorders, 6 men and 7 women with the average age of 32.5 ± 10.6 years.

Each volunteer was asked to perform two series of exercises that caused local muscle fatigue. The exercises were performed with a hand grip (resistance 20 kg): the first series was performed up to the moment of subjective fatigue (“fatigue”), the second series- up to refusal to continue work, associated with overwork (“overstrain”). The exercise was performed with the right hand (Fig. 1). The main limiting factor of the exercise was the development of muscle fatigue. The number and rate of hand movements were individual and were not recorded. In order to objectively confirm the muscle fatigue, dynamometric testing was performed at each stage of the study according to accepted physiology standards [14, 22].

Fig. 1. Performing hand grip compression exercises.
The points of application of myotonometry are marked

A complex of psychophysiological testing “Neurosoft” (Ivanovo, Russia) was used for conducting dynamometer measurements (a range of 0–100 kg, precision of measurements 0.05 kg). Before the exercise the maximum force of the right hand and a strain holding time (at least 70% of maximum force) was recorded (Fig. 2).

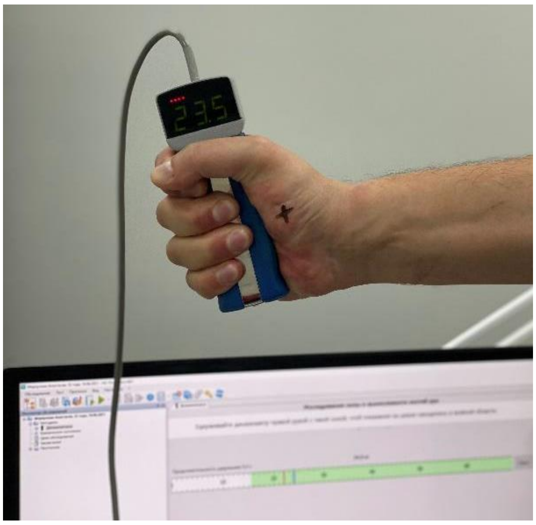

Fig. 2. Measuring the endurance of a right hand. Hand compression force is displayed in the background. Testing ends when indicators are released out of green line

A device for non-invasive digital palpation “MyotonPRO” was used for carrying out myotonometric measurements. This device allows a recording of 5 parameters [15]:

- natural oscillation frequency (*F*) (Hz) characterizing the state of intrinsic tension of the muscle, muscle tone;
- dynamic stiffness (*S*) (N/m) is the biomechanical property that characterizes the tissue's ability to resist a force of deformation;
- logarithmic decrement (*D*) of a natural oscillation indicates the elasticity of tissue being measured, as it corresponds to the dissipation of mechanical energy in the tissue during a damped oscillation;
- the ratio of the mechanical stress relaxation time and the time to cause maximum deformation (*C*), characterizing creep (Deborah number);
- mechanical stress relaxation time (*R*) (ms), is the time taken for the tissue that has been deformed to return to its initial shape after removal of the force of deformation.

Measurements were performed on the cubital and radial flexors of the carpus, and on the abductor thumb muscle. Myotonometry was performed in the position of a volunteer sitting, his right hand was angled in the cubital joint and was on the surface of the table in a relaxed state. The points of device application were selected in the muscle belly according to the method recommended by the device`s constructor [15]. It should be noted that it is difficult to measure muscles with a long belly without a clearly defined peak when choosing where to apply the instrument to the muscle. Therefore, in order to investigate the influence of the instrument’s location on results, the myotnometric parameters of the cubital flexor of the carpus were measured at several points according to the longitudinal arrangement of the muscle fibres:

– central - located in the intended centre of the belly;
– proximal, positioned 2 cm proximal to the central;
– distal, distantly located by 2 cm from the central (Fig. 3).

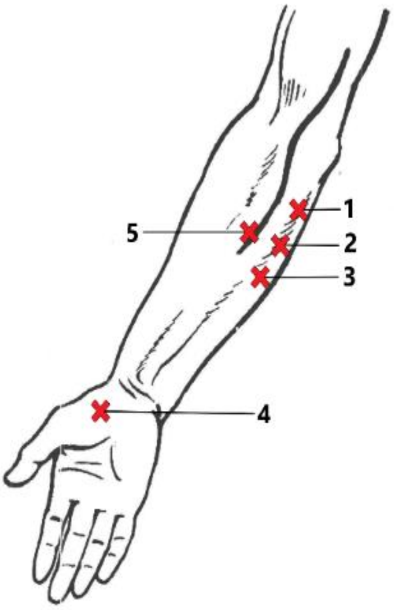

Fig. 3. Schematic representation of the location of the points at which myotonometry was conducted: 1 – proximal point in the projection of the cubital flexor of carpus; 2 – central point in the projection of the cubital flexor of the carpus; 3 – distal point in the projection of the cubital flexor of the carpus; 4 – the point in the projection of the abductor thumb muscle; 5 – the point in the projection of the radial flexor of the carpus

The tests were conducted in the following order: before the start of power exercises (test 0, background), after the «fatigue» load (test 1) and after the «overstrain» (test 2, control) (Fig. 4).

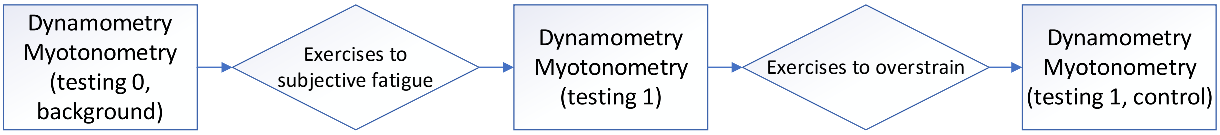

Fig. 4. Design of the study

The resulting experimental data were subjected to statistical analysis. The normal distribution of the data was evaluated using the Shapiro–Wilk test. All data had a normal distribution, which allowed the use of parametric methods of statistical analysis. The task was to determine the differences between the two specific groups, so the data obtained in the various tests were subjected to a pairwise analysis using a pair of T-criteria. The differences in the values between three measurement points obtained by myotonometry of the cubital flexor were evaluated by means of a one-way *ANOVA*. In addition, correlation analysis of force and myotonometry data using the Spearman criterion was performed. The significance criterion was set as $p < 0.05$. A description of the results was done by means of averages and standard deviations.

RESULTS

The analysis of data from dynamometry revealed a statistically significant decrease in the maximum force of the right hand after the first series of exercises of 19.8 % and after the second series of exercises of 34.5 % (Table 1). In addition, there has been a statistically significant decrease in strain holding time of 30.4 % after the «overstrain» exercise compared to the figures obtained after the "fatigue".

Table 1

Dynamometry dynamics, $M \pm SD$, $n = 13$

Indicator	Testing			*p*-value		
	0	1	2	(0-1)	(1-2)	(0-2)
Maximum force of the right hand	36.9 ± 12.4	29.6 ± 10.3	24.2 ± 7.9	< 0.001	< 0.001	< 0.001
Strain holding time, sec	10.7 ± 5.2	11.5 ± 6.4	8.0 ± 5.2	0.454	0.024	0.133

Notes: *n* – number of volunteers; 0 – background testing; 1 – testing after the “fatigue”; 2 – testing after the “overstrain”.

The results of myotonometry are presented in Table 2.

The analysis of the data showed no change in the characteristics of the abductor thumb muscle. In our opinion this is due to the fact that this muscle did not actively participate in the exercise (Fig. 1).

However, statistically significant differences between all radial and cubital flexor of the carpus properties was recorded in different tests. The largest number of changes (10 out of 12) was found for relaxation time (*R*) and creep characteristic (*C*), and the smallest (5 out of 12) was found for logarithmic decrement (*D*).

Since the most statistically changes were found in comparison with background testing, it can be concluded that the exercise performed has a significant impact on the initial state of the measured muscles.

Table 2

Myotonometry dynamics, *M* ± *SD*, *n* = 13

Muscle	Testing			*p*-value		
	0	1	2	(0-1)	(1-2)	(0-2)
			F, Hz			
Radial flexor of the carpus	16.4 ± 1.2	17.1 ± 1.8	17.2 ± 1.8	0.030	0.663	0.015
Cubital flexor of the carpus, point 1	14.8 ± 1.4	15.4 ± 1.4	15.8 ± 1.7	0.008	0.081	< 0.001
Cubital flexor of the carpus, point 2	14.8 ± 1.3	15.7 ± 1.4	16.1 ± 1.9	<0.001	0.057	< 0.001
Cubital flexor of the carpus, point 3	14.8 ± 1.3	15.7 ± 1.2	16.3 ± 1.6	0.002	0.005	< 0.001
Abductor thumb muscle	18.3 ± 1.7	18.1 ± 1.3	18.0 ± 1.4	0.599	0.447	0.393
			S, N/m			
Radial flexor of the carpus	290.9 ± 35.7	312.9 ± 49.4	322.0 ± 55.2	0.017	0.238	0.004
Cubital flexor of the carpus, point 1	254.5 ± 37.5	266.1 ± 35.9	276.4 ± 42.0	0.119	0.146	0.032
Cubital flexor of the carpus, point 2	252.8 ± 33.9	274.8 ± 37.5	284.7 ± 48.8	<0.001	0.156	0.007
Cubital flexor of the carpus, point 3	260.6 ± 31.1	275.1 ± 33.5	292.8 ± 39.8	0.019	0.007	0.005
Abductor thumb muscle	305.7 ± 43.8	294.4 ± 31.3	293.4 ± 32.8	0.102	0.860	0.056
			D			
Radial flexor of the carpus	0.98 ± 0.09	0.94 ± 0.10	0.93 ± 0.09	0.106	0.228	0.024
Cubital flexor of the carpus, point 1	0.91 ± 0.14	0.91 ± 0.12	0.91 ± 0.16	0.948	0.905	0.896
Cubital flexor of the carpus, point 2	0.99 ± 0.15	0.94 ± 0.14	0.92 ± 0.16	0.033	0.404	0.033
Cubital flexor of the carpus, point 3	1.10 ± 0.20	0.99 ± 0.13	0.96 ± 0.14	0.012	0.106	0.008
Abductor thumb muscle	1.50 ± 0.14	1.51 ± 0.21	1.48 ± 0.22	0.936	0.479	0.590
			C			
Radial flexor of the carpus	0.98 ± 0.07	0.93 ± 0.10	0.91 ± 0.10	0.004	0.234	< 0.001
Cubital flexor of the carpus, point 1	1.16 ± 0.13	1.09 ± 0.14	1.03 ± 0.12	<0.001	0.003	< 0.001
Cubital flexor of the carpus, point 2	1.20 ± 0.13	1.09 ± 0.15	1.05 ± 0.14	<0.001	0.122	< 0.001
Cubital flexor of the carpus, point 3	1.20 ± 0.14	1.09 ± 0.15	1.03 ± 0.14	<0.001	0.006	< 0.001
Abductor thumb muscle	0.97 ± 0.10	0.98 ± 0.08	0.98 ± 0.09	0.495	0.312	0.721

Continuation of Table 2

Muscle	Testing			*p*-value		
	0	1	2	(0-1)	(1-2)	(0-2)
R, ms						
Radial flexor of the carpus	16.6 ± 1.4	15.7 ± 1.9	15.3 ± 1.9	0.005	0.197	< 0.001
Cubital flexor of the carpus, point 1	19.4 ± 2.8	18.4 ± 2.6	17.5 ± 2.3	0.061	0.010	0.005
Cubital flexor of the carpus, point 2	20.3 ± 2.3	18.4 ± 2.6	17.5 ± 2.7	<0.001	0.018	< 0.001
Cubital flexor of the carpus, point 3	20.1 ± 2.4	18.3 ± 2.6	17.3 ± 2.6	0.001	0.007	< 0.001
Abductor thumb muscle	16.0 ± 1.8	16.3 ± 1.5	16.3 ± 1.4	0.307	0.980	0.331

Note: *n* – number of volunteers; 0 – background testing; 1 – testing after “fatigue”; 2 – testing after “overstrain”; *F* – natural oscillation frequency, characterizing muscle tone; *S* – dynamic stiffness; *D* – logarithmic decrement; *C* – the ratio of the mechanical stress relaxation time and the time to cause maximum deformation, characterizing creep (Deborah number); *R* – mechanical stress relaxation time [15].

The results of one-way *ANOVA* to compare values obtained at different points of the cubital flexor of the carpus measurement are presented in Table 3.

Table 3

Differences between three points of cubital flexor of the carpus, *M* ± *SD*, *n* = 13

Testing	Parameter	Point 1	Point 2	Point 3	*p*-value
Background	*F*, Hz	14.8 ± 1.4	14.8 ± 1.3	14.8 ± 1.3	0.9995
	S, N/m	254.5 ± 37.5	252.8 ± 33.9	260.6 ± 31.1	0.8289
	D	0.91 ± 0.14	0.99 ± 0.15	1.10 ± 0.20	0.0184
	C	1.16 ± 0.13	1.20 ± 0.13	1.20 ± 0.14	0.6687
	R, ms	19.4 ± 2.8	20.3 ± 2.3	20.1 ± 2.4	0.6429
After “fatigue”	*F*, Hz	15.4 ± 1.4	15.7 ± 1.4	15.7 ± 1.2	0.8139
	S, N/m	266.1 ± 35.9	274.8 ± 37.5	275.1 ± 33.5	0.7658
	D	0.91 ± 0.12	0.94 ± 0.14	0.99 ± 0.13	0.2869
	C	1.09 ± 0.14	1.09 ± 0.15	1.09 ± 0.15	0.9941
	R, ms	18.4 ± 2.6	18.4 ± 2.6	18.3 ± 2.6	0.9943
After “overstrain”	*F*, Hz	15.8 ± 1.7	16.1 ± 1.9	16.3 ± 1.6	0.7628
	S, N/m	276.4 ± 42.0	284.7 ± 48.8	292.8 ± 39.8	0.6345
	D	0.91 ± 0.16	0.92 ± 0.16	0.96 ± 0.14	0.6929
	C	1.03 ± 0.12	1.05 ± 0.14	1.03 ± 0.14	0.9236
	R, ms	17.5 ± 2.3	17.5 ± 2.7	17.3 ± 2.6	0.9706

Note: Point 1 – proximal; point 2 – central; point 3 – distal (Fig. 3); *F* – natural oscillation frequency, characterizing muscle tone; *S* – dynamic stiffness; *D* – logarithmic decrement; *C* – the ratio of the mechanical stress relaxation time and the time to cause maximum deformation, characterizing creep (Deborah number); *R* – mechanical stress relaxation time [15].

The difference was only found in logarithmic decrement in background testing, other indicators were equal in all points.

Correlation analysis between maximum hand force and myotonometry has shown a strong positive correlation between the tone (*F*) of the radial flexor of the carpus and the force of the right hand in the background (r = 0.8, p = 0.003) and control (r = 0.7, p = 0.015) testing. An average moderate positive correlation was also found between maximum right-hand force and dynamic stiffness (*S*) of the same muscle in background (r = 0.6, p = 0.047) and control (r = 0.6, p = 0.040) testing. In other cases, there was no correlation between force and biomechanical properties muscle.

CONCLUSIONS

Since no statistical changes in the biomechanical properties of the abductor thumb muscle were found during the experiment, it can be argued that changes in these characteristics can only be observed in active muscles, as a result of local muscle fatigue.

The statistically significant difference between most indicators of active muscles in background and control testings suggests that myotonometry can be used to identify muscle fatigue when local muscle loads are performing. The fact that most changes in myotonometry were detected between background testing and testing “fatigue” indicates that biomechanical and viscoelastic properties of muscles change already during subjective fatigue.

Viscoelastic characteristics of the muscle showed the greatest sensitivity to physical stress, but more research is needed, for a correct physiological interpretation of changes of these properties. Therefore, changes in muscle tone and dynamic stiffness are more useful as indicators of local muscle fatigue.

The unavailability of statistical differences between the three points of the ulna flex of the wrist indicates that it is possible to conduct myotnometric measurements at the region of the muscle belly in question, not exceeding 2 cm in the longitudinal direction of the muscle fibres.

Although there is some correlation between hand force, muscle tone and dynamic stiffness of radial flexor of the carpus it is not clear that the relation between muscle force and biomechanical properties is universal.

The statistically significant changes in biomechanical and viscoelastic muscle properties found in this study can be seen as signs of developed local muscle fatigue and a myotnometric method can be used to identify it. Changes in myotnometric indicators of active muscles can be detected already after subjective feeling of fatigue. At the same time, local muscle fatigue does not affect the change of biomechanical and viscoelastic properties of non-active muscles.

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