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EVALUATION OF THE EFFECTIVENESS OF AN UNLOADING ORTHOSIS OF THE KNEE JOINT BASED ON INDIRECT INDICATORS AND SURFACE ELECTROMYOGRAPHY DATA

С. Ковбан, П. Вербицька, П. Прокопович, І. Сидоренко, І. Прокопович. **Оцінка ефективності розвантажувального ортеза колінного суглоба за непрямими показниками та даними поверхневої електроміографії.** Одним із актуальних завдань у процесі створення біомеханічних пристроїв, а саме розвантажувальних ортезів, є визначення їх ефективності. У роботі наведено результати дослідження втоми м’язів синергістів кульшового суглоба при ізотонічних скороченнях при виконанні присідань як з використанням розвантажувального ортеза для колінного суглоба, так і без нього. Крім визначення непрямих показників, що визначають периферичну втому м’язів, а саме кількості виконаних присідань та швидкості їх виконання, в роботі використовувався ще один ефективний метод дослідження прогресування м’язової втоми – метод поверхневої електроміографії. Отримані в польових умовах дані як за непрямими показниками, так і за записами поверхневої електроміографії обробляли шляхом розрахунку середньоквадратичного значення, що дало змогу оцінити ефективність розвантажувального ортеза колінного суглоба за допомогою регресійно-статистичної моделі. Критерієм оцінки ефективності обрано коефіцієнт абсолютного нахилу лінійної регресії, побудованої на основі експериментальних даних. Дані поверхневої електроміографії записували за допомогою електроміографічного модуля зчитування iiitech та оброблені за допомогою пакета програмного забезпечення Spike Recorder, що постачається разом із модулем. Статистичну обробку результатів дослідження та розрахунки коефіцієнтів лінійної регресії проводили за допомогою пакета MS Excel. Аналіз отриманих результатів свідчить про ефективність використання залученого в експерименти ортеза, використання якого дає змогу відстрочити зниження продуктивності активних м’язових волокон і призводить до уповільнення настання периферичної м’язової втоми.
Ключові слова: наколінник, втома периферичних м’язів, поверхнева електроміографія, лінійна регресія, оцінка ефективності

S. Kovban, P. Verbytska, P. Prokopovych, I. Sydorenko, I. Prokopovich. **Evaluation of the effectiveness of an unloading orthosis of the knee joint based on indirect indicators and surface electromyography data.** One of the urgent tasks in the process of creating biomechanical devices, namely unloading orthoses, is to determine their effectiveness. The paper presents the results of a study of muscle fatigue of the hip synergists during isotonic contractions when performing squats both with and without the use of a knee joint unloading orthosis. In addition to determining indirect indicators that determine peripheral muscle fatigue, namely the number of squats performed and the speed of their implementation, another effective method for studying the progression of muscle fatigue, the method of surface electromyography, was used in the work. The data obtained in field experiments for both indirect indicators and surface electromyography recordings were processed by calculating the root mean square value, which made it possible to evaluate the effectiveness of the knee joint unloading orthosis using a regression statistical model. The coefficient of absolute slope of the linear regression, built on the basis of experimental data, was chosen as the criterion for evaluating the effectiveness. Surface electromyography data were recorded using the iiitech electromyographic reading module and processed using the Spike Recorder software package supplied with the module. Statistical processing of research results and calculations of linear regression coefficients were carried out using the MS Excel package. The analysis of the results obtained indicates the effectiveness of the use of the orthosis involved in the experiments, the use of which makes it possible to delay the decrease in the production strength of active muscle fibers and leads to a slower onset of peripheral muscle fatigue.
Keywords: knee brace, peripheral muscle fatigue, surface electromyography, linear regression, performance evaluation

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1. Introduction

Long-term impact of an external system of forces on the body of a person performing high-speed monotonous movements while solving professional problems is often associated with various soft tissue disorders. One of these disorders is considered peripheral muscle fatigue. It is believed that this variant of muscular-physiological fatigue is most often found in people who are engaged in physical labor. It occurs when certain muscle groups lack the energy to maintain their activity due to various reasons, such as a new order of contraction when changing trajectories and amplitude of movement, malnutrition, etc. It should be especially answered that the onset of peripheral muscle fatigue, along with the accompanying dullness of attention, are one of the main causes of injuries. In addition, peripheral muscle fatigue is an objective sign of a person's inability to maintain a certain level of physical effort and, as a result, indicates a decrease in the productivity of his work.

To reduce peripheral muscle fatigue, all kinds of unloading orthoses have been developed and are being developed, which are elastic mechanical systems built on the basis of both metallic and non-metallic elastic elements of various types. In turn, the presence of a sufficiently large number of designs of such devices requires methods for determining the effectiveness of their application. It will allow us to proceed to the evaluation of the design solutions obtained in these developments according to fairly simple and understandable economic or technical criteria, built on certain coefficients or ratios. For example, "efficiency – cost" or "efficiency – durability", etc.

2. Literature analysis

The problem of determining and predicting the time of onset of fatigue, after which it is no longer possible to continue to perform physical activity with the same performance, has been considered by many authors. Research in this area is related to sports and is an integral part of sports medicine. However, it is not always possible to apply the results of these studies and methods for determining fatigue to workers engaged in physical labor due to the specifics of movements in sports and in the technological process. Nevertheless, there are works devoted to the study of fatigue of manual workers.

As a criterion for determining the fatigue of a worker, his productivity was adopted [1, 2]. Performance is understood as the number of operational movements performed in the technological cycle during a given technological cycle, in other words, we are talking about the speed of execution of movements. In our opinion, this criterion is based only on indirect indicators of fatigue, such as the number of movements and the time of their execution, the relationship between which may not reflect the real situation with the occurrence of fatigue. So, in addition to peripheral fatigue, fatigue of the central nervous system ("mental" fatigue) is distinguished, in which a change in the number of movements and the time of their implementation are primarily associated with the psychological state of a person and his motivation. In addition, a number of rather rare cases are described in the literature, when a change in the number of movements and the time of their execution are associated with neuromuscular fatigue ("nervous" fatigue). This kind of fatigue is due to the nerves not being activated enough to keep the muscle moving. Insufficient activation of the nerves is the result of various pathologies or occurs with extreme levels of muscle activity and its intensity. Nevertheless, the criterion in the form of performance, although not very accurate given the above, is often used in studies to determine the physical activity of muscles due to the simplicity of its definition.

To date, the most optimal technique for studying changes in muscle strength and the phenomenon of fatigue, due to non-invasiveness and ease of use, is surface electromyography (sEMG) [2, 3]. sEMG signal acquisition is a medical technique used to record and analyze the electrical activity produced by muscles. EMG systems detect the electrical potential generated by muscles when they are neurologically activated. The EMG signal can be used to obtain certain information related to muscle activity, such as identifying medical abnormalities, levels of muscle activation, or analyzing human biomechanics [3]. The most common method is surface sEMG, in which the change in electrical signals (potential difference) over time, which corresponds to the functioning of the muscles, is read using two or three electrodes located on the outer surface of the skin above the muscle. At the same time, the main indicator is the amplitude of the sEMG signals, which is stochastic (random) in nature and therefore requires appropriate processing for interpretation and use. In some studies, it was found that the amplitude of sEMG signals depends on the applied force, since the greater the force, the more action potentials will be stimulated, which will lead to a contraction of more muscle fibers [4, 5]. The ability to correlate the amplitude of the EMG signal with muscle strength, obtained as a result of the use of electromyography, made it possible in a number of studies to establish parameters characterizing muscle activity. The experimental determination of a certain threshold and the time of exceeding this threshold by the amplitude of the EMG signal in some studies is interpreted by the authors as the duration of muscle activity [4, 5, 6].

As a rule, EMG systems are equipped with software that implements various methods for processing the amplitude and frequency of EMG signals to form the most visual representation of them in relation to time. To process data in the form of amplitudes of EMG signals, the calculation of their root mean square (RMS) is most often used. It has been established that the RMS of the sEMG signal amplitude gradually increases over time in dynamics during continuous isotonic contractions (when the flexors relax and the extensors contract and vice versa). At the same time, the RMS of the sEMG signal amplitude gradually decreases in statics with a single isotonic contraction (the flexors are relaxed and the extensors are contracted or vice versa). At the same time, changes in RMS are expressed and evaluated using a statistical curve fitting model, while determining the controlled parameter in the form of an absolute slope angle [7, 8, 9].

To obtain meaningful frequency information in the frequency analysis of EMG signals, the fast Fourier transform technique is most commonly used. In the works of some researchers, it is indicated that this method is not ideal; nevertheless, it is convenient when fast data processing is required [10, 11, 12].

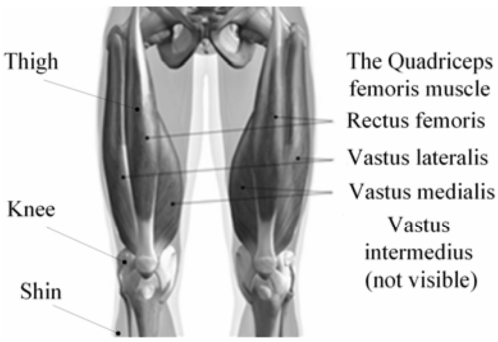
Summarizing the analysis of the literature it should be recognized that the authors mainly consider the problems associated with determining and predicting the time of onset of fatigue, after which it becomes impossible to maintain physical activity with the same performance. However, the issue of evaluating the effectiveness of the use of unloading orthoses in the literature practically does not occur, although the number of designs of these devices is constantly increasing. Therefore, scientific research related to the definition of evaluation criteria and the development of methods for evaluating the effectiveness of unloading orthoses is an urgent scientific and applied task.

Purpose of research

The purpose of the research is to identify the criterion and its interpretation as an indicator of the effectiveness of orthotics of the knee joint with the help of unloading orthoses.

3. Research method

To evaluate the effectiveness of the use of an unloading orthosis, a full-scale experiment was prepared and carried out with subsequent processing of its results. In the experiment, synergist muscle fatigue was modeled when performing a basic movement (BM) not burdened by an external load. Squatting is taken as BM, which includes two phases of movement: squatting, returning to the starting position. The considered BM basically corresponds to isotonic contractions of the quadriceps femoris muscle (quadriceps femoris) (Fig. 1, *a*).



a

b

Fig. 1. Experimental application of an unloading orthosis of the knee joint: location and structure of the quadriceps femoris muscle (quadriceps femoris) (*a*); general view of the applied unloading orthosis (*b*)

Muscle fatigue was modeled in both the free state of the lower extremities and when they were orthoticized with a knee joint unloading orthosis. Orthotics was performed using the Power Knee Defenders unloading knee joint orthosis manufactured by Joerex, which is widely used on the medical market (Fig. 1, *b*). The applied orthosis consists of upper *1* and lower *2* lodgments for its placement on the thigh and lower leg on the back of the knee. Angular movement between the lodgements, which determines knee flexion, is realized by fixing them relative to each other by means of an axis *3* that determines the orthosis flexion axis. Torsion springs *4* are coaxially arranged along the orthosis flexion axis, one end of which is in contact with lodgement *1* and the other with lodgement *2*. Belts *5* are

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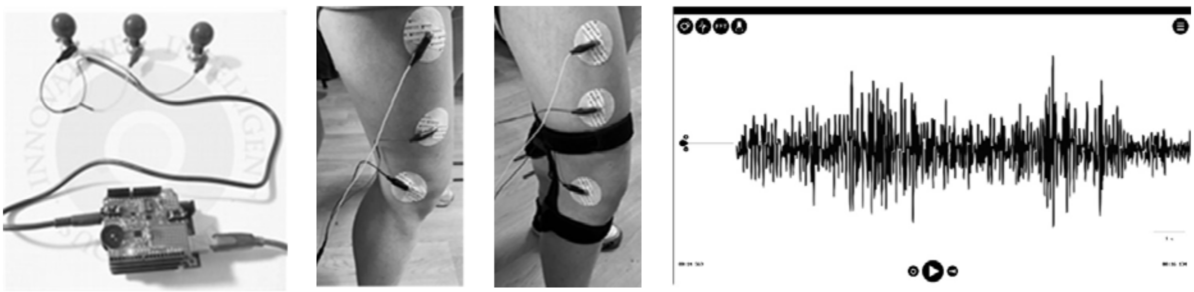
designed to fix lodgements on the human body. It is the presence of an elastic system consisting of torsion springs *4* that determines the presence of an elastic force, which, according to the developers, performs the function of unloading the knee joint and reduces the peripheral fatigue of the muscle group that ensures its flexion-extension.

In order to obtain a database for research, the program of the experiment included the execution of the BM series by the same subject for five days. At the same time, on the first, third and fifth days of the experiment, the corresponding series of BM was performed without orthotics, and on the second and fourth - with the use of orthoses. Before the start of the series, a warm-up was carried out (in the amount of five basic movements), and the performance of the series itself was accompanied by verbal rewards. A series of basic movements was carried out in a free mode without maintaining a certain pace and lasted until the subject, according to subjective sensations, did not report fatigue.

To collect experimental data, the method of surface bipolar electromyography (EMG) was used. For this purpose, a module for reading electromographic indicators from iiitech was used (Fig. 2, *a*). This module captures signals from three electrodes, which were fixed over the quadriceps femoris muscle in places corresponding to Rectus femoris, Vastus lateralis, Vastus medialis, both when performing BM series without orthotics (Fig. 2, *b*) and during orthotics (Fig. 2, *c*). The Spike Recorder software supplied with the module made it possible to visualize the electromyographic results of the basic exercise (Fig. 2, *d*).



a *b* *c* *d*

Fig.2. Surface electromyography in the experiment: module for reading electromyographic indicators iiitech (*a*); electrodes on the leg without an orthosis (*b*); electrodes on the leg with an orthosis (c); electromyogram of one basic movement in Spike Recorder (*d*)

Visualization and recording of signals in the presented software made it possible to determine the following information components: the number of BMs in a series, the series time, BM time, the amplitude of electrical impulses corresponding to BM, the frequency of electrical impulses T (Hz) in BM, the number of electrical impulses N corresponding to BM, root mean square pulse amplitude value RMS (mV).

The presence of the first two of the presented information components made it possible to calculate and analyze an indirect indicator of muscle fatigue in the form of the performance of the P_i series, which for each i-series was calculated as the ratio of the number of basic movements performed in the series (e_{bmi}) to the time (t_i) spent on the series, followed by its averaging P_a taking into account the number of series j:

$$P_i = \frac{e_{\mathrm{bmi}}}{t_i}, \quad P_a = \frac{\sum_{i=1}^{j} P_i}{j}. \tag{1}$$

In electromyographic studies, it was taken into account that the amplitude of the EMG signal is sign-variable in time, therefore, its root-mean-square value was used:

$$A_{\mathrm{RMS}} = \sqrt{\frac{\sum_{j=1}^{N} A_j^2}{N}}. \tag{2}$$

The change in the mean square value of the EMG amplitude at the beginning of a certain time interval and its end ($A_{(\mathrm{B})\mathrm{RMS}}$ and $A_{(\mathrm{E})\mathrm{RMS}}$) related to its duration, determined by some initial and final measurement time (t_{B} and t_{E}), which makes it possible to obtain the value:

$$V_{\mathrm{F}}=\frac{A_{(\mathrm{E})\mathrm{RMS}}-A_{(\mathrm{B})\mathrm{RMS}}}{t_{(\mathrm{E})}-t_{(\mathrm{B})}}, \tag{3}$$

which many researchers interpret as a criterion that determines peripheral muscle fatigue.

This criterion is used in the statistical model of “critical fatigue”, which is characterized by a zero value of the amplitude of the electromyographic signal:

$$A_{\mathrm{CF}}=V_{\mathrm{F}}t+b=0, \tag{4}$$

where V_{F} is the coefficient of linear regression, which determines the slope of the linear dependence (4); t is the time of the entire process of fatigue development; b is the value that determines the intersection of the considered linear dependence with the A_{CF} axis.

Thus, given that there is no clear relationship between the specified criterion and the psychological state of the subject, this criterion is proposed to be used as an alternative to the announced indirect indicator in the form of performance for assessing peripheral muscle fatigue and the effectiveness of orthotics. Also, using a similar indicator, in the form of a linear regression coefficient, it is proposed to estimate the duration of the execution of one basic movement during a series, which will also indirectly clarify the effectiveness of orthotics. The corresponding coefficients of linear regressions were calculated using the MS Excel package.

4. Results

When determining an indirect indicator in the form of an average performance P_a, the databases obtained during electromographic studies were processed by selecting the relevant information components and their subsequent processing (Table 1).

Table 1

Information components and the definition of an indirect criterion in the form of average performance

Types of indicators	Indications by day of experiment				
	Day 1	Dey 3	Day 5	Day 2	Day 4
Orthotics	Without orthosis			With orthosis	
Series time, sec	86	87	101	164	191
Number of BMs in a series, pcs.	66	55	67	106	125
Performance by series P_i, BM/sec	0.77	0.63	0.66	0.65	0.65
Average performance P_a, BM/sec	0.69			0.65	

Focusing on the average performance, determined according to expressions (1), we can conclude that orthotics are ineffective and even negative, since the use of orthoses led to a decrease in productivity by 6 %. However, the graphical interpretation of the results of the obtained data demonstrates a fairly clear picture of the fact that this is not entirely true. First, it should be noted that the performance in the Pi series is unstable (Fig. 3, *a*). Moreover, in the absence of orthoses, the performance by series of the experiment tends to decrease (square markers on the presented graph), and in the case of orthotics, it has a slight increase (triangular markers on the presented graph). This is the first inconsistency of the applied proxy indicator.

In a more detailed study of the change in the time of performing one basic movement during the series, it was found that on days 2 and 3, where the orthosis was used in the experiment, this time decreases by the end of the series (Fig. 3, *c* and *f*). And on the days when the orthosis was not used in the experiment (4 and 5, except for the 1st), the time for performing BM by the end of the series increases (Fig. 3, *b*, *d*, and *f*). A regression analysis of the time t_{BM} of performing one movement during a series of N basic movements, carried out for series *j*, where the data obtained were interpreted by a linear relationship of the form:

$$t_{\mathrm{BM}j}=K_jN_j+b, \tag{5}$$

made it possible to establish that the average coefficient of linear regression of the obtained linear dependencies:

$$K_a=\frac{\sum_{j=1}K_j}{j}, \tag{6}$$

positive, in the absence of an orthosis and negative – in the case of its use (Table 2).

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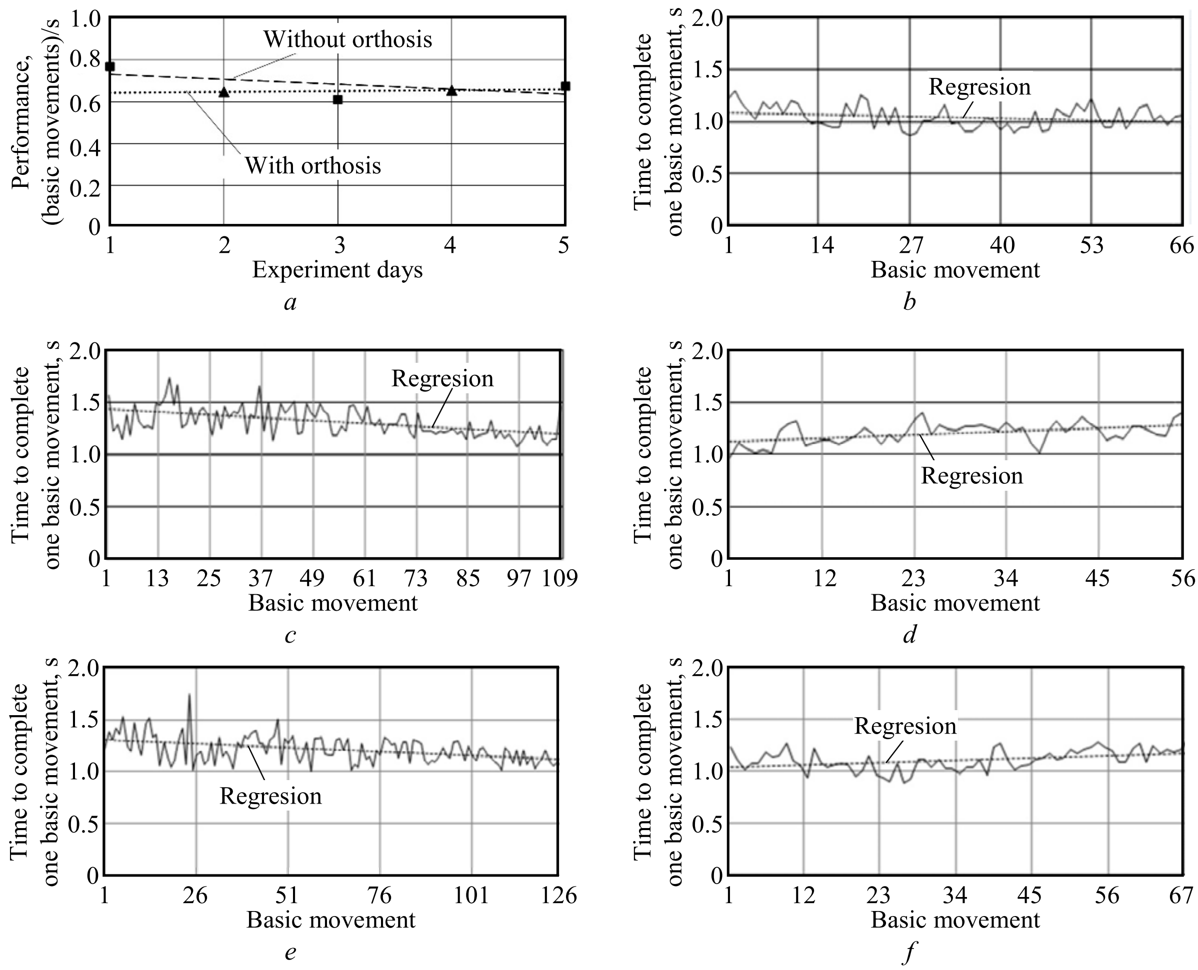

Fig. 3. Definition of an indirect indicator in the form of productivity: productivity by days of the experiment (*a*); change in the time of performing one basic exercise in 1 day without an orthosis (*b*); change in the time of performing one basic exercise within 2 days with an orthosis (*c*); change in the time of performing one basic exercise for 3 days without an orthosis (*d*); change in the time of performing one basic exercise within 4 days with an orthosis (*e*); change in the time of performing one basic exercise within 5 days without an orthosis (*f*)

Table 2

Information components and the definition of an indirect criterion in the form of average performance

Experiment Day (Series)	№	Linear Regression	Coefficient linear regression K_i	Average linear regression coefficient K_a	Notes
	1	$T_1 = -0.0014N_1 + 1.0938$	–0.0014	0.0013	Movements slow down
	3	$T_3 = 0.0032N_3 + 1.1142$	0.0032		
	5	$T_5 = 0.0021N_5 + 1.0364$	0.0021		
	2	$T_2 = -0.0023N_2 + 1.4323$	–0.0023	–0.00305	Movements are accelerating
	4	$T_4 = -0.0015N_4 + 1.3067$	–0.0015		

The revealed contradictions, when using the indirect indicator under consideration, allow us to somewhat doubt the assessment of the effectiveness of its application. Separately, it should be noted the high productivity recorded in 1 day (series) of the experiment. In our opinion, this may be due both to the psychological state of the subject, subject to verbal rewards and the desire to perform the maximum number of basic movements, and to the absence of pain, since the accumulation of lactic acid in the muscles has not yet occurred.

Processing the results of electromyographic studies made it possible to establish a predictable increase in RMS during the performance of basic exercises in all series, which is theoretically associated with the recruitment of new motor units to compensate for impaired muscle capacity for productive strength (Fig. 4).

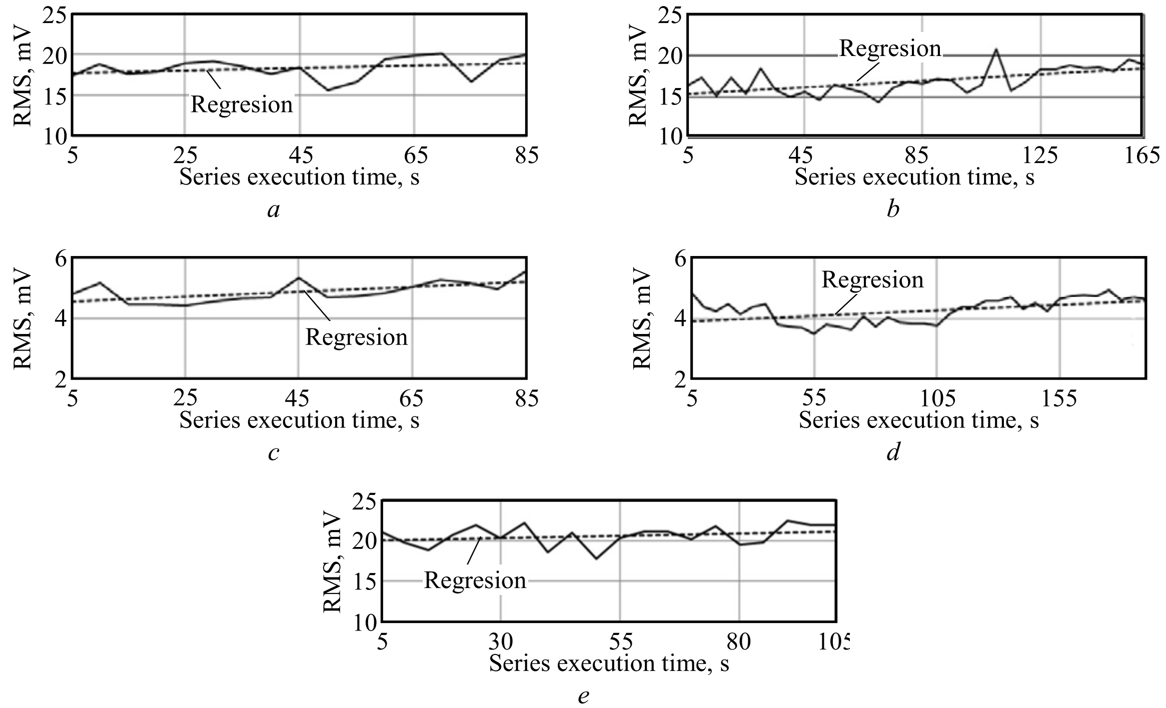

Fig. 4. Electromyographic parameters of the series: series 1 day without an orthosis (*a*); series 2 day with orthosis (*b*); series 3 day without orthosis (*c*); series 4 day with orthosis (*d*); series 5 day without orthosis (*e*)

The conducted regression analysis, according to expression (4), shows that the corresponding coefficients of linear regression V_{Fj}, which is nothing more than the rate of fatigue in each *j* series, are quite closely related to orthotics (Table 3).

Table 3

Regression analysis of electromyographic studies, determination of the effectiveness of orthotics

	№	Linear regression of RMS values of EMG amplitudes	Fatigue rate V_{Fj}	Average fatigue rate V_{Fa}	Orthotic efficiency
Experiment Day (Series)	1	$RMS_1 = 0.015T_1 + 17.635$	0.015	0.0116	0.0116/0.0045=2.57
	3	$RMS_3 = 0.008T_3 + 4.5009$	0.008		
	5	$RMS_5 = 0.012T_5 + 19.942$	0.012		
	2	$RMS_2 = 0.002T_2 + 1.5346$	0.002	0.0045	
	4	$RMS_4 = 0.007T_4 + 7.8163$	0.007		

It was found that on the 2nd and 4th days (series) of the experiment with the use of an orthosis, the rate of fatigue was significantly lower than in the series when the orthosis was not used. It should be noted that it was in these series that both their greatest duration in time and greater number of basic movements were observed, which indirectly confirms the slowdown in the growth of peripheral fatigue (See Table 1). Thus, it can be assumed that the use of the criterion in the form of fatigue rate V_{Fj} (or its average value over several V_{Fa} series) when interpreted as the indicator "before use – after the use of the device in question", it allows to evaluate the effectiveness of orthotics, and in the case of using several devices for orthotics, to determine the most effective one.

For the experiment, it can be stated that the orthosis of the knee joint with an orthosis of the company .... is effective, since its use slowed down the recruitment of new motor units and made it possible to delay the decrease in the generated strength of active muscle fibers due to a 2.57-fold decrease in the onset of fatigue.

Conclusions

According to the results of the research, the following was established:

1. The value of an indirect indicator of efficiency, in the form of performance, is significantly affected not only by peripheral fatigue, but also by fatigue of the central nervous system, in which changes in the number of movements and the time of their execution are primarily associated with the psychological state of a person and his motivation. Therefore, the assessment of the effectiveness of orthotics using this indicator should be recognized as insufficiently accurate, and its use is possible only with a preliminary assessment.

2. The method of surface electromyography is an effective tool for evaluating orthotics, which allows you to quickly collect record and compare the necessary data on the electrical activity of muscles for further evaluation of the effectiveness of orthotics.

3. The data of electromyographic studies make it possible to identify a criterion in the form of fatigue rate V_{Fj} (or its average value over several series V_{Fa}), the value of which makes it possible to establish the relationship between the number of basic movements and the recruitment of new motor units during the generation of force by active muscle fibers.

4. Fatigue rate V_{Fj} (or its average value over several series V_{Fa}) can be used to evaluate the effectiveness of orthotics, since it determines the change in the time of onset of fatigue.

5. The results of the study showed the effectiveness of orthotics of the knee joint with cuts from the manufacturer Joerex, since the time for fatigue onset is 2.57 times lower than in the case without orthotics.

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