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MODELING OF ELECTROSTIMULATION CHARACTERISTICS TO DETERMINE THE OPTIMAL AMPLITUDE OF CURRENT STIMULI

The subject of research- *the process of human skeletal muscles electrical stimulation during medical therapy. The subject of the study is a mathematical model of electrostimulation characteristics, which links the amplitude of muscle contraction and the stimulating effect amplitude.* ***The current work develops*** *a mathematical model in the form of an analytical expression to describe the muscle contraction amplitude dependence on electrical stimulus amplitude.* ***Tasks to be solved:*** *to analyze the dependence peculiarity of muscle contraction amplitude in stimulating impulse amplitude; conduct structural and parametric identification of the model; compare the results obtained using practical data, evaluate the model accuracy; use the obtained model for analytical description with the aim of a priori determination of the optimal stimulus amplitude.* ***Methods used*** *mathematical modeling method, methods of structural and parametric identification of models, approximation methods, parametric optimization methods, mathematical analysis methods.* ***Results obtained*** *an analytical model in the form of a 5th degree polynomial is proposed, which reflects the dependence of muscle contraction amplitude in the stimulus amplitude; the degree of the polynomial is selected and the coefficients of the model are obtained using parametric optimization; a model trajectory was built and the accuracy of modeling was estimated; an equation was obtained and its possible solutions were found to determine the optimal value of the stimulus amplitude; the practical application of the research results was substantiated. The results obtained can be used in the selection of individual effects of electrical stimulation during one session, as well as with extrapolation during the entire rehabilitation process.* ***Scientific novelty:*** *an analytical description showing the dependence of skeletal muscle contraction amplitude on the electrical stimulus amplitude was obtained, which allows determining individual optimal parameters of electromyostimulation.*

Keywords: *skeletal muscles; electrical stimulation; stimulus amplitude; contraction amplitude; mathematical model; optimal parameters.*

Introduction

Muscle electrical stimulation is a therapeutic application of an electric current to enhance the motor activity of skeletal muscles, as well as smooth muscles of internal organs. Electrical stimulation is a method of physiotherapy aimed at restoring or increasing the functionality of muscle and nerve tissues after damage.

For this, exponential or rectangular currents are used in the form of single pulses or a series of pulses with pauses between them, diadynamic, sinusoidal modulated currents, rhythmic direct current, as well as other currents close to biopotential parameters of stimulated muscles or organs [1].

Such currents, causing motor excitement and muscle contraction, reflexively enhance blood and lymph circulation, as well as the whole complex of metabolic and trophic processes aimed at the energy and flexibility provision of working muscles [2, 3].

During electrical stimulation, the impulses of electric current have a sufficiently large strength and, passing through the muscle, have an stimulating effect not only on the muscle and receptor structures of this muscle, but also on the vegetative fibers located in this muscle. Fig.1 in a generalized form presents a set of processes occurring in the muscle and in the body during electrical stimulation.

The electrical current used in electrical stimulation to produce evoked muscle contractions is characterized by a large number of different parameters. Therefore, the optimal selection of parameters is a non-trivial problem. Especially considering the characteristics of each individual patient and the individual characteristics of a group or a specific individual muscle. The approach to solving this problem lies in the use of electromyography data [3-5] and mathematical modeling of the electrostimulation process [6].

It is known that each individual muscle fiber obeys the Frank-Starling law "all or none" [7, 8], that is, when the strength of stimulation is above a certain threshold level [9], a complete contraction occurs with the maximum strength for a given fiber and an increase in the strength of contraction with an increase in the strength of stimulation is impossible [10, 11].

Since the muscle consists of many fibers with different levels of sensitivity to excitation [8], the amplitude of contraction of the skeletal muscle depends on the strength of irritation and obeys a gradual law [8, 9]:

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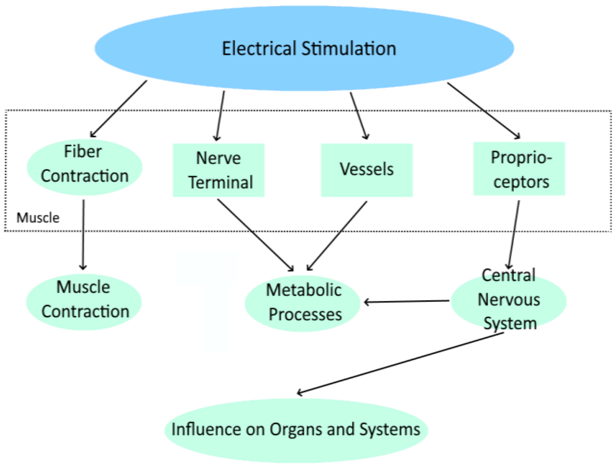

Fig. 1. Set of physiological reactions during electrical stimulation

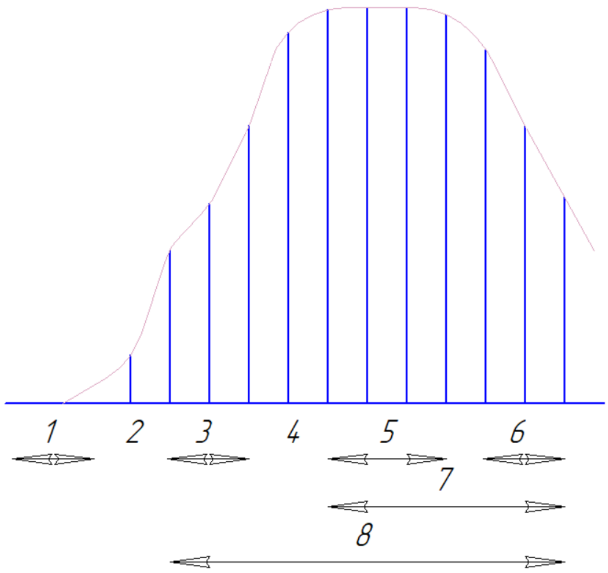

Fig. 2. Stimulation modes:
1 – subthreshold; 2 – threshold; 3 – submaximal; 4 – maximal; 5 – optimal; 6 – pessimal; 7 – supermaximal; 8 – suprathreshold

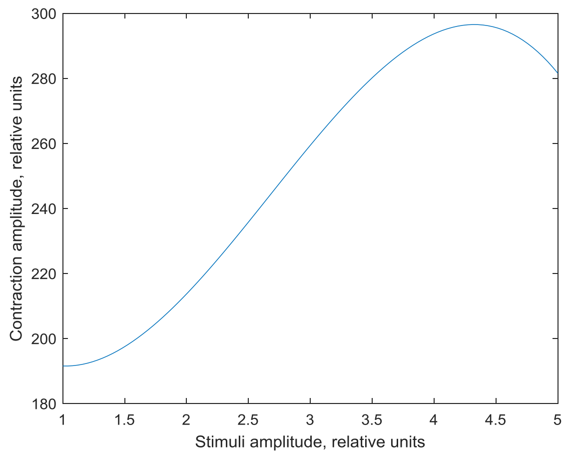

Fig. 3. Dependence of muscle contraction amplitude on electrical stimulation intensity

the greater the strength of the suprathreshold stimulus, the greater the amplitude of contraction [9-11]. The muscle does not react to subthreshold stimuli by contraction [12-14]. Under the action of threshold stimuli, the contractile response is minimal [15]. As the intensity of the stimulus increases, the muscle contraction amplitude increases since an increasing number of less excitable muscle fibers are involved in the process of excitation [16]. At maximum contraction, all muscle fibers are involved in the process of excitation and contraction [17, 18]. Therefore, a further increase in the stimulus intensity is not accompanied by an increase in the contraction amplitude [19. 20].

Thus, to manifest a specific function of muscle tissue, it is necessary that the acting stimulus has a certain strength equal to or exceeding a known critical value, called the threshold (Fig. 2). Stimuli that have a strength greater than the threshold are called suprathreshold (submaximal). When exposed to them, the magnitude of the tissue response increases to a certain limit. All stimuli that give the maximum response are called optimal. Stimuli that are larger than optimal, but elicit a smaller response than with optimal stimulation, are called pessimal [21].

Based on the foregoing, the following dependence of the muscle contraction amplitude on the stimulating impulses amplitude can be obtained (Fig. 3).

Therapeutic electrical stimulation should be accompanied by optimal parameters of stimulating impulses for each specific patient or group of stimulated muscles. This makes it necessary to simulate the electrical stimulation curve for carrying out a priori analytical calculations [2-4].

Thus, the aim of this work is to develop a mathematical model in the form of an analytical expression to describe the dependence of muscle contractions amplitude on electrical stimuli amplitude.

This study includes several stages: analysis of existing models; selection of a suitable mathematical description (approximating function) and determination of its parameters by minimizing a certain error function; obtaining an equation and its analytical solution to determine the optimal amplitude of the stimulating action; constructing a model trajectory of the modeling object and evaluating the model accuracy.

1. Analysis of existing models

Currently, there are several models of electrical stimulation. Thus, the model [22, 23] considers many biophysical processes, but it is difficult to apply it in practice.

In [24] a generalized model of muscle activity research is proposed, which is based on the synthesis of three components: electrical circuit of muscle cell replacement, biomechanical model of upper limb functioning, mathematical model of electromyographic signal formation, which allows reproducing the action potential of a single motor unit taking individual features of the human nervous and muscular system into account. This also allows analyzing the features of the process of muscle activity but does not allow using it for practical calculations.

In [25], a detailed review of the numerical models of electrical stimulation, which require the organization of special computational procedures, is carried out. Such models do not make it possible to determine in practice the optimal amplitude of stimuli for each individual patient, based on his or her individual peculiarities of electrostimulation characteristics. At the same time, in a number of cases, it is sufficient to have an estimated model of electrostimulation based on the "black box" principle. An approximating analytical expression that links the stimulus amplitude and the response amplitude can serve as such a model.

2. Research essence

The approximation problem (in its classical sense) is a representation of arbitrary complex functions f (x) (it may even be unknown in advance) by functions φ (x) that are simpler and more convenient for use in practice in such a way that the deviations of the resulting new function F (x) off(x) in some domain of definition Ω were the smallest by a certain criterion, i.e. for the function f (x), it is necessary to construct a function F (x) of the form:

$$F(x) = a_0\varphi_0(x) + a_1\varphi_1(x) + \ldots + a_n\varphi_n(x), \qquad (1)$$

so, to minimize the weighted root-mean-square error σ^2 over some interval (a, b):

$$\sigma^2 = \int_a^b r(x)\left[F(x) - f(x)\right]^2 dx, \qquad (2)$$

where $r(x)$ is given non-negative weight function.

Since the function f (x) modeled in this case is given only on a discrete set (m + 1) of points x_0, x_1, x_2, …, x_m, it is necessary to minimize the weighted root-mean-square error of the form

$$\sigma^2 = \sum_{k=0}^{m} r_k\left[F(x_k) - f(x_k)\right]^2, \qquad (3)$$

where r_k are positive weights given a priori. All r_k can be taken equal to 1.

This is easiest to do in the case when the functions $\varphi_r(x)$ are polynomials of degree r, pairwise orthogonal with weights r_k on a given set of points. I.e., when

$$\sum_{k=0}^{m} r_k\varphi_i(x_k)\varphi_j(x_k) = 0, \quad (i \neq j). \qquad (4)$$

As studies have shown [26, 27], in the considered case, the problem is greatly simplified, and polynomial functions of a certain degree can be used:

$$\varphi(x) = a_n x^n + a_{n-1}x^{n-1} + a_1 x + a_0, \qquad (5)$$

where a_i is some ratios; n is a polynomial degree. The problem then reduces to determining the required degree of n and determining the values a_i $(i = \overline{1, n+1})$

Considering the smooth nature of the modeled dependence, polynomials of degree from 3 to 6 were tested (Fig. 4). The final choice was made for a polynomial of degree n = 5, as it most accurately and simply displays the electrical stimulation curve (curve n 5) and has a derivative of the fourth degree, which is important for further theoretical calculations, i.e.

$$\varphi(x) = a_5x^5 + a_4x^4 + a_3x^3 + a_2x^2 + a_1x + a_0, \qquad (6)$$

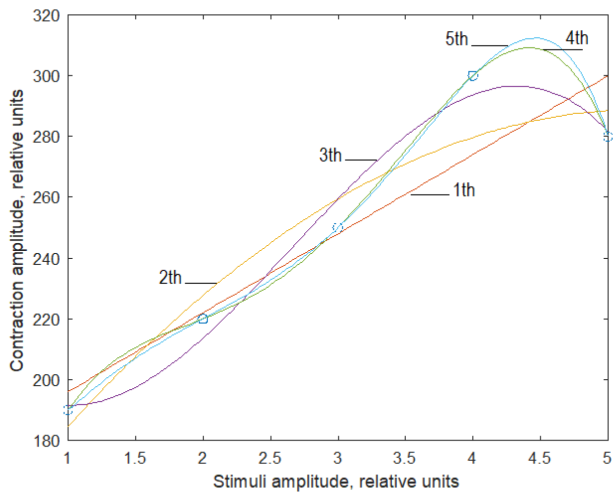

Fig. 4. To the choice of the optimal degree of the polynomial

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To determine the unknown coefficients $a_0, \ldots, a_5$, a parametric optimization procedure was implemented according to the criterion of minimizing the error function σ:

$$\sigma = \sqrt{\sum_{k=0}^{m}\left[f(x_k) - \varphi(x_k)\right]} \quad (7)$$

in the space of variable (controlled) parameters $a_i (i = \overline{0, n})$. The dimension of the space of controlled parameters equals to 6.

Various optimization methods use the calculation of the values of the objective function (error function) and/or the values of the gradients. But regardless of the method used, any can be described by the following iterative formula:

$$x^{k+1} = x^k + \alpha_k S^k, \quad (8)$$

where x^k, x^{k+1} is a vector of controlled parameters at points k and k + 1; S^k is a direction of movement from point x^k to point x^{k+1}; α_k is a numerical coefficient of the stroke size in the direction of S^k.

To find the extremum of the objective function, the method of random directions was used. In accordance with it, from the selected initial point x^0 a transition occurs to the next point x^1 with a stroke $\alpha_0 > 0$ in a random direction $S^0 = \left[S_1^0, S_2^0, S_3^0, S_4^0, S_5^0, S_6^0\right]^t$, whose components are S_i^0, normally distributed on the interval [-1, 1].

The criterion for stopping the process was the fulfillment of the condition:

$$\frac{\left|x^{k+1} - x^k\right|}{\left|x^k\right|} < E, \quad (9)$$

where E is a vector, whose components are the admissible error levels of each controlled parameter.

As a result, the following analytical expression was obtained for the approximating function F_m:

$$F_m(x) = a_5 x^5 + a_4 x^4 + a_3 x^3 + a_2 x^2 + a_1 x + a_0, \quad (10)$$

where x is a selected current stimulus amplitude; $a = (a_0, a_1, a_2, a_3, a_4, a_5)$ is a model parameter vector.

To determine the optimal amplitude of the stimulating effect, let us find the first derivative of the function:

$$F_m'(x) = a_1 + 2a_2 x + 3a_3 x^2 + 4a_4 x^3 + 5a_5 x^4. \quad (11)$$

It is known that some point x^* is the extremum point of the function $F_m(x)$, if at this point the derivative is equal to zero or does not exist [28]. Therefore, we equate $F_m'(x)$ to zero, and obtain an equation of the 4th degree

$$a_1 + 2a_2 x + 3a_3 x^2 + 4a_4 x^3 + 5a_5 x^4 = 0 \quad (12)$$

and solve it with respect to x to find the value of the optimal stimulus value.

As is known (the Abel-Ruffini theorem), the fourth degree of an algebraic equation is the highest, at which there is an analytical solution in radicals in general form (i.e., for any coefficients). For this, Vieta theorem, a solution through a resolvent, a Descartes-Euler or Ferrari solution [27] can be used.

Since we are only interested in real positive roots, then we need to find only two points $x_1^*, x_2^* > 0$.

Let us rewrite equations (12) in the form:

$$a x^4 + b x^3 + c x^2 + dx + e = 0, \quad (a \neq 0). \quad (13)$$

Let us introduce the notation $x = y - \frac{b}{4a}$. Then we obtain the following incomplete equation:

$$y^4 + p y^2 + 2y + t = 0, \quad (14)$$

where $p = \frac{8ac - 3b^2}{8a^2}$;

$$y = \frac{8a^2 d + b^3 - 4abc}{8a^3};$$

$$t = \frac{16ab^2 c + 64a^2 bd - 3b^4 + 256a^3 c}{256a^4}.$$

Its solution is sought in the form $y = \pm\sqrt{R_1} \pm \sqrt{R_2} \pm \sqrt{R_3}$. Since 8 variants of combinations of signs are possible four roots are superfluous. Only those combinations are chosen for which it turns out to be true.

$$(\pm\sqrt{R_1}) \cdot (\pm\sqrt{R_2}) \cdot (\pm\sqrt{R_3}) = -\frac{q}{8}. \quad (15)$$

Obviously, in the case under consideration, the root will necessarily be the combination $y^* = \sqrt{R_1} + \sqrt{R_2} + \sqrt{R_3}$, where R_1, R_2, R_3 are cubic equation roots

$$R^3 + \frac{p}{2}R^2 + \frac{p^2 - 4r}{16}Z - \frac{q^2}{64} = 0. \qquad (16)$$

3. Results

Coefficients of the polynomial

(a = -0.8455;8.5158; -28.5341; 39.403; 0; 181.4599),

were determined for the found optimal value of the polynomial n = 5 degree. On this basis, a model trajectory of electrical stimulation object was built (Fig. 5), which is adequate to the real curve of electromyostimulation in Fig. 3.The model accuracy was estimated using the modulus of maximum deviation $\varepsilon = \max|y_i - y_{mi}|$, where y_{Mi} are response values calculated using the model, and y_i are experimentally obtained data. The error does not exceed 5%. For the considered specific curve in Fig. 3, the situation is greatly simplified, since one of the coefficients of equation (11) is equal to 0 and you can immediately go to the equation of the third degree. Its solution gives the value of the optimal stimulus amplitude $x^* \approx 4.438$, which corresponds to the experimental data.

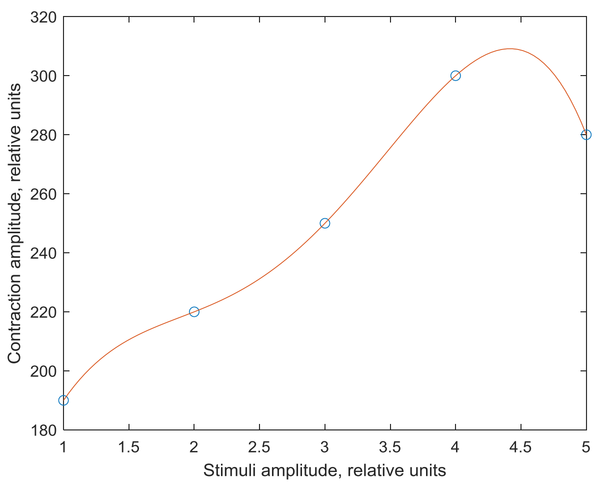

Fig. 5. Model object trajectory

The advantage of such modeling also lies in the possibility of using this model with extrapolation of the results, and such extrapolation occurs in the course of multiple sequential procedures. Based on the results of the previous stimulation, further behavior is predicted to readily reach the individual threshold stimulation. However, it should be borne in mind that in this case a change in the electrostimulation characteristic itself is possible – an increase or decrease in the steepness of the fronts, etc. In this case, the model should be corrected: in the simplest case, to repeat the parametric identification of the model, in a more complex case, to use structural identification, which may consist in changing degree of the polynomial or the choice of another approximating function, with further identification of parameters.

Practical application of results obtained provides a way to calculate the optimal amplitude of stimulating effects for one session based on individual electrostimulation curve, and, if interpolation is used, for several sessions as well.

Conclusions

Dependence of muscle contraction amplitude on the stimulating impulses amplitude has a significantly nonlinear character and contains an extremum point. An analytical model of electromyostimulation characteristics is proposed, which describes the amplitude of muscle contraction dependence on the amplitude of stimuli. The model was obtained by approximating this dependence with a polynomial of the 5th degree. The optimal values of the polynomial coefficients are calculated, which ensure the minimum simulation error. On this basis, an analytical expression was obtained for calculating the optimal amplitude of electrical stimuli. A model trajectory of the electrostimulation object was obtained. Its comparison with the experimental electromyostimulation curve allows estimating the accuracy of the model at 95 %. The value of optimal amplitude of electric stimuli was found theoretically, which coincides with the experimental data. The results obtained can be used for adaptive procedures for electrical stimulation and for the optimal choice of its parameters, as well as for reaching the optimal mode during a number of rehabilitation sessions. The error is within acceptable limits for practice, which makes it possible to use such a model in the course of engineering activities in the construction of adaptive electrical stimulation devices.

Further research in this area involves obtaining an analytical expression to describe the dependence of the amplitude of muscle contraction on the frequency of the stimulating signal and evaluating the adequacy of models in the domain of external parameters.

Contribution of authors: development of a mathematical model and its structural and parametric identification, selection and use of software tools for modeling and presentation of results, assessment of model

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accuracy – **Olha Yeroshenko**; formulation of research goals and objectives, analysis of existing models, analysis of research results, formulation of conclusions – **Igor Prasol**; analytical review and analysis of information sources – **Mykhailo Suknov**. All authors have read and agreed to the published version of the manuscript.

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МОДЕЛЮВАННЯ ЕЛЕКТРОСТИМУЛЯЦІЙНОЇ ХАРАКТЕРИСТИКИ ДЛЯ ВИЗНАЧЕННЯ ОПТИМАЛЬНОЇ АМПЛІТУДИ СТИМУЛІВ СТРУМУ

О. А. Єрошенко, І. В. Прасол, М. П. Сукнов

Об'єкт дослідження – процес електростимуляції скелетних м'язів людини під час проведення лікувальної терапії. **Предмет** вивчення – математична модель електростимуляційної характеристики, яка пов'язує амплітуду скорочення м'язів та амплітуду стимулюючого впливу. **Мета** роботи – розробка математичної моделі у вигляді аналітичного виразу для опису залежності амплітуди м'язових скорочень від амплітуди електричних стимулів. **Завдання, що вирішуються**: проаналізувати особливість залежності амплітуди скорочення м'язів від амплітуди стимулюючих імпульсів; провести структурну та параметричну ідентифікацію моделі; порівняти отримані результати із практичними даними, оцінити точність моделі; використовувати одержану модель для аналітичного опису з метою апріорного визначення оптимальної амплітуди стимулів. **Методи**, що використовуються: методи математичного моделювання, методи структурної та параметричної ідентифікації моделей, методи апроксимації, методи параметричної оптимізації, методи математичного аналізу. Отримані **результати**: запропоновано аналітичну модель у вигляді полінома 5 ступеня, що відображає залежність амплітуди скорочення м'язів від амплітуди стимулів; обрано ступінь полінома та отримано коефіцієнти моделі шляхом параметричної оптимізації; побудовано модельну траєкторію та оцінено точність моделювання; отримано рівняння та знайдено можливі його рішення для визначення оптимального значення амплітуди стимулів; обґрунтовано практичне застосування результатів дослідження. Отримані результати можуть бути використані при доборі індивідуальних впливів електростимуляції протягом одного сеансу, а також екстраполяції протягом всього процесу реабілітації. **Наукова новизна**: отримано аналітичний опис залежності амплітуди скорочення скелетних м'язів від амплітуди електричних стимулів, що дозволяє визначити індивідуальні оптимальні параметри електроміостимуляції.

Ключові слова: скелетні м'язи; електростимуляція; амплітуда стимулів; амплітуда скорочень; математична модель; оптимальні параметри.

МОДЕЛИРОВАНИЕ ЭЛЕКТРОСТИМУЛЯЦИОННОЙ ХАРАКТЕРИСТИКИ ДЛЯ ОПРЕДЕЛЕНИЯ ОПТИМАЛЬНОЙ АМПЛИТУДЫ СТИМУЛОВ ТОКА

О. А. Ерошенко, И. В. Прасол, М. П. Сукнов

Объект исследования – процесс электростимуляции скелетных мышц человека при проведении лечебной терапии. Предмет изучения – математическая модель электростимуляционной характеристики, которая связывает амплитуду сокращения мышц и амплитуду стимулирующего воздействия. **Цель** работы – разработка математической модели в виде аналитического выражения для описания зависимости амплитуды мышечных сокращений от амплитуды электрических стимулов. **Решаемые задачи:** проанализировать особенность зависимости амплитуды сокращения мышц от амплитуды стимулирующих импульсов; провести структурную и параметрическую идентификацию модели; сравнить полученные результаты с практическими данными, оценить точность модели; использовать полученную модель для аналитического описания с целью априорного определения оптимальной амплитуды стимулов. Используемые **методы:** методы математического моделирования, методы структурной и параметрической идентификации моделей, методы аппроксимации, методы параметрической оптимизации, методы математического анализа. Полученные **результаты:** предложена аналитическая модель в виде полинома 5 степени, которая отображает зависимость амплитуды сокращения мышц от амплитуды стимулов; выбрана степень полинома и получены коэффициенты модели путем параметрической оптимизации; построена модельная траектория и оценена точность моделирования; получено уравнение и найдены возможные его решения для определения оптимального значения амплитуды стимулов; обосновано практическое применение результатов исследования. Полученные результаты могут быть использованы при подборе индивидуальных воздействий электростимуляции в течение одного сеанса, а также с экстраполяцией в течение всего процесса реабилитации. **Научная новизна:** получено аналитическое описание зависимости амплитуды сокращения скелетных мышц от амплитуды электрических стимулов, что позволяет определить индивидуальные оптимальные параметры электромиостимуляции.

Ключевые слова: скелетные мышцы; электростимуляция; амплитуда стимулов; амплитуда сокращений; математическая модель; оптимальные параметры.

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