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Igor Prasol,
Olexandr Dovnar,
Olha Yeroshenko

METHOD OF DIAGNOSING SOME DISEASES OF THE NEURO-MUSCULAR SYSTEM AND FEATURES OF DATA PROCESSING IN SOFTWARE

Electromyostimulation is a method of restorative treatment based on electrical stimulation of nerves and muscles. The electric current, which is used in electrical stimulation to obtain induced muscle contractions, is characterized by a large number of different parameters. However, not every possible option of electrical stimulation is highly effective. To solve the task of diagnosing some diseases of the neuromuscular system, it is important to organize the software by analyzing the parameters of the evoked potentials. Therefore, the object of research is the processes of skeletal muscle contraction under the influence of natural electrical pulses of the nervous system or under the influence of external electrical stimulation. The subject of research is models describing the processes in muscles during contraction and methods of data processing. In the course of the study, such research methods as mathematical modeling methods and methods of processing medical and biological data were used.

The paper examines the experimental strength-duration dependence of skeletal muscle and obtained mathematical models for the normal state of the neuromuscular apparatus and different degrees of denervation. On the basis of electrodiagnosis of a patient with impaired motor functions, the dynamics of changes in the patient's condition and the effectiveness of treatment were traced. Based on the results of the study, an analysis of the parameters of the evoked potentials of the stimulation electromyogram during adaptive electrostimulation was carried out in order to control its effectiveness or establish a diagnosis in some diseases of the neuromuscular system. This made it possible to develop a method for correcting errors in the interpretation of one of the quality parameters and increase the reliability of the diagnosis. The obtained results can be used in the improvement of technical devices for electrostimulation therapy, as well as control of the effectiveness of rehabilitation procedures.

Keywords: *skeletal muscle, diagnostics of the neuromuscular system, modeling, evoked potentials, electrical stimulation, algorithm, software.*

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1. Introduction

Electromyostimulation is a method of restorative treatment based on electrical stimulation of nerves and muscles.

Electric current, which is used in electrical stimulation to obtain induced muscle contractions, is characterized by a large number of different parameters [1, 2]. However, not every possible option of electrical stimulation is highly effective [3, 4].

Studies of the influence of sinusoidal and rectangular signals for filling trapezoidal, bell-shaped and sharp-end pulses show that the optimal signals, at which the muscles contracted almost painlessly, were sharp pulses filled with a sinusoidal or rectangular signal [5–7].

Electromyogram (EMG) analysis is a subject of electromyographic semiotics, which establishes a connection between certain characteristics of potentials and physical, physiological and pathological phenomena corresponding to them.

EMG analysis includes assessment of the shape, amplitude and duration of the action potentials of individual muscle fibers and motor units (MU); characteristic of the interference activity that occurs during voluntary contraction of the muscle (analysis of the spectrum and correlation function). The result of the analysis is the answers to the questions asked, that is, some discrete values of the quantities included in the survey.

To solve the task of diagnosing some diseases of the neuromuscular system, the organization of software by analyzing the parameters of evoked potentials is relevant.

The aim of research is to develop a method of diagnosing some diseases of the human musculoskeletal system based on the force-duration dependence and computer analysis of the evoked potential parameters of the skeletal muscle. For this, the following main tasks are solved:

- experimental construction of force-duration curves for normal and different degrees of denervation;
- selection of appropriate analytical expressions modeling these curves;
- obtaining parameters of evoked potentials by means of external electrical stimulation;

– development of a method of correcting errors in the interpretation of one of the qualitative parameters of evoked potentials during their computer processing, which allows to increase the reliability of the diagnosis.

2. Materials and Methods

The object of research is the process of skeletal muscle contraction under the influence of natural electrical pulses of the nervous system or under the influence of external electrical stimulation. *The subject of research* is models describing the processes in muscles during contraction and methods of data processing.

2.1. Obtaining the force-duration curve. The most accurate quantitative characteristic of the neuromuscular apparatus is obtained by evaluating the ability of the nerve and muscle to respond to pulses of a certain duration at certain current values by constructing a force-duration curve. The physiological basis of this method is that at constant amplitude of stimulation, the muscle is relatively insensitive to very short pulses, while the nerve is quite sensitive to them [4–6]. Since normally the nerve is generally more sensitive to current than the muscle, when stimulated with threshold and near-threshold pulses in the motor point of the muscle, its contraction is a consequence of transsynaptic excitation coming from the nerve terminals irritated by the current [7, 8]. Thus, the parameters of strength and duration of pulses, determined by threshold contractions, normally refer to the nerve, and in case of complete denervation due to degeneration of the nerve, these parameters also refer to the muscle. An intermediate case occurs with partial denervation or partial reinnervation.

Construction of the force-duration curve is carried out as follows. Having found the movement point in the muscle, the rheobase is determined. Rheobase is the smallest current strength for «infinite» pulse duration, which causes minimal muscle contraction [8, 9]. In the practical determination of rheobase, a current pulse lasting 300 ms is used. Normally, rheobase is 4–8 mA [5, 6]. The obtained rheobase value is plotted on the graph, where the values of the pulse durations in milliseconds are plotted along the abscissa axis, and the corresponding current values in milliamperes are plotted along the ordinate axis [6, 10]. Then the duration of the pulse is decreased to 100 ms and the minimum current strength at which the minimum muscle contraction occurs is found, and this value is plotted on the graph [11, 12]. A similar procedure is repeated, reducing the pulse duration to 50; 30; 10; 5; 4; 3; 2; 1; 0.5; 0.4; 0.3; 0.2; 0.1; 0.05 ms [13, 14]. As a result, a number of points are obtained, on the basis of which the force-duration curve for this muscle is constructed. The experimental curves obtained in this way are shown in Fig. 1 (curved raw data).

With a normal neuromuscular apparatus (Fig. 1, the initial data is normal), the maximum duration of the pulse, during which contraction is not caused at any current values, is 0.05–0.1 ms. The corresponding point on the graph appears in the upper left corner. The curve approaches a hyperbola. Since the neuromuscular apparatus normally responds to currents of short duration, the rise of the curve from the rheobase begins in the left part of the graph when the pulse duration is less than 1 ms.

With complete denervation of the muscle (Fig. 1, initial data – complete denervation), the response is caused by direct stimulation of the muscle fibers. The muscle does not respond to short pulses, therefore the rise of the current curve from rheobase begins already in the right part of the graph with a pulse duration of 30–50 ms.

With partial denervation (Fig. 1, initial data – partial denervation), the rise of the curve begins between the specified duration values, and one or two breaks in the curve may be observed, which corresponds to the algebraic summation of the points of the curves for the nerve and muscle.

To model these dependencies, it is necessary to obtain some analytical expression that establishes the relationship between input and output variables. At the initial stage of modeling, the structural identification of the model is performed. It consists in choosing the appropriate functional dependency. At the next stage, the parametric identification of specific parameters (coefficients) of the model takes place [15]. The type of model is selected on the basis of a priori data, so a finite number of model parameters are subject to adjustment [16]. This approach is related to the implementation of machine optimization algorithms and allows for quite effective identification of even complex systems.

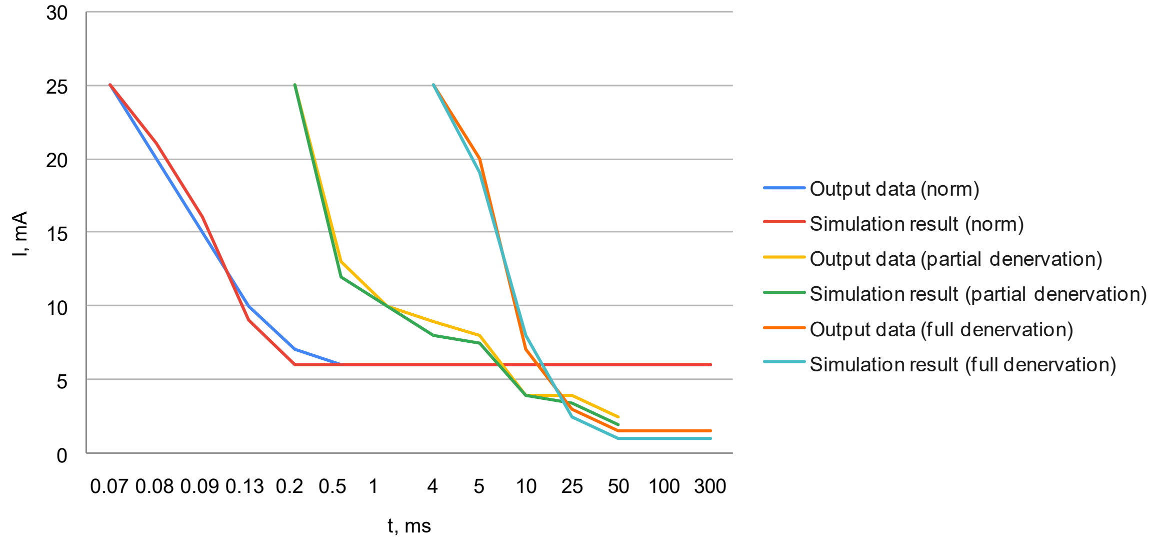

Fig. 1. Force-duration curves at normal, partial denervation, and complete denervation

Let's use the method of the learning model or the reference model, which belongs to the parametric methods of system identification [17, 18]. In accordance with this method, the reaction of the studied system to the test impact is compared with the reaction of the model of a given species to the same impact [19, 20]. The comparison error is used to adjust the parameters of the model according to the criterion of minimizing the deviation of the response of the system and the model.

In the case of univariate analysis (one independent variable), the experimental data connecting the input and output can be represented as:

$$\{x_i, y_i\}, \tag{1}$$

where x_i – the input data; y_i – initial data; $i=1...n$, n – the number of experimental points. The analytic function can be written as:

$$\hat{y} = f(x,\{a_k\}), \tag{2}$$

where $\{a_k\}$ – function parameters.

Then the deviations of the experimental data from the corresponding values of the model are recorded as:

$$\Delta y_i = y_i - \hat{y}_i, \tag{3}$$

where $\hat{y}_i = f(x_i,\{a_k\})$.

The condition for implementing the least squares method:

$$\sum_{i=1}^{n} \Delta y_i^2 \to \min. \tag{4}$$

Minimization of the sum of squared deviations is implemented using machine algorithms.

As a result of this identification, let's obtain the following mathematical expressions:

$$y(x) = 5 + \frac{0.4}{x - 0.056}; \tag{5}$$

$$y(x) = 4 + \frac{5}{x} + \sin(x) + \frac{\cos\left(\frac{x}{20}\right)}{10x} - 0.49x; \tag{6}$$

$$y(x) = 1 + \frac{8}{\frac{x}{2} - 1.8}, \tag{7}$$

where x – the pulse duration; y – the current strength.

They are used to describe the experimental dependences in Fig. 1 (source data). The corresponding model trajectories are shown in Fig. 1 (simulation result). Obviously, they quite accurately repeat the experimental data in the diagnostically significant ranges of effects.

Thus, it simulated on the computer the empirical force-duration curves for the normal state of the neuromuscular apparatus and different degrees of denervation, and then using electrostimulation methods for diagnosing a patient with impaired motor functions, it is possible to trace the dynamics of changes in the patient's condition and monitor the effectiveness of treatment.

2.2. Electrostimulation diagnostics of the neuromuscular system. EMG analysis in response to electrical stimulation is a complex method that includes a number of independent methods [9]:

1) registration and analysis of the evoked potential of muscles and nerves: nerve action potential, M-response, H-reflex, F-wave. At the same time, the following parameters are analyzed: latent period, shape, amplitude, duration of the evoked potential, the dynamics of the change of the evoked potential with a gradual increase in the strength of the stimulus;

2) determination of the number of functioning motor units;

3) determining the speed of determining the pulse along the motor and sensitive fibers in different segments of the nerve trunk;

4) calculation and analysis of a number of coefficients: craniocaudal and motosensory, asymmetry, deviation from the control value of the indicator.

The nerve action potential is caused by the electrical activity of peripheral nerve fibers in response to electrical stimulation of the nerve trunk. The nerve action potential is the total action potential consisting of the potentials of individual sensitive and nerve fibers of different diameters, degree of myenization, and excitation threshold. A distinction is made between the action potential of a mixed nerve, which represents a complex response of motor and sensory nerve fibers, and the action potential of sensitive and motor nerve fibers. When studying the nerve action potential, attention is paid to the intensity of the threshold irritation, the shape, amplitude and duration of the evoked potential, its latent period. With a gradual increase in the strength of the stimulus, the amplitude of the nerve action potential increases and, as a rule, reaches its maximum value at the strength of the stimulus, which does not yet provide the maximum amplitude of the M-response [12–14]. Most researchers use superficial (cutaneous) bipolar stimulating electrodes.

In the practice of EMG research of patients with various movement disorders, it is important to determine the degree of change of this or that indicator compared to the norm, as well as the dynamics of the indicator with the progression of movement disorders or regression of symptoms against the background of the ongoing therapy. For this purpose, the coefficients of deviation from the norm and deviation from the original value for any EMG indicator are investigated (Table 1).

2.3. Organization of software for diagnostics by analyzing parameters of evoked potentials. When making a diagnosis, the interpretation of the results of measuring parameters plays a significant role. Since the diagnosis is made on the basis of a combination of qualitative concepts of the «more-less-norm» type, it is important to be able to correctly convert quantitative values into qualitative ones. This or the opposite task occurs everywhere during the processing of medical and biological information and is solved in different ways [7–9]. Conversion errors can lead not only to an error in making a diagnosis, but also to the impossibility of making it. At the same time, the probability of an interpretation error increases at the border of qualitative areas, especially such as «decreased – slightly decreased, increased – slightly increased». Accounting for the possibility of conversion errors affects the diagnosis program, as it significantly complicates its logic. In addition, after the therapy, not only a change in the diagnosis is possible, but also a change in quality indicators, for example, a transition from the «decreased» category to the «slightly decreased» category, which can indicate a positive dynamics of treatment.

Table 1

The main parameters of evoked potentials in some diseases of the neuromuscular system

Clinical condition of the patient	Main parameters							
	Amplitude of the M-response, µV		Duration of M-response, ms	Amplitude nerve spike, µV	SPC_M, m/s	SPC_S, m/s	*MU* number	C_M/C_S
	A_{max}	A_{min}						
Healthy person	6266 ± 263	25.1 ± 2.0	19.6 ± 1.2	51.2 ± 5.8	61.0 ± 1.5	66.7 ± 1.5	245 ± 9	91 ± 2
Polyneuropathy	Decreased	Increased	Norm	Decreased	Decreased	Decreased	Decreased	Norm
Muscular dystrophy	Decreased	Increased	Norm	Decreased	Decreased	Decreased	Decreased	Decreased
Hemiparesis	Increased	Increased	Norm	Slightly increased	Slightly increased	Slightly increased	Decreased	Norm
Spinal amyotrophy	Decreased	Increased	Decreased	Slightly decreased	Decreased	Decreased	Decreased	Norm
Myotonia	Increased	Increased	Increased	Increased	Increased	Increased	Decreased	Norm

Notes: SPC_M – speed of pulse conduction through motor fibers; SPC_S – speed of conduction of sensory conduction pulse; C_M – motor fiber coefficient; C_S – coefficient with a sensitive nerve fiber

To account for the above, it is proposed to build a diagnostic program that will process the coded examination results in a special way.

According to the diagnostic table, eight quantitative indicators are involved in making a diagnosis, the quality of which is divided into five groups: normal, slightly decreased, decreased, slightly increased, increased. Let's give each grouping level a number from 0 to 4: 0 – normal, 1 – slightly decreased, 2 – decreased, 3 – slightly increased, 4 – increased. Now, if to arrange the indicators in a certain order and replace the qualitative indicator with the corresponding number, let's get the eight-digit word S in the five-year numbering system (code), which corresponds to some diagnosis. The resulting word can be written as a number D in the usual decimal number system. This number will also reflect the same diagnosis.

For example, for a healthy person, the word will be: 000000005 or 010. But in case of an error in the interpretation of the diagnosis, «healthy» will correspond to 000000015=510, and 000003005=7510, etc.

In this way, it is possible to obtain a set:

$$M=\bigcup_{i=1}^{6} m_i, \qquad (8)$$

where $m_i, i=\overline{1,6}$ – the set of numbers, where $m_i=\bigcup_{j} D_{ij}$, where D_{ij} – the j-th decimal number corresponding to the i-th diagnosis.

The algorithm for obtaining the elements of the set M consists in constructing all possible values of the S codes with subsequent conversion from the decimal numbering system. The problems of building jam-resistant codes in information theory are developed quite fully [7], but practically all jam-resistant coding is associated with an increase in the bit rate of the code word. In our case, error correction in one bit of the code can be avoided without increasing the bit size of the code word.

3. Results and Discussion

Let's consider the example of obtaining a subset of the possible values of the set D in the diagnosis of polyneuropathy with an error in the interpretation of A_{max}.

So, according to the Table 1 and the coding of gradations of quality indicators adopted above, the five-year word S in the absence of interpretation errors will be equal to 240222205, which according to the translation table (Table 2) will be equal to 3902210.

In case of an error in the interpretation of A_{max}, the set S_{err} will contain 4 values of the vector S, namely: $S_{err}=\{04022220;14022220;34022220;44022220\}$, which corresponds to the set $D_{err}=\{39020;39021;39023;39024\}$.

Table 3 shows a fragment of the set M.

The code table can be calculated once and saved, for example, in a file on an external medium.

Table 2

S to D translation table

WCGQI v_i	5^7	5^6	5^5	5^4	5^3	5^2	5^1	5^0
S	0	2	2	2	2	0	4	2
$S_i{*}v_i$	0	31250	6250	1250	250	0	20	2
$D=\sum_{i=1}^{8} S_i v_i$	39022							

Note: *WCGQI* – weight of the coding of gradations of quality indicators

Table 3

A fragment of the set M of codes that take into account one interpretation error

Diagnosis	Without error	Error in interpretation								
		A_{max}				A_{min}				…
Healthy person	0	1	2	3	4	5	10	15	20	…
Polyneuropathy	39022	39020	39021	39023	39024	39002	39007	39012	39017	…
Muscular dystrophy	189022	189020	189021	189023	189024	189002	189007	189012	189017	…
Hemiparesis	42899	42895	42896	42897	42898	42879	42884	42889	42894	…
Spinal amyotrophy	38947	38945	38946	38948	38949	38927	38932	38937	38942	…
Myotonia	36848	36845	36846	36847	36849	36828	36833	36838	36843	…

It should be noted that this method is limited to taking into account only one error. This is due to the fact that a double error can lead to false conclusions, because in this case the same code word can refer to different diagnoses. However, this is not a defect of the tool, but refers to the system of diagnosing diseases.

4. Conclusions

In the course of the study, experimental force-duration dependences during skeletal muscle contraction were considered, and mathematical models were obtained for the normal state of the neuromuscular apparatus and different degrees of denervation. The error of modeling the strength-duration characteristics in the case of pathology does not exceed 5 %, which is quite acceptable for practice. An analysis of the process of processing the parameters of evoked potentials of the stimulation electromyogram during adaptive electrostimulation was carried out in order to control its effectiveness or establish a diagnosis in some diseases of the neuromuscular system. This made it possible to develop a method of correcting errors in the interpretation of one of the qualitative parameters, which increases the reliability of diagnosis, to track the dynamics of changes in the patient's condition and to monitor the effectiveness of treatment.

The proposed method of data processing reduces the probability of an error in the interpretation of measurements and conclusions regarding the state of the neuromuscular system, which will significantly facilitate the process of choosing the appropriate therapy for the practicing physician.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this study, including financial, personal, authorship, or any other, that could affect the study and its results presented in this article.

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Data availability

The manuscript has associated data in the data repository.

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Igor Prasol, *Doctor of Technical Sciences, Professor, Department of Biomedical Engineering, Kharkiv National University of Radio Electronics, Kharkiv, Ukraine, ORCID: https://orcid.org/0000-0003-2537-7376*

Olexandr Dovnar, *PhD, Associate Professor, Department of Radio-Electronic and Biomedical Computer-Aided Means and Technologies, National Aerospace University «Kharkiv Aviation Institute», Kharkiv, Ukraine, ORCID: https://orcid.org/0000-0001-7171-0024*

✉***Olha Yeroshenko,*** *Assistant, Department of Electronic Computers; Postgraduate Student, Department of Biomedical Engineering, Kharkiv National University of Radio Electronics, Kharkiv, Ukraine, e-mail: olha.yeroshenko@nure.ua, ORCID: https://orcid.org/0000-0001-6221-7158*

✉*Corresponding author*

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**Serhii Zinchenko,
Oleh Tovstokoryi,
Oleksandr Sapronov,
Kostiantyn Tymofeiev,
Andrii Petrovskyi,
Artem Ivanov**

COLLISION AVOIDANCE BY CONSTRUCTING AND USING A PASSING AREA IN ON-BOARD CONTROLLER

The object of research is the processes of automatic optimal passing of one's own ship with many dangerous targets, including maneuvering ones, by the method of constructing the area of permissible passing parameters in the on-board computer. According to the European Maritime Safety Agency (EMSA), the largest number of ship accidents in 2014–2019 occurred due to collision (32 %). On modern ships, for observation and passing with targets, ARPA (automatic radar plotting aid) is used, which allows to automate manual operations, and the built-in function «Playing the maneuver» provides the navigator with a convenient graphic interface for solving passing problems. At the same time, ARPA is an automated system that assumes the presence of an operator in the control circuit. The presence of a person in the control circuit is related to the «human factor», which is a prerequisite for the occurrence of various types of accidents, including ship collisions. The most effective means of reducing the influence of the «human factor» on control processes is the introduction of automatic control modules in automated systems. The paper develops a method for the passing module, which allows automatic and optimal passing with many targets, including maneuvering ones. The number of targets for passing is not limited by the method, but is limited only by the capabilities of the ARPA to track the targets. The obtained results are explained by the fact that at each step of the on-board computer, a region of permissible passing parameters is constructed for all purposes, passing parameters that optimize a given optimality criterion are selected from the constructed region, the selected parameters are used as software in the control law. The developed method can be used on ships, subject to integration into the existing automated system of an on-board computer with an open architecture, to increase the capabilities of automatic traffic control, in this case, the possibility of automatic optimal passing with many objectives, including maneuvering.

Keywords: *passing of ships, safety of shipping, optimization of control processes, automatic control module, simulation stand.*

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1. Introduction

According to the European Maritime Safety Agency (EMSA), the causes of ship accidents in 2014–2019 were: collision (32 %), loss of control (30 %), equipment failure (14 %), grounding (13 %), fires (6 %), flooding (3 %), loss of structural integrity of the hull (1 %) and others (1 %). As can be seen from the given data, the largest share of the causes of accidents is collisions. A radar station is a tool for measuring the parameters of