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Formation of the control signals based on application of the neural network approaches in spine rehabilitation systems

Nikolay V. Dorofeev*[1], Anastasia V. Grecheneva[2] and Oleg R. Kuzichkin[2]

[1]Vladimir State University named after A. G. and N. G. Stoletovs, 87 Gorkiy St., 600000, Vladimir, Russia
[2]Belgorod National Research University, 85 Pobedy St., 308015 Belgorod, Russia

ABSTRACT

The article substantiates the necessity of correction of control signals depending on the state of the spine and the movements performed. The generalized structural scheme of the control unit of executive mechanisms in spine rehabilitation systems is considered. As a result of the operation of the control unit, motor exercises are corrected in rehabilitation techniques based on the results of modeling the permissible degree of flexure of the spine. An example of patterns of motor actions is given and a generalized model of motion patterns is described.

KEY WORDS: DIAGNOSTIC, REHABILITATION, NERVOUS SYSTEM, GONIOMETRY, MUSCULOSKELETAL SYSTEM, NEURAL NETWORK

INTRODUCTION

The efficiency of modern technical means makes it possible to implement algorithms for real- time processing large amounts information. It is lead to increase the efficiency and quality of medical systems, in particular, rehabilitation systems of the spine. The complexity of developing of this class systems is associated with a greater risk of harm to the health of the patient due to an incorrect diagnosis. This risk also includes erroneous decisions of the rehabilitation system that are incompatible with the life of the patient. The need for adaptation to the various physiological parameters of the patient taking into account of injuries to the spine causes even greater difficulties, (Sobolev *et al.*, 2017 Kulik, 2017).

The aim of the present work is to improve the quality of management of rehabilitation exoskeletons due to the use of neural network algorithms for estimating the permissible degree of flexure of the yesterday.

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THE PROBLEM OF MANAGEMENT OF THE REHABILITATION SYSTEMS

Currently, the functionality of existing rehabilitation systems is insufficient for patients with spine pathologies. This is due, first of all, to their limited application in conditions of low mobility of the patient (fractures, gunshot wounds, etc.) or the lack of a priori information on the patient's permissible movements (during rehabilitation) without causing additional harm to his health. However, the process of rehabilitation is accelerated if the correct load on the pathological parts of the spine is calculated (Yezhov *et al.*, 2013; Tuktamyshev & Bezmaternykh, 2014; Vengerova & Solovyova, 2008; Zubareva, 2011, Maksimova, 2012; Kulik, 2017, Sobolev *et al.*, 2017).

The control signals for the rehabilitation exoskeleton are formed on the basis of the patient's desired movements and are limited by the physiological parameters and state of the patient.

Arbitrary movements of the patient are formed by the exoskeleton on the basis of the recorded nerve (electroencephalography), muscle (electromyography). Involuntary movements of the patient are formed by the mechanical (strain gage) signals of the exoskeleton at different stages of motor processes in various (informative) areas of the patient's body, (Grecheneva *et al.*, 2017).

Problems in recording arbitrary movements of the patient are the error of the measuring path, the quality of recognition of informative signals and pathology of the human neuromuscular system.

So, for example, all movements of the musculoskeletal system of a human without pathologies begin in the central nervous system, namely in the motor zone of the cerebral cortex. The generated electrical signals of movement (motion impulses) from the brain through the spinal cord are transmitted to the peripheral nervous system along those nerve fibers (motor neurons) that must cause the necessary contractions of the muscular system, (Sobolev *et al.*, 2017).

Motor neurons have feedbacks, which receive information from muscle fibers, receptors and other sensory receptors, in order to further coordinate movement and prevent muscle damage. Since the moment of formation of an impulse in the cerebral cortex before the movement (contraction or relaxation of the muscles), some time passes, individual intervals of which are described in (Sinitskaya & Gribanov, 2014; Zakharova *et al.*, 2012; Grecheneva *et al.*, 2017).

In general, the movement (especially arbitrary) is the result of complex neuropsychophysiological processes in which a plan of motion or reaction to stimuli is formed, and its constant correction occurs throughout the entire movement. In addition to the motor zone of the cerebral cortex, other areas of the brain are involved: the posterior parietal cortex, the limbic system, the cerebellum, the frontal cortex, etc. (Sinitskaya & Gribanov, 2014).

When processing and analyzing the signals of motor neuron activity, attention should be paid to the fact that useful signals, although cyclic, are not stationary. In addition, the distribution of the noise component of the signals is not normal (Zakharova *et al.*, 2012).

Functional changes of any part of the path from the place of formation of motor signals to the muscle cause changes in the parameters of motion of the involved kinematic pairs and the musculoskeletal system as a whole. Figure 1 shows the averaged electromyograms obtained (Fig. 2a and 2b) and the dynamics of the deviation angle from the axis of the spine (Fig. 2c and 2d) in the state of rest of a healthy person (Fig. 2a and 2c) and a person with a tremor of the back muscles (Fig. 2b and 2d) (Butukhanov, 2009).

Deviations in the electrophysiological signals involved in the locomotion activity of the musculoskeletal system, from normal values for healthy people manifest themselves in amplitude, phase, shape, and other characteristics of the signals and depend on the different concentration of the attention, the accuracy etc. (Voznesenskaya, 2006; Doronin & Doronina, 2010; Rakhmilevich *et al.*, 2012; Efimov, 2012, Zakharova & Shemirova, 2016; Shchenyavskaya & Zakharova, 2015; Zakharova *et al.*, 2016).

The need for high accuracy of recording of the patient movements is due to possible damage to nerve fibers and the nervous system as a whole. When a nerve tissue is damaged, a number of processes occur successively, leading to the death of damaged nerve cells and the subsequent death of intact ones. According to modern ideas, the main factors leading to the destruction of nerve cells are a violation of microcirculation, hypoxia and ischemia. There is a link between the degree of neuronal damage and the change in the level of the constant potential and the membrane potential of neurons (Sufianova and Shapkin 2014; Shanitsin *et al.*, 2013).

Damage to the nervous tissues of the spinal cord changes the frequency and amplitude of the spinal cord signals and depends on the amount of pressure (compression) and the degree of damage to the nerve fiber. Relying on the works on a dependence of the amplitude of the electrospinogram on the subdural pressure can be described in accordance with Table 1.

Thus, damage to the spinal cord causes an increase in spontaneous electrical activity, and in case of significant damage, further decrease in spontaneous electrical activity. In this case, the frequency characteristics of the activity of the spinal cord correspond to the frequency characteristics of activity of the cerebral cortex, but with

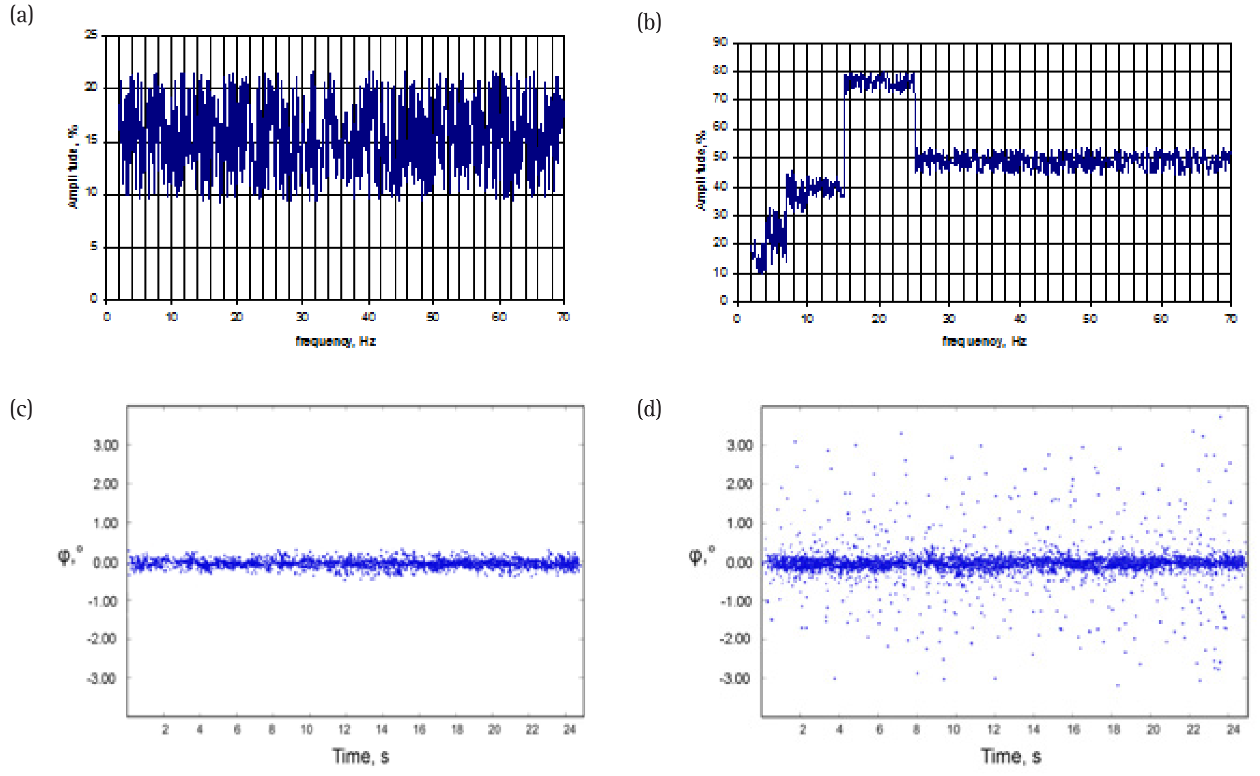

FIGURE 1. Recording of the averaged electromyogram (a, b) and the dynamics of the deviation angle from the axis of the spine in the state of rest of a healthy person (c) and a patient with a tremor of back muscles (d)

smaller amplitude (in the spinal cord). A rupture of the spinal cord increases the level of the constant potential and lowers the values on the electro-spinogram of segments lying below the trauma, and leads to an increase in electrophysiological changes as the distance decreases from damage.

Segments lying above the damage zone are characterized by a decrease in the level of the constant potential and the total amplitude on the electrospinograms, a decrease in the magnitude of electrophysiological deviations. With pressure on the spinal cord, the level of the constant potential shifts and the amplitude decreases on the electrospinograms. The degree of violations in signals decreases is removed from the site of pressure. When the pressure on the spinal cord decreases, repolarization occurs and the amplitude increases again on the electrospinograms. A complete restoration of the level of constant potential does not occur. Thus, the complex processing of the values of the level of the constant potential and electric activity of the spinal cord makes it possible to evaluate the electrophysiological violations and functional changes in the spinal cord both in the injury zone and in neighboring areas (Kulik, 2017).

Thus, the formation of control signals for the rehabilitation exoskeleton is determined not only by the chosen recovery technique, but also by the patient's vertebral state (vertebral, interarticulate fluid, interarticulate cartilage and neural fiber regions).

CONTROL UNIT FOR REHABILITATION EXOSKELETON

The task of the control unit for the rehabilitation exoskeleton is to generate control signals for the actuators (Figure 2).

The control unit consists of two functional parts: a forecast generation unit and a decision block. The forecasting unit evaluates the location, extent and likelihood of damage to the bony, cartilaginous and nerve tissues of the spine. The prognostic estimation is formed on the

Table 1. Dependence of the amplitude of the electrospinogram from subdural pressure

Pressure, mm. gt;	183	250	300	350	400	450	500	550	560
Amplitude, μV	31±9	40±10	52±12	54,5±15,5	64±18	78±20	82,5±15,5	73±15	68±15

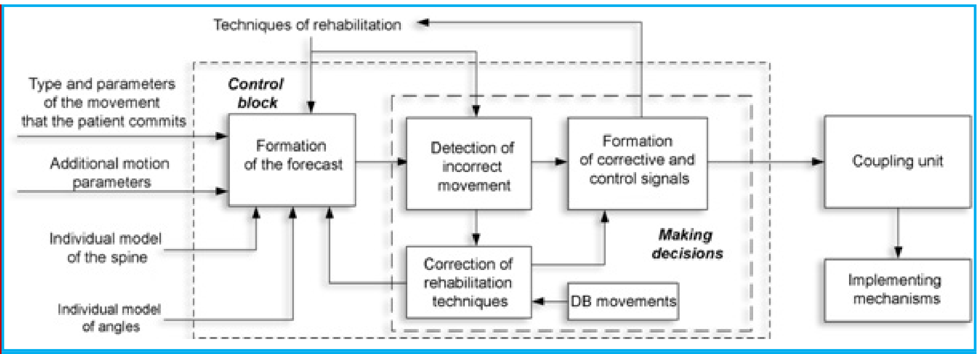

FIGURE 2. The control unit for rehabilitation exoskeleton

basis of the information angular model of the patient, characterizing the permissible deviations in patient movements, the individual spine model describing the geometric and spatial parameters of the main parts of the spine, the data on the movement (type, speed, angles and EMG and EEG data). The performed movements are performed in accordance with the rehabilitation technique. The algorithm of the control unit is shown in Figure 3.

A lot of work has been devoted to the main dependencies of the behavior of the musculoskeletal system, joints and their connecting components, pain sensations and thresholds of perception of pain, for example (Pezhovic *et al.*, 2003; Pinchuk *et al.*, 2008; Shilko & Ermakov, 2008; Suslov *et al.*, 2008; Babchina *et al.*, 2017; Grecheneva *et al.*, 2016; Grecheneva *et al.*, 2017). Formation of prognostic estimates of damage to the spinal sections during motion on the basis of individual models and parameters of movements are given in (Dorofeev *et al.*, 2017).

The vector of predictive estimates for each type of tissue is described by the vector F={L(X,Y,Z), P(X,Y,Z)}, where L is the three-dimensional vector for estimating the degree of damage, and P is the damage probability. The change in the projection vector in time F(t) is used in conjunction with the vector M(t), describing the rehabilitation technique (rehabilitation exercise). The vector M(t)={K(t), C(t)} characterizes the space-time change in

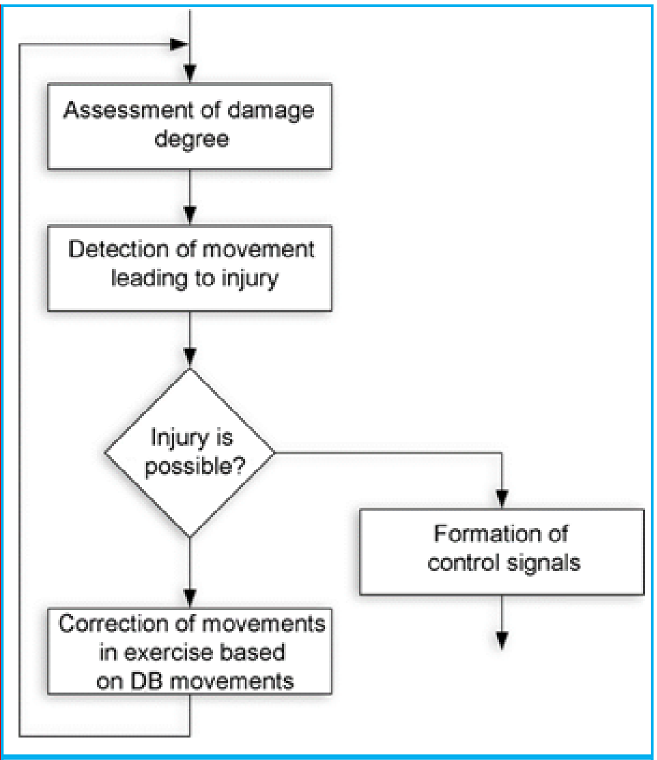

FIGURE 3. The algorithm of the control unit

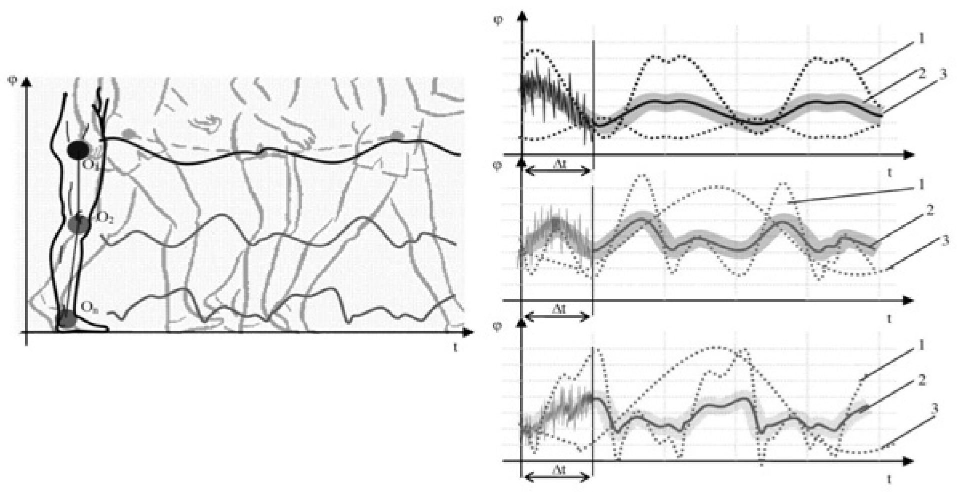

FIGURE 4. Sample Motion Action Templates

the position of the kinematic pairs of the spine **K(t)** and the space-time characteristics of the motion (tempo, frequency, etc.) *C***(t)**.

Classification of movements occurs on the basis of pre-formed patterns of motor actions (Figure 4). The motion pattern can be described by the vector

$$\vec{T}(t) = \{\vec{T}_D(t), \vec{Ib}(t), \vec{Un}(t), \vec{Pst}, \vec{Ppt}\} \qquad (3)$$

where $\vec{T}_D(t)$ is the vector of spatial change in the position of the kinematic pairs; $\vec{Ib}(t)$, $\vec{Un}(t)$ are the vectors describing the change in electrophysiological parameters during the time of motion (some examples are presented in [16]); $\vec{Pst}$ is the vector describing the spectral-temporal characteristics (frequency, power spectra, etc.) of patterns of goniometric and electrophysiological signals; $\vec{Ppt}$ is the vector describing the space-time characteristics of the motion (tempo, amplitude, speed, acceleration, etc.).

Motion patterns are stored in a database, supplemented for individual characteristics and various pathologies. Database updates are necessary for automatic learning and retraining of the neural network.

When implementing the system of direct control of the exoskeleton, it is necessary to have information about the magnitude and position of the goniometric vectors and vectors of the stator and exoskeleton rotor linkage, which are measured by means of various sensors. Unlike vector systems, the direct torque control system uses only current and voltage sensors and does not require the use of a speed sensor. However, accurate estimation of the position of the flux-linkage vector of each of the exoskeleton servo drives is problematic, therefore, state observers are often used to determine the flux linkage. In the case of a medical rehabilitation exoskeleton, the patient's angular model is an observer of the state, the input of which is measured goniometric data, the components of the servo vector of the state, and an output of the general state vector is output. As an observer, it is proposed to use an artificial neural network (Fig. 5).

It is assumed that combining the method of direct torque control and neural network technologies will sig-

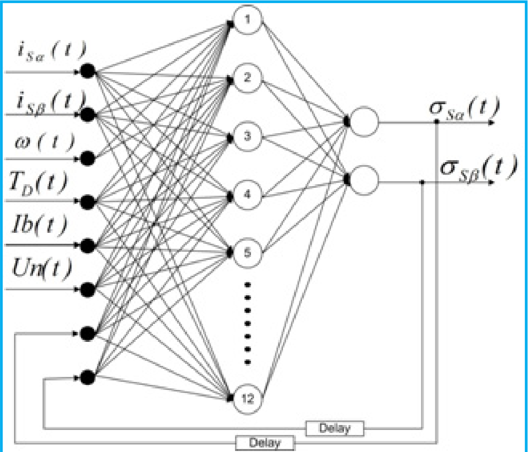

FIGURE 5. The structure of the neural network. Input signals of such a network are stator current signals $i_{S\alpha}$ $i_{S\beta}$ of the i-node of the exoskeleton, ω the rotor frequency, $\vec{T}_D(t)$ is the vector of spatial change in the position of the kinematic pairs; $\vec{Ib}(t)$, $\vec{Un}(t)$ are the vectors describing the change in electrophysiological parameters during the time of motion and feedback c from the neural network output delayed by one step of training (Delay block), and output signals - signals that determine the mode of operation of the exoskeleton nodes $\sigma_{S\alpha}$, $\sigma_{S\alpha}$.

nificantly improve the quality of control of an asynchronous traction electric drive, as well as the robustness of the control system (resistance to changes in the parameters of the control object), thereby improving the quality of control and identification.

Simulation of the operation of the control unit was performed on the CT of patient data, which has a curvature of the cervical spine. When the head was tilted to an angle of more than 59 degrees on average, the patient experienced pain. In 87% of cases, the head inclinations were accompanied by a slight crunch in the cervical region.

Initial exercises for modeling the operation of the control unit included the inclination of the head by 90 degrees. As a result of the operation of the control unit, the initial exercises were adjusted, the maximum inclination of the head was 64 degrees (Figure 6).

CONCLUSION

Thus, the developed algorithms of the control unit allow to correct motor exercises in the rehabilitation technique for the physiological characteristics of the patient, and also do not allow the executive mechanisms to make movements dangerous to health. It should be noted that the permissible limits for the search for optimal exercises of the control unit are set by the expert and for automated work should be automatically determined from the CT data and the simulation results. These boundaries in the example under consideration were set rigidly, which was the reason for the discrepancy between the results of modeling and pain sensations of the patient being studied.

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