Development of an algorithm for determining the degree of fatigue of a human operator under the influence of vibration

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Abstract. The article discusses the issue of selecting methods for studying human muscle fatigue in the operator-joystick system. The article discusses ways to measure potentials from human muscles. The applicability of the chosen method for evaluating the work of the research object is considered. This article provides an overview of the methods for diagnosing muscle fatigue parameters in the operator-joystick system.

1. Introduction
There are several methods for diagnosing the state of human muscles [1-5]; it is of interest to find a research algorithm that is suitable for diagnosing operator parameters online.

In humans, as in all vertebrates, skeletal muscle fibers have four most important properties [6]:
• excitability - the ability to respond to a stimulus by changes in ion permeability and membrane potential;
• conductivity - the ability to conduct an action potential along the entire fiber;
• contractility - the ability to contract or change the tension when excited;
• elasticity - the ability to develop tension when stretched.

Under natural conditions, muscle excitation and contraction are caused by nerve impulses coming to muscle fibers from nerve centers. Under experimental conditions, electrical stimulation is used to induce muscle contraction.

Direct irritation of the muscle itself is called direct irritation; irritation of the motor nerve, leading to a contraction of the muscle innervated by this nerve (excitation of neuromotor units), is an indirect irritation. Due to the fact that the excitability of muscle tissue is lower than that of the nervous one, the application of electrodes of the irritating current directly to the muscle does not yet provide direct irritation: the current, spreading through the muscle tissue, acts primarily on the endings of the motor nerves located in it and excites them, which leads to a contraction muscles.

In modern medicine, there are many different methods for determining pathologies in the work of the human musculoskeletal system. In work [1], magnetic resonance imaging (MRI) was used as a research method. MRI can show the presence of muscle symptoms, helps to determine the pattern of distribution of muscle involvement, indicating preserved and affected muscles and the extent of their changes, and also resolve suspicions of myopathy due to a specific clinical picture.
The study [2] used muscle sonomyography at rest and under load. The results showed that the ultrasound method can diagnose a sharp increase in blood flow.

In [3], the Doppler myography method was used to further determine the spectral characteristics of the results obtained. It was found that skeletal muscles perform low-frequency vibration movements during contraction. The states of tension and rest of muscle tissues differ markedly from each other both in the frequency characteristics of the registered movements, which is expressed, in particular, in an increase in the spectral component with increasing load.

In work [4] it was revealed that the cutaneous EMG derivation allows in a number of cases a good assessment of the synchronization process in the work of peripheral motor neurons. The author has repeatedly observed a gradual increase in the amplitude of rare rhythmic activity with an increase in the force of contraction. In this case, the oscillation frequency remains practically unchanged.

When analyzing the amplitude characteristics of muscle responses during the repetition of the speed-strength test in [5], a certain tendency was found. It was expressed in a gradual increase in the voltage of the evoked potentials up to the maximum figures by the 5th attempt. At the same time, the degree of voltage increase in different muscle groups of the right and left extremities had different values. It should be borne in mind that the magnitude of the maximum muscle response correlates with the number of functioning motor units in the muscle groups under study. Three types of relationship between the dynamics of myographic parameters and changes in sports results were revealed.

Skeletal muscle is made up of motor units (MUs), the smallest muscle elements that can be activated by willpower. MU consists of the anterior horn cell or motor neuron, an axon, and all muscle fibers excited by this axon. The number of muscle fibers per motor fiber is called the coefficient of innervation. The innervation coefficient for various muscles can range from ten to hundreds of units [6]. Muscle contraction is the sum of the stimulation and contraction of several MUs. The mechanism of muscle contraction is described by the theory of sliding threads, according to which the shortening of each muscle fiber during contraction occurs as a result of the movement of thin threads in the intervals between thick ones without changing their length [7].

Electromyography (EMG) methods are the most autonomous methods for obtaining human biopotentials. There is both invasive and non-invasive EMG. Invasive (needle-like) requires special experimental conditions. Skin EMG is used to assess the state of the body as a whole, while stimulation EMG can show changes online.

It is proposed to use two methods for obtaining EMG. First, a stimulation myogram is taken at rest, after which a "normal" curve is recorded. Then the muscle is examined in a state of overload. Both curves will be called "reference" and they are sent to the control unit. After calibration, a cutaneous EMG measurement is performed. The received data is compared with the reference values and when approaching critical values, a warning about the presence of overloads is displayed.

Thus, a method for studying muscles in the operator-joystick system was determined.

Controlling movements is unthinkable without coordinating the activity of a large number of muscles. Therefore, for the implementation of the movement, a motor program must be formed. The motor or central program is considered as a prepared set of basic motor commands, as well as a set of ready-made corrective subroutines that ensure the implementation of the movement, taking into account the current afferent signals and information coming from other parts of the central nervous system.

The mathematical model of the EMG signal can be simplified by the following equation [8]:

\[ u(n) = \sum_{q=0}^{N-1} h(q)e(n - q) + w(n) \]  

\[ u(n) \] – the biopotentials of the EMG signal, \( h(q) \) – is the action potential of one MU, \( e(n) \) – the stimulus, \( w(n) \) – is the additive white Gaussian noise, \( N \) – is the number of MU involved in the contraction process.

The action potential extends from the neuromuscular joints in both directions within the muscle fiber through the tubular system [8].
Stimulation of each MU by a neuronal signal causes their contraction, as a result of which an electromyographic signal (EMG) is generated, which is the sum of the action potentials of all cells involved in the process [9-11].

Let's define the muscles for which it is necessary to conduct EMG. To control the joystick, a person uses more than 30 muscles, it will be impossible to examine the myogram for each. It is proposed to use EMG of the biceps of the shoulder as a muscle responsible for controlling the subject's arm.

2. Materials and methods
The problem of discrete control of power linear drives in [12] is considered by the example of solving a one-dimensional control problem for a vibration platform. The proposed circuit solution is shown in figure 1. The task of controlling the presented circuit using a spatial joystick is a very urgent technical problem. We will use the proposed structural diagram and implement on its basis a control system for assessing the capabilities of a human operator of a mobile machine [13, etc.]. As rods 1 and 2, we use linear actuators of variable length. We will ensure their hinge fastening at points 3 and 4, as well as at point 0. We assume that the base is stationary, and at point 0 a laser designator is installed, the movement of which depends on the movement of the Z 3 type joystick. Control is carried out by a human operator. The task is to find the control laws that minimize the "parasitic" acceleration of point 0 when performing manipulation operations using two linear angle sensors and one digital one.

A human operator as a system with delay allows realizing original control in space, since it relies not only on tactile sensors, but also on a more perfect system of spatial stabilization inherent in it by nature.

As input parameters for the control circuit, we use the signals from the "pseudo Z3 type" joystick. A Z3 type joystick is a manipulator capable of transmitting signals along coordinates, X, Y, Z. As a joystick, we will use the JoyStick V1.0 module [14, etc.].

X and Y movements are monitored by analog potentiometric sensors, Z coordinates are controlled by a digital input. The Z input is digital and provides pseudo-linear control along the third coordinate, and therefore the joystick will be considered "pseudo three-coordinate". The 2D system changes its parameters along the two precision tracking coordinates. No Z movement is required. This idealization eliminates the use of a central analogue processor (DAC) in the signal processing circuit along the Z coordinates. Control by the third Z coordinate is necessary when implementing the mechanism on two coupled systems with 4 linear drives. The proposed technical solution is necessary for debugging the algorithm of interaction of the "microcontroller - joystick - power drives" system.

3. Results and discussion
To control the power drive, we will use a microcontroller system coupled with a motor control system. The microcontroller control system allows realizing control functions, it is equipped with 32 kb of flash
memory, 2 kb of which is reserved for the so-called bootloader (storing the program and related static resources) [12-15].

Linear drives 3 and 6 of small power based on a DC motor with a plastic gear 5 and a linear transmission with a rubber stop 4 are used as a power drive.

Figure 2. Physical model of a control system for two drives.

The complexity of controlling a system consisting of two drives lies in the need to simultaneously supply two control signals and the need to take into account the complex interaction when moving point 0. Due to the design features of the circuit, it is possible to provide high rigidity with small dimensions, high speed of movement of point 0 in the desired direction in comparison with analogues. To assess the operator's activities, a physical model of the control system was assembled.

The operator, visually controlling the object, sets the direction of movement, using two analog and one digital sensors (potentiometric), structurally implemented in a single control unit (joystick) 7. Information goes to the inputs of the microprocessor system 9 and based on the developed algorithm (figure 3) signals are generated controls coming to the motor control board 8. Power drives 4 are hinged on the base 2 at nodes 3, 6 (in figure 2 they correspond to points 3 and 4) between themselves and the movable platform 5 (point 0 in figure 1) A laser is installed on the platform 5 target designator powered from the power pins of the microprocessor board 9. To power the circuit, voltage is supplied from two sources. The first 6 V power supply, rated for 500 mA current, is connected to the power connector of the microprocessor board 9. The second power supply through adapter 1 with 9 V voltage, rated for at least 1A current is connected to the motor control board 8. Power supplies, switching circuits and a target designator were not shown in figure 2 to make them easier to read.

During the tests, the physical model of the system showed its operability, the control algorithm was debugged, the design possibilities for varying the base between the fasteners 3, 4 and the angles relative to the base were determined. Technological changes were made in the design of the drives,
which made it possible to increase their travel from 20 mm to 25. Due to the use of more rigid protective corrugations, the function of automatic exit from the critical upper point is provided.

Figure 3. Control algorithm.
The human operator is on the seat, electrodes are applied to the arm (biceps and forearm) to take an electromyogram. The results obtained during the experiment are sent to the data processing unit with the reference values of the EMG curves. Then the data is transferred to the control system. The palm controlling the joystick is aimed at the target with the controller, which also transmits the results to the control system. All information is transferred to a PC for further analysis. The importance of control and monitoring of dynamic processes is indicated in the work of V.M. Mikhailov [15].

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