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A virtual tool for the rehabilitation of patients based on the developed heart rate measurement model

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ABSTRACT

Relevance. The development of intelligent information and measurement systems for patient rehabilitation is an important area of modern biomedical engineering. Particular attention is paid to synchronizing physiotherapeutic interventions with individual physiological processes to improve the effectiveness of rehabilitation procedures for patients with peripheral circulatory disorders. **Aim of the study.** The aim is to develop a heart rate measurement model and a virtual hardware-software device for synchronizing electrical stimulation with the natural rhythm of peripheral blood flow. **Objectives.** The objectives include developing a model for determining the arrival time of the arterial pulse wave at the affected limb area, implementing a virtual measurement and stimulation system, and experimentally evaluating its functionality and effectiveness. **Methods.** The study applies methods of cyber-physical systems design, biomedical signal acquisition and processing, mathematical modeling, virtual instrumentation, and automated feedback control. The hardware-software system was implemented using multifunctional data acquisition equipment and the LabVIEW programming environment. **Scientific novelty.** A model and an approach to controlling electrical stimulation are proposed that enable the generation of stimulation pulses synchronized with the actual propagation of the arterial pulse wave. Unlike conventional approaches with predefined stimulation intervals, the developed system dynamically adjusts stimulation timing according to individual changes in the patient's heart rhythm and peripheral blood flow characteristics. **Practical significance.** The developed virtual device provides automated monitoring of physiological signals, real-time generation of synchronized stimulation pulses, and assessment of rehabilitation effectiveness using indicators of limb temperature and peripheral blood circulation. The proposed solution can support the development of adaptive physiotherapeutic equipment and personalized rehabilitation technologies. **Results.** Experimental investigations confirmed the functionality of the developed virtual device and demonstrated stable synchronization of electrical stimulation pulses with the patient's physiological rhythm. The rehabilitation procedures were accompanied by increased limb temperature and improved peripheral blood supply, indicating positive changes in the monitored physiological parameters. **Conclusions.** The developed heart rate measurement model and virtual rehabilitation device provide a technological basis for adaptive electrical stimulation synchronized with natural blood flow dynamics. The obtained results demonstrate the feasibility of integrating virtual instrumentation, biomedical signal processing, and automated control into intelligent rehabilitation systems.

Keywords: virtual instrumentation; biomedical signals; heart rate; electrical stimulation; physiological monitoring; adaptive control

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INTRODUCTION

Peripheral arterial disease (PAD) of a living biological organism is manifested by systemic atherosclerosis of vessels. Such obliterating atherosclerosis of the vessels of the lower extremities leads to significant changes in the condition of the extremities and, as a result, requires operative and medical treatment. A unified approach to assessing the current state of a living biological organism is unable to respond promptly and in situ to changes in the state of a living biological organism. The unified approach uses technologies and hardware with no feedback inherent in cyber-physical systems and virtual assets based on them [20]. This restrains the development of

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new technologies for the rehabilitation of living biological organisms. Therefore, with the development of technologies, instrumental methods of targeted action on the organs of biological organisms are relevant, which should replace trivial physical exercises with their shortcomings. Adaptive modeling approaches have also been applied to the management of technologically integrated systems, demonstrating the relevance of accounting for changing operating conditions in the development of information-based decision-making frameworks [26].

With diseases of the arteries of the lower extremities, rehabilitation and movement exercises are significantly complicated. At the 1st stage of the disease, biological beings complain of pain in the leg muscles when walking about 1 km. The pain makes the patient limp, after rest the lameness disappears. The indicated pain is associated with ischemia of the muscles and is due to the difficult access of arterial blood to them. 2A stage – pain appears when walking a distance of 200 to 500 meters. 2B stage – lameness occurs when walking less than 200 meters. At this stage, hypotrichosis, changes in the nails, hypotrophy of the lower leg muscles, and pallor of the skin of the distal parts of the lower limbs can be observed. There is usually no pulse on the foot. At the same time, methods of treatment with sufficient efficiency are still poorly developed, and methods of rehabilitation of patients with obliterating atherosclerosis of the vessels of the extremities are absent.

LITERATURE REVIEW AND PROBLEM STATEMENT

Recent studies demonstrate growing interest in the use of electrical stimulation as an auxiliary method for the rehabilitation of patients with peripheral arterial disease (PAD). Jéhannin et al. [2] conducted a systematic review of lower-extremity electrical stimulation methods for improving walking impairment in patients with PAD. The analysis included studies using neuromuscular electrical stimulation (NMES), transcutaneous electrical stimulation, and functional electrical stimulation. The authors reported positive effects of NMES on maximal walking distance; however, they emphasized that the available evidence was limited by the small number of randomized controlled trials, small sample sizes, heterogeneity of stimulation protocols, and methodological limitations. Therefore, the authors concluded that further controlled studies are required to objectively determine the clinical effectiveness of electrical stimulation in patients with PAD.

The effectiveness of NMES was also investigated by Babber et al. [5], who studied footplate neuromuscular electrical stimulation in patients with PAD and intermittent claudication. The study included both a pilot investigation and a randomized clinical trial. The authors observed significant improvements in initial and maximum claudication distances, while ultrasound measurements demonstrated an increase in blood volume flow and mean blood velocity during stimulation. The study also reported high treatment compliance. These results indicate that electrical stimulation may influence not only functional parameters but also peripheral hemodynamics, which is particularly important for the development of rehabilitation systems based on physiological feedback.

The relationship between electrical stimulation and peripheral blood flow was further investigated in studies involving patients with lower-extremity arterial insufficiency. The study examining the immediate effects of electrical stimulation, diathermy, and physical exercise demonstrated changes in lower-limb arterial blood flow following the application of physical rehabilitation modalities [4]. Such findings support the possibility of using peripheral physiological parameters as objective indicators for monitoring the response of the vascular system to therapeutic stimulation.

An experimental model of peripheral arterial disease was used to investigate the effect of chronic electrical stimulation on nutritive microcirculation [6]. The results demonstrated the potential of electrical stimulation to improve impaired peripheral microcirculation. This direction is important for the development of adaptive rehabilitation technologies because it suggests that electrical stimulation can be considered not only as a means of influencing muscle activity but also as a method capable of modifying peripheral vascular responses.

Particularly relevant to the present study are recent results obtained by Pellinger et al. [3]. The authors investigated the acute effects of transcutaneous electrical nerve stimulation applied to

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the lower leg in patients with PAD. The study demonstrated an increase in leg blood flow and exercise capacity following stimulation, providing additional evidence that electrical stimulation can produce measurable hemodynamic effects in patients with peripheral arterial disease. The significance of these results for the present research lies in the possibility of using changes in peripheral physiological parameters to evaluate the effectiveness of stimulation in real time.

The main manifestation of peripheral arterial disease under the influence of physical exertion is the presence of pain in the leg muscles due to insufficient blood circulation. To assess the functional degree of severity of peripheral arterial disease, variable intensity pain sensations are measured. Determine the distance or time to the onset of pain and its maximum value. The results of measurements of the Ankle-Foot Brachial Pressure Index, obtained before and after the treadmill test, in addition to pain measurements, give a more objective assessment of the severity of the disease. Measurement of AFBPI immediately after an intense running test can help diagnose PAD in severe cases, as well as determine the degree of peripheral circulatory impairment. Exercise increases systemic blood pressure (i.e. brachial blood pressure), whereas pressure distal to the arterial lesion in the lower extremity falls with exercise due to dilation of secondary arterioles. However, the method causes a negative physiotherapeutic effect [1], [9].

In Ukraine, rehabilitation of sick biological organisms with obliterating atherosclerosis of the vessels of the limbs is carried out by carrying out a physiotherapeutic procedure [12], which consists in the application of pulses of electric voltage (current) to two electrodes tightly placed on the affected part of the limb for a certain period of time. In particular, the effect of sinusoidal modulated currents (amplipulse therapy) [1],[19] is prescribed, precisely in those cases when biological organism has a pronounced tendency to spasm of blood vessels and ischemia of the I and III stages. They affect the limbs, the mode is sinusoidal, the modulation frequency is 70 Hz, the modulation depth is 75%, the duration of the modulation packets is 1-3 s. The duration of the procedure is 5 minutes every day. The course of treatment is 10 sessions. After a month, amplipulsterapiya is repeated.

However, when using this method and the device for its implementation, rehabilitation of patients with obliterating atherosclerosis of the vessels of the limbs is not achieved. The fact is that the rather rigidly observed parameters of the current during the procedure do not take into account the specific condition of the patient: they are evaluated based on averaged indicators. In addition, they do not take into account the real value of the patient's heart rate during the procedure. Moreover, they are not able to take into account changes in the rhythm of the heart during the procedure. The main thing is that the rigidly set parameters of the current supplied to the electrodes applied to the limb do not coincide in time with the rhythm of blood supply to the damaged vessel of the limb.

The following technologies are known [1], [19], [23], implemented in the activity of scientific and practical medical or veterinary rehabilitation centers:

– formation of a database on the state of health, psychophysiological features and reserve capabilities of the body of various categories of biological organisms;

– creation of a methodological base for research and practical work in the field of physical rehabilitation;

– the use of hardware and software complexes in the process of medical and biological control in physical rehabilitation, research methods in physical rehabilitation, psychomotor, psychophysiology, physiotherapy, massage, physical rehabilitation in somatic and surgical diseases, technical means in physical rehabilitation;

– participation in preventive screening studies;

– development and implementation of individual and group recovery and rehabilitation programs, which involve te complex use of non-medicinal methods aimed at increasing the functional reserves of the biological organism health, restoring his optimal working capacity, and in the presence of diseases - for faster recovery, prevention of disease relapses and restoration of working capacity.

At the same time, the equipment recommended by such centers mainly includes according to [1], [23]:

– rehabilitation physiotherapy complex PhySys;

– device for rehabilitation with laser radiation Opton;

– four-channel device for rehabilitation with a magnetic field Dimap V;

– electrotherapeutic device with biofeedback MYOMED 932;

– LINFOenergy lymphatic drainage complex for combined rehabilitation with pneumatic pressure and magnetic field;

– Radarmed 950+ device for microwave rehabilitation of joints and internal organs;

– device Curapuls 970 for rehabilitation of joints and internal organs by high-frequency heating;

– complex for the rehabilitation of musculoskeletal system TRAComputer;

– en-Puls device for rehabilitation and regeneration with radial shock wave therapy;

– apparatus for rehabilitation and regeneration by focused shock wave therapy with the Piezowave ultrasonic localization module;

–device for cryorehabilitation Cryo-6;

– hardware complex Diagnost-1.

An important methodological issue in the development of rehabilitation systems is the reliable acquisition and processing of physiological signals. Singh et al. [10] developed a LabVIEW-based ECG monitoring system that combined signal acquisition, analog-to-digital conversion, digital filtering, heart-rate calculation, and arrhythmia analysis. The proposed system demonstrated the feasibility of using LabVIEW as a software platform for real-time processing of physiological signals obtained through a data-acquisition device. This approach is particularly relevant to the present study because the proposed rehabilitation system also requires real-time acquisition and processing of physiological information and subsequent generation of a control signal. The development of intelligent information systems in healthcare has also been investigated by Tryhuba et al. [25], who proposed a structural model for medical project planning based on computational intelligence. Their study highlights the importance of integrating information processing, intelligent analysis, and decision-support components into healthcare information systems.

The application of LabVIEW for biomedical signal acquisition and processing has also been considered in systems designed for ECG data acquisition [11]. Such approaches demonstrate the suitability of graphical programming environments for implementing measurement algorithms, digital signal processing, visualization, and real-time monitoring. In the context of the present research, these capabilities can be extended from ECG monitoring to the detection of physiological events associated with the propagation of the arterial pulse wave and the generation of synchronized stimulation signals.

The LabVIEW Biomedical Toolkit provides additional functionality for processing biomedical signals, including ECG analysis and extraction of characteristic features [9], [13]. The availability of specialized software tools facilitates the implementation of algorithms for physiological signal preprocessing, feature detection, and parameter estimation. However, the existing approaches are primarily focused on monitoring and diagnostic applications, whereas the present study considers the use of physiological information as a feedback signal for controlling a rehabilitation procedure.

The reviewed studies demonstrate that two important research directions are developing in parallel. The first is associated with the investigation of electrical stimulation as a rehabilitation method for patients with PAD and with the assessment of its influence on walking capacity and peripheral blood flow [2], [3], [4], [5], [6]. The second concerns the development of computerized systems for acquisition, processing, and analysis of physiological signals using platforms such as LabVIEW [9], [10], [11], [12], [13].

However, the analyzed approaches generally consider electrical stimulation and physiological monitoring as separate processes. In particular, the reviewed studies do not sufficiently address the problem of real-time synchronization of stimulation pulses with the patient's current cardiac rhythm and with the moment of arrival of the arterial pulse wave at the affected limb region. This limitation creates a research gap for the development of adaptive rehabilitation systems capable of changing the timing of stimulation according to the current physiological state of the patient. Adaptive approaches to healthcare information systems have also been investigated by Malanchuk et al. [27], who developed a method for adapting the architecture of hospital district development project portfolios to changing environmental conditions. Although focused on healthcare project management rather than physiological control, their research demonstrates the

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applicability of adaptive information system architectures in the medical domain.

Therefore, the development of a virtual measurement and stimulation system that combines physiological signal acquisition, detection of the arterial pulse-wave arrival, real-time processing, and adaptive generation of electrical stimulation pulses represents a relevant direction for further research. Such an approach can provide a transition from predetermined stimulation protocols toward physiologically synchronized and feedback-controlled rehabilitation.

Peripheral arterial disease, particularly obliterating atherosclerosis of the lower limb vessels, is accompanied by impaired peripheral blood circulation, insufficient tissue perfusion, and the development of ischemic manifestations that limit patients' physical activity and functional capacity. The effectiveness of rehabilitation in such patients largely depends on the ability to account for the individual functional state of the cardiovascular system and the dynamics of blood flow in the affected limb.

Traditional physiotherapeutic electrical stimulation devices generally operate according to predefined stimulation parameters and fixed timing modes. They do not account for the patient's current heart rate, its changes during the procedure, or the moment when a subsequent pulse wave reaches the affected area of the limb. Consequently, the electrical stimulation is not temporally synchronized with the natural blood circulation process and does not provide adaptive response to changes in the patient's physiological state.

This problem is particularly relevant to the development of rehabilitation systems based on the cyber-physical approach, since such a system should not only provide a physiotherapeutic intervention but also acquire information about the patient's current physiological state, process the obtained data automatically, and adjust the intervention parameters accordingly. Therefore, there is a need to develop a virtual hardware-software device capable of determining heart rhythm parameters and the moment when the pulse wave reaches the affected area in real time, as well as generating an electrical stimulation signal synchronized with the natural rhythm of blood flow.

Thus, the scientific and technical problem consists in developing and experimentally validating a virtual adaptive electrical stimulation device that measures the patient's physiological parameters, determines the moment when the pulse wave reaches the affected area, and synchronizes the stimulation with the current heart rhythm based on the principles of cyber-physical systems and the LabVIEW hardware-software platform.

RESEARCH AIM AND OBJECTIVES

The purpose of this study is to develop a virtual tool for measuring the heart rate and the synchronized delivery of an electrical stimulation signal to the muscles of the problem area of the biological organism based on the LabVIEW hardware and computing platform.

To achieve the goal, the following problems must be solved:

– develop a virtual measurement and electrical stimulation device based on the LabVIEW hardware-software platform and the NI USB-6008/6009 multifunction data acquisition device;

– develop an algorithm for synchronizing electrical stimulation pulses with the current heart rhythm and the moment when the pulse wave reaches the affected area of the limb;

– implement measurement and automated generation of electrical stimulation signals using physiological feedback;

– conduct an experimental study of the developed virtual device and evaluate the effectiveness of the proposed approach based on changes in limb temperature and blood supply parameters.

MATERIALS AND METHODS

Rehabilitation of diseased biological organisms is aimed at counteracting the functional loss of working capacity. Therefore, with the development of technologies, instrumental methods of targeted action on the organs of biological organisms should replace other methods with their shortcomings.

To determine the state of the limb's blood supply, a complex study method was used, based on the involvement of sensors of pressure, temperature, and the mass of blood filling the limb. Experiments were conducted using modern measuring devices, including virtual ones, with automated processing of measurement results.

DEVELOPMENT OF PULSE SCANNING TECHNOLOGY AND PRESENTATION OF THE SCANNED SIGNAL BY A SMART ACTUATOR TO THE DISEASED AREA IN ORDER TO CORRECT ITS PHYSICAL CONDITION

Let's consider in more detail the equipment for the rehabilitation of sick biological organisms for obliterating atherosclerosis. The existing devices are physiotherapy and rehabilitation tools, designed like conventional devices, and therefore are not able to control the outcome of the procedure, take into account the achieved result and automatically introduce an amendment to the protocol of the future procedure based on it. Moreover, they are not able to automatically, during the procedure, introduce corrections to the rhythm of pulses delivered by the smart actuator, as well as change their form and duration.

PhySys [21] rehabilitation physiotherapeutic complex described above is performed as follows. Here, in one multifunctional rack, the following types of procedures are laid out: electrodiagnostics; electrotherapy; ultrasound therapy, selection and adjustment of depth of influence, selection of thermal effect, micromassage; vacuum therapy; combined ultrasound + electrotherapy; combined electrotherapy + vacuum therapy; combined ultrasound + electrotherapy + vacuum therapy. At the same time, the main types of currents are: TENS – asymmetric, symmetric, alternating, SMT (amplipulse therapy), diadynamic current, Trabert currents, faradic, rectangular and triangular currents, galvanic current (ionophoresis), microcurrents, high-voltage pulses, alternating current with a fundamental frequency 8000 Hz, combined medium / low frequency current, etc. Programs are selected based on preliminary diagnosis before application. In orthopedics, such recommended diseases and disorders are: ankylosing spondylitis (Bekhterev's disease), osteoarthritis of the hip joint, osteoarthritis of the knee joint, osteoarthritis of the shoulder joint, pain in the lower back, pain in the neck, periarthropathy of the shoulder joint, syndrome of the long head of the biceps muscle , myofascial pain syndrome, myalgia, myogelesis, muscle hypertonicity, tenodynia, tenomyalgia, insertional tendopathy, epicondylitis, “tennis” elbow, sprained ligaments, impingement, Sudeck's atrophy, spastic torticollis, muscle atrophy, etc.

Its closest field of application concerns diseases of the cardiovascular system: diseases associated with arterial occlusion, peripheral blood circulation disorders, electrical stimulation of calf muscles, angioneuropathy, and functional blood circulation disorders. Such a disease as obliterating atherosclerosis of the limb is not included in the given list, that is, rehabilitation with the help of the specified device is not provided for.

The device Myomed 932 [22] – a stationary professional device for electrotherapy, electro diagnostics of the state of the muscles – provides the possibility of biological feedback based on the parameters of electromyography (EMG) and pressure. The presence of 18 forms of current and modes of electro diagnostics make Myomed 932 a complex device for electro diagnostics and electrotherapy. For example, motor functions can be restored. For example, for manometry of the pelvic floor, pressure sensors are used in combination with EMG sensors of the abdominal muscles. Both feedback signals are displayed simultaneously on one diagram of the Myomed 932 device. However, this prototype cannot be used for the rehabilitation of patients with obliterating atherosclerosis of the vessels of the limbs, since the electromyography method as such is suitable for direct action on muscles, and not on vessels.

In contrast to the above-mentioned means of rehabilitation, we investigated the indirect effect of electromyography. It manifests itself precisely due to the provision of automatic scanning of the pulse or the frequency of blood flow to the limb with simultaneous reproduction of the received frequency so that the arrival of each specific wave of natural blood flow to the diseased part of the limb coincides in time with the delivery of an impulse to this area, and the duration of the impulse corresponds to the duration of the blood wave through the damaged area. Thus, acting on the muscles at certain moments determined by the device, gradually, as the procedure progresses, the conditions for the flow of the blood wave, which is naturally supplied to the limb due to the work of the heart, are facilitated.

To improve the rehabilitation process, to obtain data on the time-varying rhythm of the heart and to correctly determine the moment of arrival of the blood wave to the limb, a smart sensor with a constant inertia of less than 0.05 of the heartbeat period is used, and a smart actuator with such the most constant inertia, and the smart sensor is installed on the limb

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above the blood flow at a distance of 5-50 cm from the place of installation of the smart actuator.

Cyberphysical system for the purposes of rehabilitation of sick living organisms with obliterating atherosclerosis of the vessels of the limbs is proposed for the first time. Its structure involves the presence of a smart sensor (here to determine the parameters of the heartbeat and, most importantly, the moment of arrival of the blood wave to the damaged vessel of the limb) and a smart actuator (here it produces electrical impulses that are applied to the area with the damaged vessel). who work together. For a patient with obliterating atherosclerosis of the vessels of the limbs, the system must regulate or control a certain physical parameter. The last can be considered the patency of blood vessels, the improvement of which leads to an increase in the temperature of the limb and can be measured instrumentally with the help of a temperature sensor. Another instrumentally controlled parameter can be increased pulsation of the vessels of the limb (in the area of the ankle-foot joint), measured by a strain gauge. An increase in the degree of blood filling of the blood vessels of the limb of a biological organism in the supine position can also be controlled with the help of pre-balanced scales, since a sensitive and accurate method of measuring the mass (torque moment) has been developed [15], which makes it possible to feel the movement of the blood mass of 0.2 g over a distance 1 cm, that is, a change in the torque by 2·10-6 kgm.

On the basis of the LabVIEW platform, a virtual tool was developed for measuring the heart rate and the synchronized delivery of an electrical stimulation signal to the muscles of the problem area of the biological organism. Having previously determined the necessary parameters for the generated signals, a structural diagram of the built device was formed. For this, the possibilities were carefully studied, the parameters of the generated signals, the limits of their permissible values and the limits of uncertainty of the specified values were determined.

To determine the moment of arrival of the wave of arterial blood pressure, it is suggested to use a thermistor capable of quickly sensing fairly minor temperature fluctuations when tightly pressed to the skin of the leg (foot). The diagram for connecting the thermistor to the measuring unit of the virtual device is shown in Fig. 1.

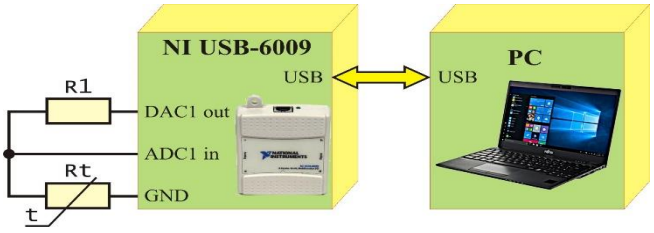


Fig. 1. **Connection diagram of the thermistor to the measurement and control unit of the NI USB-6009 unit**

***Source*: compiled by the authors**

To set the operating current of the thermistor, it is recommended to use a digital-to-analog converter included in the mentioned unit. The DAC output is connected to the thermistor through resistor R1. As a result, the resistor and the thermistor form an output voltage divider equipped with a DAC; the dividing factor of the divider depends on the temperature of the thermistor. The NI USB-6009's USB output connects to a PC's USB port using a suitable cable. So, the proposed scheme of the measuring channel is quite simple. From the set of radio technical elements included in the NI USB-6009 unit, only a thermistor and a resistor are used. As shown below, the resistor demands high accuracy, low temperature coefficient and stability of characteristics over time. Other requirements for the thermistor: low inertia (time of propagation of the blood wave through the body to the specified place on the leg is less than 0.1 s.) and high sensitivity in relation to the temperature drop caused by the passage of the said blood wave.

The thermistor conversion function is close to an exponential:

$$R_T = A \cdot e^{-\frac{B}{T}}, \quad (1)$$

Here, RT is the resistance of the thermistor at temperature T; A is a coefficient that characterizes the change in the resistance of the thermistor when the temperature changes. The deviation of the real transformation function from the exponential function does not exceed 0.01°C. Therefore, to determine the conversion function of a certain thermistor in experimental studies, it is sufficient to calibrate it at two fixed temperatures x. It is noted [14] that the limit of permissible deviation of the thermistor resistance at 293 K is ± 5% of the nominal resistance. Also, the limit of permissible deviation of the temperature coefficient of its resistance is ± 5 %. From the nominal

value equal to ~4 % / K. The inertia of the thermistor is important. In order for the inertia constant of the virtual device for rehabilitation to be negligible as a whole, the thermistor should have high thermal conductivity at a low mass, and its thermal inertia constant should not exceed 0.1 s. The peculiarity of its use is the following: for the diagnosis of a slight (~0.1 K) increase in temperature, the temperature coefficient of resistance (TCR) of the thermistor is important. The output signal of the thermistor must be sufficient in terms of electrical characteristics for further operation of the electronic circuit. For TCR 4% / K and a current strength of ~ 1 mA, when a temperature increase of 0.1 K is detected, a voltage drop of ~ 80 mV is carried out on the thermistor with a resistance of 20,000 Ohms

To increase the efficiency of the developed method, it is proposed to coordinate the presence of the average control signal with the moment of arrival of the pulse from the heart. Thus, even when there are differences between each subsequent signal and, accordingly, the arrival of a wave of blood flow, the control signal is automatically aligned with the change in rhythm. In addition, when the location of the actuator on the limb changes, the virtual device automatically shifts the actuator trigger point.

The conversion function of the NI USB-6009 block [7] with a connected thermistor is not known precisely enough, in particular for metrology tasks. To determine it, we will simulate measurements using a thermistor. To do this, it is replaced by a large amount of electrical resistance. The following resistance values are set in turn – from 5 kΩ to 55 kΩ – in steps of 5 kΩ, by connecting them alternately to the ADC1 and GND inputs of the NI USB-6009 block. As a result, a non-linear transformation function of the indicated block was determined, which is up to 3%. The specified value is insignificant for the operation of the created rehabilitation tool.

TCR of the metal oxide resistor R1 does not exceed 0.02 % per 1K. For comparison, the same thermistor coefficient is 4 % per 1K. Therefore, the effect of the used additional resistor does not exceed 5% and can be neglected.

The effect on the measurement result of the resistance of the power wires can also be neglected, even for a two-wire connection scheme; the length of copper wires with a cross-sectional area of 0.2 mm2 can be up to 50 m. As a result of the examination, the use of a thermistor to detect the increase in temperature of a limb of a biological organism and to start the smart actuator for the supply of an electrical impulse based on its signal is justified. At the same time, a non-contact method using an IR pyrometer specially calibrated according to [17] is proposed for monitoring the temperature of the limb.

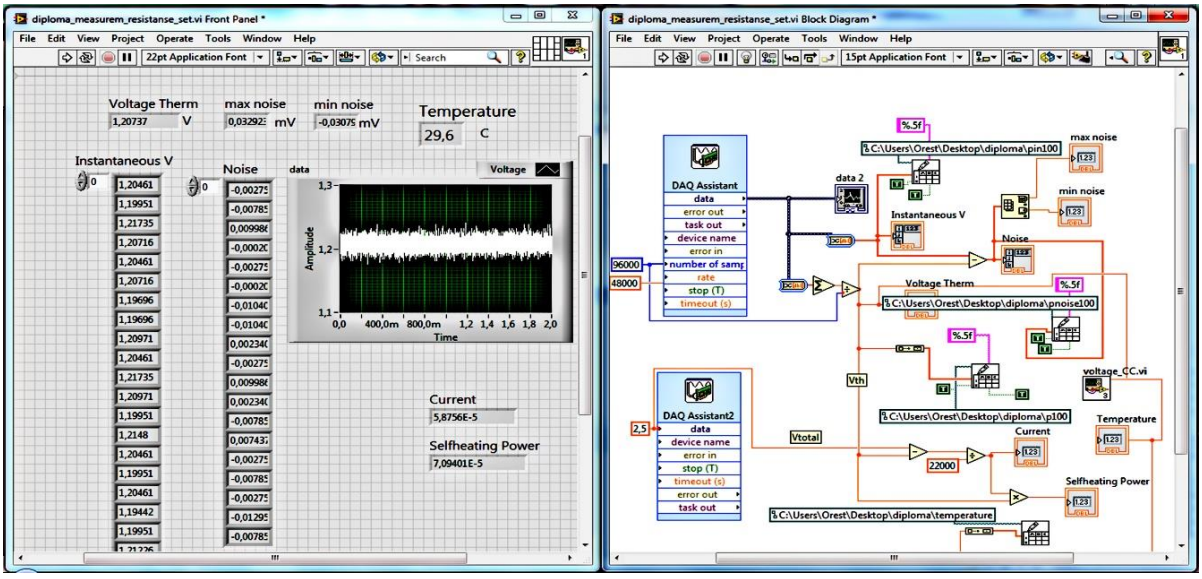


Fig.2. **A virtual device for the rehabilitation of biological organisms of patients with obliterating atherosclerosis of the vessels of the limb in the part of determining the moment of blood flow according to the thermistor readings**

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On the left, on the front panel (Fig. 2), there are indicators of the average voltage on the thermistor "Voltage Therm", the maximum value of the noise "max noise", the minimum value of the noise "min noise", the average value of the current through the thermistor "Current" and the power of self-heating caused by current measurement – "Self-heating power", as well as arrays of instantaneous voltage values on the thermistor "Instantaneous U", noise value "Noise"; graph showing the value of the instantaneous voltage across the thermistor during measurement. The block diagram on the right shows DAQ Assistant configured to measure voltage from an analog input with a sample size of 96000 and a sample rate of 48000.

The measurement results are sent to the "Data" graph and displayed on the front panel. They are also sent to the Instant U indicator and displayed on the front panel, as well as written to a spreadsheet file. These data are averaged, and the resulting value is sent to the "Voltage Therm" indicator and converted into an array for writing to a table file. The determined difference between the array of measured values and the average value is sent to the Noise indicator for display on the front panel, as well as for writing to a spreadsheet file. In addition, the maximum and minimum deviations from zero are selected from this array, which are highlighted on the "max noise" and "min noise" indicators, respectively. DAQ Assistant2 is configured to generate 2.5 V as the measurement current source. In addition, the measurement currents of the thermistor and its self-heating are calculated.

The program contains a routine that converts the thermistor voltage to a temperature in degrees Celsius using the conversion function:

$$t = (T - 273.15) = 21.359U_{THERM}^4 - 115.77U_{THERM}^3 + \\ +225.92U_{THERM}^2 - 228.49U_{THERM} - 138.63 \quad (2)$$

In addition, the unit produces pulses of various shapes (rectangular, triangular, and trapezoidal) to be applied to the electrodes glued to the skin of the problem area of the leg. Their amplitude does not exceed 5 V, and the duty cycle is ~ 1.0 Hz, which corresponds to the pulse frequency. The beginning of each subsequent cycle is a signal from the thermistor.

The operation of the block diagram of the means for measuring and analyzing the characteristics of the blood circulation of a biological organism mainly consists in the in situ synchronization of each alternating wave of blood pressure in the problem area of the limb with the generation of an electrical stimulation signal, which leads to an increase in the throughput of the affected artery. Taking into account the frequency of heart contractions during a 10-minute session, 600 repeated actions are performed, which ultimately leads to the appearance of a rehabilitation effect. It was evaluated based on the results of non-contact measurement of the skin temperature of the same area of the affected leg. After 10 minutes of the procedure, the temperature of the controlled zone increased by ~10C.farms, and return to them with cargo.

CREATION OF A VIRTUAL TOOL FOR THE REHABILITATION OF PATIENTS WITH OBLITERATING ATHEROSCLEROSIS OF THE VESSELS OF THE LOWER EXTREMITIES BASED ON THE SOFTWARE AND HARDWARE PLATFORM LABVIEW

To increase the accuracy of receiving information and its timely use in time with the time-varying rhythm of the heart, a temperature (pressure) sensor with a digital output and high sensitivity was used as a smart sensor, capable of working as a signal source in the software and hardware platform, and as a smart - the actuator uses a digital hardware unit compatible with the mentioned platform and capable of generating pulses of various forms with a maximum amplitude of 5 volts at an automatically set frequency corresponding to the current heartbeat frequency. The latter is a block of the NI USB 6008/6009 Bus-Powered Multifunction DAQ USB Device type with software based on the LabVIEW hardware and software platform [8], [18], which are necessary to create a virtual means of measuring the heart rate and sending an electrical stimulation signal synchronized with the work of the heart. It should be noted that this tool can be created by any enterprise if there is a cheap NI USB 6008/6009 type device, standard software from National Instruments, USA and a personal computer.

Within the limits of the specified platform, when executing a virtual device in an automated mode in the language of graphic programming, hardware and software were developed for an instrumental method of rehabilitation of patients with obliterating atherosclerosis of the vessels of the extremities by means of in situ electrical stimulation taking into account the heart rhythm.

In addition, as a result of the conducted research, the method of extracting information from the biological organism was optimized thanks to the study of temperature and features of cardiographic information, the determination of separate categories of informativeness of cardio signals and the characteristics of the passage of the pressure wave of arterial blood flow through the arteries, in particular, the limbs, including the involvement of nanotechnological means of extracting information from the biological organism (of an azure interferometer [24] with a sensitivity of 1 nM in real time). It was used for non-contact calibration of the ultrasonic smart distance sensor of the IFM company [16], when monitoring the last passage of the pressure wave of the arterial blood flow along the artery of the limb (by measuring the distance to a pulse-sensitive place, for example, the lateral surface of the heel). This makes it possible to control on the spot changes in the state of arterial blood flow as a result of the rehabilitation procedure.

The device for the rehabilitation of a biological organism with obliterating atherosclerosis of the vessels of the limb is made on the basis of a smart actuator that delivers electrical impulses to the affected part of the limb, carrying out a physiotherapy procedure of a given duration and intensity, and a smart sensor that monitors the integral and/or current result of the procedure. To achieve a rehabilitation effect, increase efficiency and improve multifunctionality, the device is created virtual, for which it is additionally equipped with a hardware and software platform, the software unit of which is installed in the computer; a hardware unit capable of performing the functions of a smart actuator is allocated outside the computer; the smart sensor is made of low inertia, able to determine in real time the moment of arrival of each next wave of blood flow to the affected part of the limb and send a signal to the software block of the platform, where it is analyzed, a trigger pulse is generated for the hardware block, which generates a pulse of the required polarity, duration, modulation, etc., applied to the electrodes at the moment of time that coincides with the arrival of the wave of blood flow, facilitating the conditions of blood flow along the affected vessel of the limb precisely during the period of arrival of blood. As a result of multiple repetitions of the delivery of pulses synchronized in time with the natural work of the heart, pulse-based rehabilitation of the vessels of the diseased limb is carried out.

Fig. 3 shows a diagram of the conversion function of the NI USB-6009 block when measuring the resistance of a linear sensor, which in the room temperature range is a film platinum resistance thermometer with a constant thermal inertia of less than 0.1 s.

Fig. 4 shows a routine for measuring the voltage of a smart sensor – a tightly glued resistance thermometer that determines the temperature of a limb and its changes during the arrival of a blood wave.

The device works as follows. First of all, the virtual device already formed on the basis of the LabVIEW platform is calibrated to work with certain smart sensors, for example, with a temperature sensor based on a film platinum thermometer of low inertia resistance. The latter is pre-connected to the hardware unit, as shown in Fig. 3, and the transformation function of this unit is studied, which is necessary to ensure the accuracy of temperature measurement when determining with the help of a smart sensor the moment of arrival of a wave of warm blood to the place where the sensor is attached to the limb.

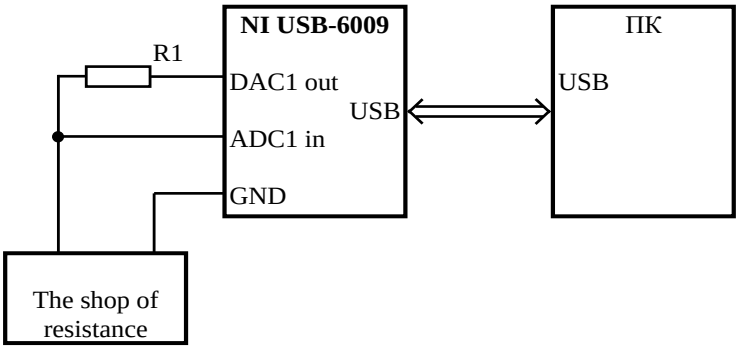


Fig.3. **NI USB-6009 unit conversion function research scheme**
Source: **compiled by the authors**

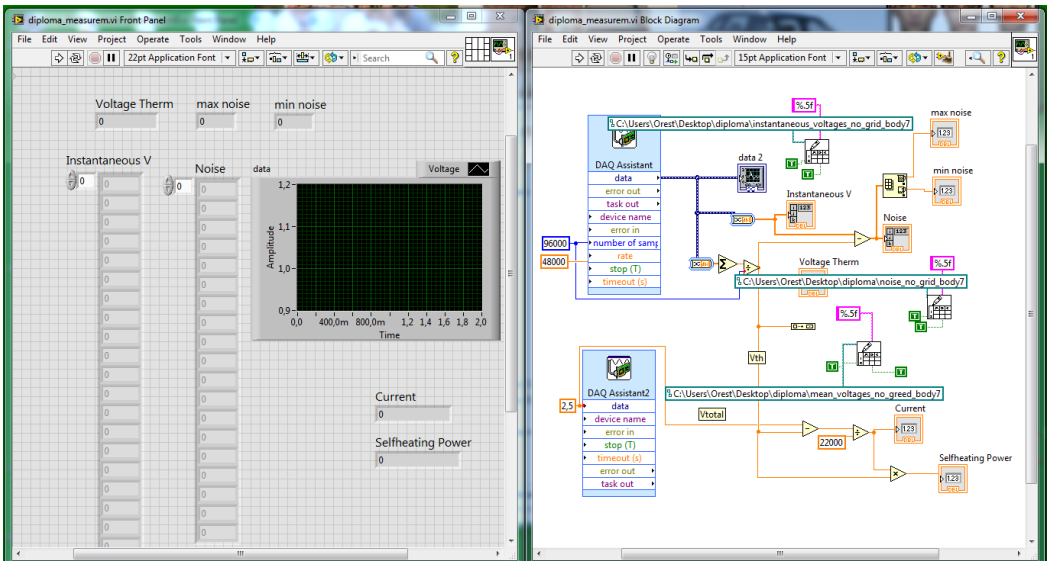


Fig.4. **A subroutine of the LabVIEW hardware and software platform, designed to measure the voltage of a smart sensor, is displayed on a PC**

***Source*: compiled by the authors**

Next, the smart sensor is fixed on the limb above the affected area, approximately 5-20 cm. The time for the blood wave to travel the specified distance is enough for the low-inertia sensor to activate and transmit a signal to the hardware unit. The latter produces an electric pulse with an amplitude of 3-5 V and transmits it to two glued electrodes fixed on the affected area. Thus, this pulse is given simultaneously with the arrival of the blood wave to the indicated place. The shape and duration of the pulse are regulated with the help of a hardware unit that can work with a frequency of up to 0.1 - 999 Hz at an amplitude of up to 10 V.

Due to the implementation of the studied method and device, procedures were performed on 5 biological organisms with signs of obliterating atherosclerosis of the vessels of the lower extremities (2nd stage of the disease). The temperature of the limb increases by 1-2 0C after the session. Otherwise, as a result of the procedure, a rehabilitation effect is achieved, which is estimated as an improvement in vascular patency by 7-12% in one session. Four consecutive sessions with an interval of 2 days between them improved the condition of the biological organisms, as assessed by an increase in the temperature of the limb to acceptable values - 28 0C.

DISCUSSION OF THE RESULTS

The obtained results confirm the feasibility of using a virtual hardware-software device for adaptive electrical stimulation in the rehabilitation of patients with obliterating atherosclerosis of the lower limb vessels. Unlike traditional physiotherapeutic devices, in which stimulation parameters are mainly predefined before the procedure and remain unchanged, the proposed device generates a control signal based on the patient's current physiological state. This makes it possible to move from a fixed electrical stimulation mode to an adaptive mode based on physiological feedback.

The conducted studies demonstrated that the use of a low-inertia temperature sensor makes it possible to detect physiological signal changes associated with the propagation of the pulse wave and to use the acquired information to determine the appropriate moment for generating an electrical stimulation pulse. An important advantage of this approach is the ability to account for changes in heart rate during the procedure. When the duration of the cardiac cycle changes, the system automatically adjusts the time interval between subsequent stimulation pulses, maintaining their synchronization with the current blood flow rhythm.

The results obtained using the hardware component based on the NI USB-6008/6009 demonstrated the feasibility of implementing both measurement and control functions within a single hardware-software system. The use of LabVIEW enables simultaneous signal acquisition, digital signal processing, determination of the sensor activation moment, and generation of the actuator control signal. This provides the basis for implementing a closed-loop cycle of "physiological parameter – measurement – processing – control – physiotherapeutic intervention."

The results of the experimental evaluation are of particular interest. After a session lasting approximately 10 minutes, the temperature of the controlled limb area increased by approximately 1–2 °C. Within the scope of the conducted study, the improvement in peripheral blood supply was estimated at 7–12%. After four consecutive sessions with two-day intervals, a further increase in limb temperature was observed, reaching values close to 28 °C. This dynamic indicates a positive response of peripheral blood circulation to the proposed synchronized electrical stimulation mode.

However, an increase in limb temperature cannot be considered the only direct indicator of restored arterial patency. Skin temperature may be affected by systemic circulation, ambient temperature, the condition of the skin and underlying tissues, limb position, and other physiological factors. Therefore, the observed temperature response should be considered as one of the indirect indicators of changes in peripheral perfusion. More objective confirmation of the effectiveness of the proposed method in future studies should combine temperature monitoring with the ankle-brachial pressure index, pulse-wave parameters, peripheral blood volume, and other clinically validated indicators.

Comparison of the proposed approach with conventional electrical stimulation methods highlights its main advantage—the temporal adaptation of the physiotherapeutic intervention to the individual physiological dynamics of the patient. In conventional systems, the frequency, duration, and timing of stimulation pulses are primarily determined by a predefined treatment program. In the proposed virtual device, the timing of each pulse is determined from the current measurement, allowing changes in heart rate and the position of the actuator relative to the pulse-wave detection site to be taken into account.

Another important feature of the developed device is its modular architecture. Replacing or adding sensors makes it possible to expand the range of physiological parameters used to control the rehabilitation procedure. In particular, pressure, temperature, pulse, and peripheral blood-volume sensors can be integrated into the system. This creates the possibility of transitioning from single-parameter to multiparameter physiological feedback, in which decisions concerning changes in electrical stimulation parameters are based on a combination of measured physiological indicators.

At the same time, the obtained results have certain limitations. The experimental evaluation was conducted on a limited number of patients; therefore, the reported values cannot be considered definitive evidence of the clinical effectiveness of the proposed method. In addition, the present study focused primarily on the technical performance of the virtual device and on changes in temperature and peripheral blood supply. Confirmation of clinical effectiveness requires further studies involving larger samples, control groups, standardized treatment protocols, and a comprehensive set of objective hemodynamic indicators.

Thus, the results demonstrate the technical feasibility of implementing adaptive electrical stimulation based on physiological feedback and synchronizing the stimulation with the current heart rhythm. The developed virtual device based on LabVIEW and NI USB-6008/6009 integrates measurement, data processing, and control functions within a unified cyber-physical system. The observed increase in limb temperature and improvement in peripheral blood supply parameters following the procedures indicate the potential of the proposed approach. Further development of the system should focus on improving the accuracy of pulse-wave arrival detection, expanding the range of monitored physiological parameters, and conducting larger-scale experimental and clinical studies.

CONCLUSIONS

A virtual apparatus has been developed for the rehabilitation of biological organisms suffering from obliterating atherosclerosis of the vessels of the extremities. It scans the heart rhythm, monitors changes in frequency, and generates signals to electrodes attached to the muscles. Signals are sent precisely at the moment of passage of each current wave of blood circulation, which contributes to the improvement of vascular patency and the achievement of a rehabilitation effect in patients. Thus, the temperature of the limb increases by 1-2 degrees. The restoration of blood circulation in it was estimated at 7-12%, as a result of a session lasting 10 minutes. Four sessions in few days turned out to be enough for a noticeable improvement in blood circulation.

A virtual device has been combined the functions of an electrocardiograph - to determine the heart rate - and an electromyostimulator - to enhance the power of arterial blood flow, taking into account the heart rate. Since it allows you to scan the work of the heart, when the frequency of its work changes, it monitors these changes and its output signals to the electrodes attached to the muscles at the exact moment of passage of each current wave of blood circulation, which helps to improve the patency of

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blood vessels and achieve a rehabilitation effect in biological organisms suffering from obliterating atherosclerosis of the vessels of the extremities.

FUTURE WORK

Further research should focus on improving the accuracy, adaptability, and functional capabilities of the developed virtual rehabilitation device. First, the algorithm for determining the moment when the pulse wave reaches the affected area of the limb should be improved, taking into account individual characteristics of blood circulation and possible changes in heart rate during the procedure.

A promising direction is the transition from using a single physiological parameter to multiparameter feedback. For this purpose, the system should integrate temperature, pressure, pulse, peripheral blood volume, and other biomedical sensors. This will make it possible to improve the accuracy of assessing the patient's peripheral blood circulation and provide more adaptive control of the electrical stimulation parameters.

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Data Availability: The experimental data were obtained during the investigation of the developed virtual rehabilitation device based on heart rate measurement and synchronized electrical stimulation. The experimental parameters, measurement results, and graphical materials are presented in the main text of the manuscript. Additional experimental data may be made available by the corresponding author upon reasonable request

Use of Artificial Intelligence Tools: During manuscript preparation, artificial intelligence tools may have been used solely for grammatical and stylistic proofreading. Artificial intelligence was not used to generate scientific results, develop mathematical models, perform experimental investigations, or formulate conclusions. All scientific contributions, experimental results, and conclusions represent the authors' own intellectual work

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Віртуальний засіб для реабілітації пацієнтів на основі розробленої моделі вимірювання частоти серцевих скорочень

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АНОТАЦІЯ

Актуальність. Розроблення інтелектуальних інформаційно-вимірювальних систем є важливим напрямом сучасної біомедичної інженерії. Особливого значення набуває синхронізація фізіотерапевтичного впливу з індивідуальними фізіологічними процесами для підвищення ефективності реабілітації пацієнтів із порушеннями периферійного кровообігу. **Метою дослідження** є розроблення моделі вимірювання параметрів серцевого ритму та віртуального засобу синхронізації електростимуляції з природним ритмом периферійного кровотоку. **Завдання дослідження** передбачають визначення моменту надходження артеріальної пульсової хвилі до ураженої ділянки кінцівки, реалізацію віртуальної системи вимірювання та електростимуляції й експериментальне оцінювання її працездатності. **Методи.** Використано методи проєктування кіберфізичних систем, оброблення біомедичних сигналів, математичного моделювання, віртуальних вимірювань та автоматизованого керування зі зворотним зв’язком. Систему реалізовано з використанням обладнання для збирання даних і середовища LabVIEW. **Наукова новизна.** Запропоновано модель адаптивного керування електростимуляцією, що забезпечує синхронізацію стимулюючих імпульсів із проходженням артеріальної пульсової хвилі. На відміну від систем із фіксованими інтервалами стимуляції, розроблений засіб динамічно коригує момент подання імпульсів відповідно до змін серцевого ритму та периферійного кровотоку. **Практична значимість.** Розроблений засіб забезпечує моніторинг фізіологічних сигналів, формування синхронізованих імпульсів у реальному часі та оцінювання результативності реабілітації за температурою кінцівки й показниками кровообігу. Рішення може застосовуватися для створення адаптивного фізіотерапевтичного обладнання. **Результати.** Експериментально підтверджено працездатність розробленого засобу та можливість синхронізації електростимуляції з фізіологічним ритмом пацієнта. Під час реабілітаційних процедур спостерігалося підвищення температури

кінцівки та покращення показників периферійного кровопостачання. **Висновки.** Розроблена модель і віртуальний засіб створюють технологічну основу для адаптивної електростимуляції, синхронізованої з динамікою кровотоку. Результати підтверджують можливість інтеграції віртуальних вимірювань, оброблення біомедичних сигналів та автоматизованого керування в інтелектуальні реабілітаційні системи.

Ключові слова: віртуальні вимірювальні системи; біомедичні сигнали; частота серцевих скорочень; електрична стимуляція; фізіологічний моніторинг; адаптивне керування

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