A Mobile Exoskeleton Control System Using Electromyographic Signals from Human Muscles

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The aim of the study was to develop a wireless system of registration and analysis of electromyographic (EMG) signals from human muscles to provide intelligent assistance to patients with motor disorders.

Results. Single-channel and four-channel systems for translating muscle tension signals into exoskeleton control commands and control algorithms have been developed and tested. They have an advantage in mobility, portability and availability of wireless EMG signal sensors-amplifiers (myographs). Experimental testing of both systems has demonstrated a high quality of EMG signal and the ability of proportional actuator control. The mobile myographic can be applied in the field of functional diagnosis, neurointerfaces, medical rehabilitation, assistive devices, control systems, and gaming applications.

Key words: surface electromyography; neurointerface; neurorehabilitation; intelligent assistive device; exoskeleton.

One of the most promising directions in the technologies of regenerative medicine is the development of interfaces for bidirectional interaction of a human with robotic rehabilitation devices. A special interest has been recently given to the adaptive control using bioelectric signals from the human central and peripheral nervous system [1]. Owing to a rapid progress in development and miniaturization of electronic components, more research is focused on the development of interfaces with human muscles, as such interfaces have a large number of degrees of freedom. New technologies [2], mathematical methods, and approaches using nonlinear dynamics and neuronal networks are being constantly developed to solve a fundamental problem of extracting a control signal from the electromyographic (EMG) signals of the human muscles [3, 4].

Various algorithms of EMG signal processing are used to estimate the muscle tension degree. The most common method is based on the calculation of root mean square (RMS) error in a sliding time window [5], being often sufficient for obtaining general information about the tension of one or several groups of muscles. To estimate more detailed characteristics reflecting complicated contraction patterns, spectral characteristics of EMG signal, isolation of potentials of motor unit action [6] using classification [7] and different methods of machine learning [8–10] are used.

Interfaces for muscle signal translation are used in biomedical applications to control electromechanical upper limb prostheses [11], for rehabilitation complexes [12] and exoskeletons of both upper and lower limbs [13–17]. Since rehabilitation is one of the most perspective directions, the development of interfaces for exoskeletons is of special interest. Interfaces for patients with complete and partial spinal cord damage [15], for

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robotic ankle control [16], sit-to-stand posture change [13], or control of the upper limb muscle signals [18] have already been designed.

An interface for proportional control of the exoskeleton during single support phase using a four-channel EMG recording system is presented in this work. The proposed method of exoskeleton proportional control (joint flexion/extension angles) using residual muscle activity signals of lower limbs is intended to initiate biofeedback mechanisms, which in turn will accelerate rehabilitation processes. In case of paraplegia, the proportional control can be implemented using sensors placed on arbitrary muscle showing the contractile ability in response to pilot intention to make a movement. First, to solve the problem of exoskeleton proportional control, a single-channel EMG recording device with a miniature form-factor and wireless data transmission has been developed. It can be placed on any muscle for monitoring EMG activity and formation of control signals for exoskeleton actuators. Later, a four-channel EMG recording system was designed on the basis of the single-channel device enabling registration of the low limb muscle activity using the same signal processing unit to control four exoskeleton leg actuators.

Materials and Methods

A single-channel system. A single-channel system uses a single-channel wireless EMG registration device (myograph) based on AD8221 differential amplifier (DA) (Analog Devices, USA) and Attiny microcontroller (Atmel Corporation, USA). The system is powered by 3.7 V 250 mA·h lithium-polymer (Li-Pol) battery. The device translates the registered EMG signals to the control unit via a radio channel using NRF24L01 transmitter (Nordic Semiconductor, Norway) (Figure 1 (a)).

The control unit, based on Atmega328 (Atmel Corporation, USA) microcontroller, consists of NRF24L01 radio receiving module, control and data transfer board, and is connected via USB-interface with the computer provided with Ubuntu operating system or to BeagleBoard-XM board (BeagleBoard.org Foundation, USA) (in the real experiment with the exoskeleton).

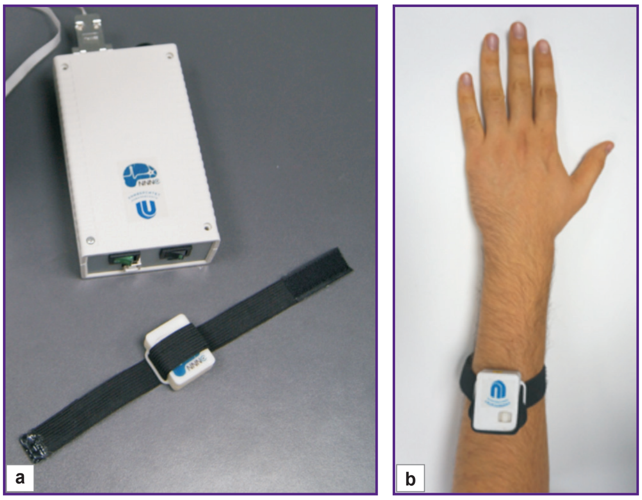

Figure 1. Single-channel system of EMG signal registration:
(a) single-channel myograph and control unit; (b) myograph attached to the forearm for extensor muscle activity registration

The control unit, which continuously receives data from the myograph as a sequence of digital signal values with 1 kHz sampling rate, implements the main function of muscle signal processing and translation into the control commands. The unit calculates the muscle tension force as a root-mean-square error of the original EMG signal in the 300 ms time window using the algorithm developed by the authors and defines it as a RMS signal. The processed RMS signal is then transmitted to the controlled device via the COM-port.

In this control system, the control signal was normalized to minimal and maximal muscle contraction (RMS signals). In this mode, the obtained RMS values

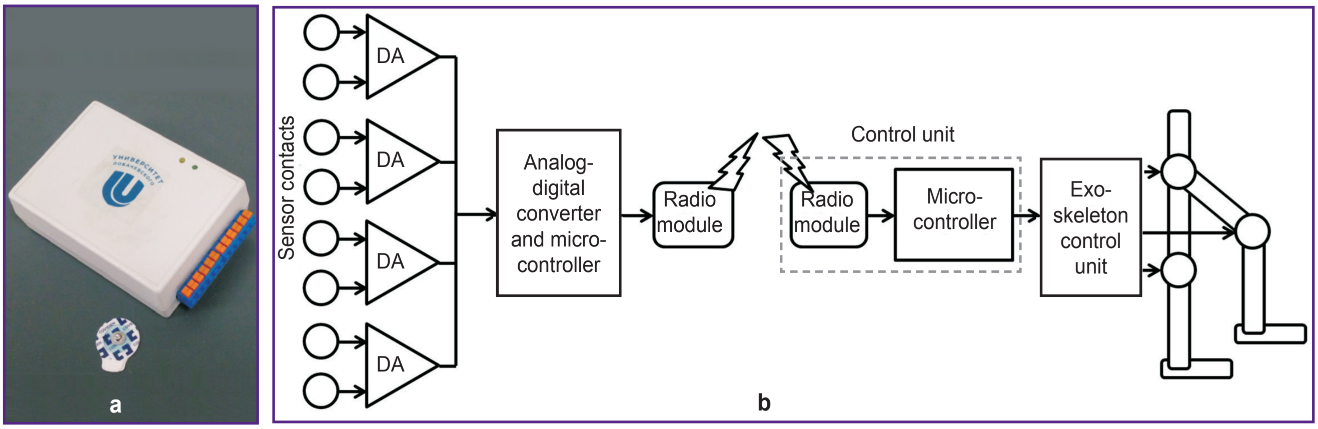

Figure 2. Four-channel system of EMG signal registration:
(a) 4-channel myograph and medical electrode; (b) schematic diagram of converting EMG signal into the control commands for exoskeleton actuators; DA — differential amplifier

are analyzed, the program finds and stores minimal and maximal values, while a person is periodically relaxing and contracting his muscles to the maximum extent possible.

A four-channel system. A 4-channel control system (Figure 2) was implemented on the basis of the single-channel one, and consists of four interconnected single-channel amplifiers, one unifying Atmega328 microcontroller, and one NRF24L01 radio module for simultaneous translation of signals from four muscles to the interface device.

The data obtained from the interface device are transferred via the USB-interface to the BeagleBoard-XM microcomputer-based exoskeleton control unit. Using the controller developed algorithm, the control unit processes pairwise EMG signals from muscle-antagonists to obtain the appropriate differential RMS signal. The received signal is the basis for the calculation of the exoskeleton actuator rotation angle. A digital PID controller was used to form a corrective control action on the actuator.

The force moment value on the PID controller output was quantified using the following formula:

$$u(t)=P+I+D=K_p e(t)+K\int_0^{\hat{o}} e(t)\int t+K_d\frac{\int e(t)}{\int t},$$

where in this implementation: P is proportional, I — integral, D — differential components of the function; K_p, K_i, K_d are their respective coefficients; $e(t)$ is an error at the current moment.

An exoskeleton was composed of the control unit, mechanical framework, four brushless motors and a battery. The framework allows the pilot to bend each leg in the hip, knee and ankle joints (Figure 2 (b)).

Results

System characteristic testing. To evaluate the feasibility of using a wireless device, an amplifier of muscle tension EMG signals, the main system characteristics have been tested.

The results of the test showed the main characteristic of the amplifier, the differential signal gain coefficient, to be equal to 500.

Further, the common-mode signal reduction coefficient (CMSRC) in the myograph reflecting the accuracy of analog signal processing, especially in amplification of weak signals, has been estimated. CMSRC was defined as a relation of the coefficients of differential signal gain to common-mode signal gain. The value of CMSRC was found to be 101.6±0.4 dB. The CMSRC value of the AD8221 differential amplifier used in the developed device was equal to 100 dB, which agrees with the experimental measurements and characterizes a high quality of signal amplification and common-mode noise reduction.

The third key characteristic of the device, signal/noise ratio (SNR), has also been tested. SNR is a dimensionless quantity equal to the relation of the desired signal power to the noise power, which reflects the effect of the noise on the characteristics of signal extraction. In the series of the experiments, signals of sinusoidal form with a frequency of 35 Hz and amplitudes of 100, 200, and 500 μV were applied from the voltage signal generator to the sensor of the wireless EMG signal amplifier.

A mean SNR for 100 μV input signal was 11.9±0.5 dB, for 200 μV — 19.3±0.7 dB, for 500 — μV 29.2±0.9 dB. Series of SNR values measured experimentally showed stability of this characteristic but in the majority of cases such a level cannot be considered very high. However, normal values in these signal amplifiers (usually 50 dB and more) are indicated for measurements performed in ideal conditions. They may include shielding, switched-off consumer devices, a large laboratory room, application of hardware filters in the experiment. Such accurate measurements in real noisy conditions are unachievable. Besides, the microcontroller and radio module, being additional sources of noise, are also included into the system of the wireless amplifier. Thus, the values of SNR measured in the conditions close to real-world may be considered high, as they insignificantly less than the standard values obtained in the ideal conditions.

To compare the capabilities of the developed device, a mobile myograph, with its analogs, their main technical characteristics have been analyzed (see the Table).

The presented comparison shows that the mobile myograph is not any inferior to the world analogs by its main parameters and can perform the necessary tasks of EMG control.

Testing of the developed systems interface with an exoskeleton. The single-channel system of EMG signal registration and processing was tested for the quality of online interfacing with various actuators on an electromechanical prosthetic wrist and a lower limb exoskeleton in the proportional control mode.

In the experiment with the wrist model, a coordinated control of electromechanical finger bending with the delay not exceeding 300 ms has been achieved. Being placed on different arm muscles the mobile myograph could provide an adequate proportional control.

Then the control of one exoskeleton motor (leg bending) was tested using the myograph placed on the human shin flexor muscle. The best result in that experiment was a full visual imitation of movements. However, a number of drawbacks of such a neurocontrol system were revealed in the course of the experiment. The first one was the response time of the exoskeleton construction, caused by its mass and dimensions, leading to high values of the construction inertia moments. This disadvantage is an engineering problem, which will be solved in future by improving the construction. The second drawback is connected with a high muscle tension. In this case, the RMS signals become unstable and depend nonlinearly on the contracting force resulting in the difficulty of exoskeleton motor control.

Comparative table of EMG device characteristics

Characteristics	Device name								
	Neurotech	Myocom	Myomed 134	Neuromyan	Delsys	BTS FREEEMG	Noraxon	Thalmic Myo	Mobile system (developed by the authors)
Reference	neurotech.ru	www.rista.ru	www.enraf-nonius.org/	www.medicom-mtd.com	www.delsys.com/products/	www.btsbioengineering.com	www.noraxon.com/products/	www.myo.com	www.unn.ru
Producer country	Russia	Russia	Netherlands	Russia	USA	USA	USA	Canada	Russia
Type	Wireless	Wire	Wire	Wire	Wireless	Wireless	Wireless	Wireless	Wireless
Number of module channels	1	4 or 8	11 barometry channel, 2 myography channels	2. 4 or 5	1	1	1	8	1–8
EMG signal passband (Hz)	No data	20–500	0–400	Lower passband edge: 0.01–300 Hz; upper edge: 10–20 kHz	20–450	No data	No data	No data	20–400
Sensors	EMG	EMG	EMG, barometry	EMG	EMG, accelerometer	EMG	EMG	EMG, accelerometer	EMG, accelerometer, gyroscope
Analog-digital converter capacity (bits)	No data	16	No data	16	16	16	16	8	12
Sampling rate (Hz)	No data	200	No data	200,000	1,926	1,000	1,500 or 3,000	200	450
Communication interface	2.4 GHz, proprietary	USB	No data	USB	2.4 GHz, proprietary	Wireless IEEE 802.15.4	2.4 GHz, UGWG4USBB33 module	BLE	BLE
Power supply	Storage battery	USB	100–240 V±10%, 50–60 Hz	No data	Storage battery	Storage battery	190 mA storage battery	400 mA storage battery	Storage battery
Charging time (h)	4	No data	No data	No data	2	No data	3	2	2
Continuous operation time (h)	6	No data	No data	No data	7	6	8	8	8
Wireless communication range (m)	5	No data	No data	No data	20	20	30	15	15
Sensor mass (kg)	0.03	No data	1.2	No data	0.0147	0.01	0.014	0.093	0.03 or 0.07
Sensor dimensions (mm)	55×35×15	No data	170×170×70	No data	37×26×15	41.5×24.8×14 base electrode; Ø 16×12 additional electrode	34×24×14	10 — thickness, 60–100 — diameter	40×32×14

End of Table

Characteristics	Device name								
	Neurotech	Myocom	Myomed 134	Neuromyan	Delsys	BTS FREEEMG	Noraxon	Thalmic Myo	Mobile system (developed by the authors)
Electrodes	2 medical electrodes: for EMG, ECG, respiration — disposable self-adhesive electrodes and clamping tapes, for EEG — a special headband with a set of electrodes	4 blocks of 2 medical electrodes + + 1 reference	No data	Blocks of 2 made-in electrodes + ground electrode	4 electrodes (99.9% Ag), 2 patent-pending stabilizing references	2 trailing electrodes and 1 on the housing	3 electrodes: 2 trailing medical, 1 reference on the box	3 stainless steel electrodes	3 medical electrodes per channel
Receiver type	Receiver + PC	PC	Off-line	PC	EMG, accelerometer	Case: charger/ receiver + PC; proprietary mobile device	Transceiver + PC	PC or smartphone	PC or smartphone
Number of sensors in the system	4	1	1	1	16	20	16	1	1–8

N o t e. EMG: electromyography; PC: personal computer.

Motors located on the hip and knee of each exoskeleton leg were used to actuate the skeleton. To drive the motors, the value of the torque was sent through a special software interface to their controllers. The value sign determined the direction of motor rotation. Rotation angle sensors were also placed on the hips and knees of the exoskeleton.

Original programs of data processing and interpretation were developed to control the exoskeleton by the signals of muscle activity [19, 20], and two 4-channel amplifiers were also developed to register EMG signals. In the course of preparation for the experiment, four pairs of EMG electrodes were attached to the following muscles of each pilot leg (Figure 3 (a)):

hip flexor muscle (musculus iliopsoas);

hip extensor muscle (gluteus maximus);

shin flexor muscle (ischium-femoral muscles);

shin extensor muscle (musculus quadriceps femoris).

Each pair of electrodes was located along the muscle at a distance of 2 cm. Data from each sensor were processed in real time to remove a constant component of the signal, then RMS value was calculated to isolate a desired signal of muscle contraction force.

Proportional control was performed in compliance with the algorithm presented on Figure 3 (b).

First, the difference between RMS signals of the flexor and extensor was calculated. Then, the difference values were normalized taking into account motor angular ranges and fed to the PID controller, which computed the torque for exoskeleton motor control (see “Materials and methods”). Values obtained from the angle rotation sensor were used by the PID controller as a feedback to calculate the error. The program in the control unit computed the moments according to the described algorithm and sent them to the exoskeleton motor controller resulting in movement execution.

According to the results of testing, the 4-channel system showed a good response and predictability. However, the stability of the exoskeleton control reduced when the load increased. Having analyzed the results it has been established that an optimal operation of the control system requires a high precision of inertia moment consideration when calculating the force moments applied to the motors. In future, methods of computing inertia moments of exoskeleton and patient body will be developed for control algorithm correction.

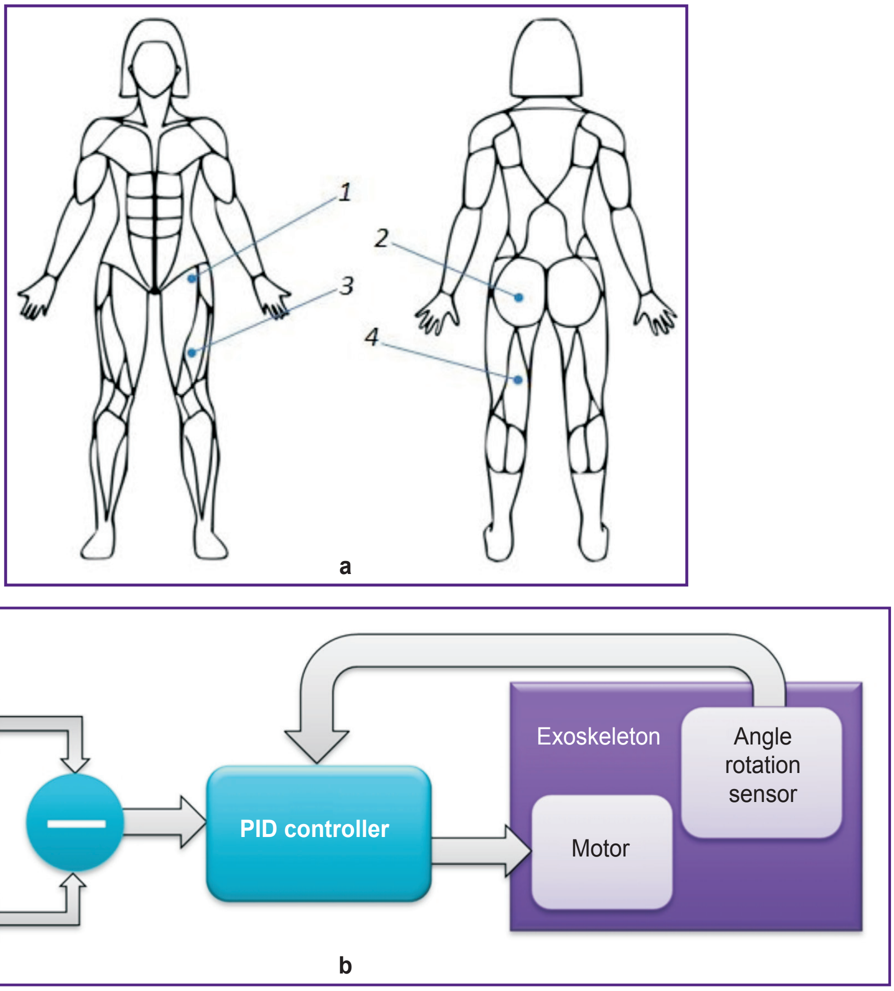

Figure 3. Exoskeleton motor control using the signals from four muscles:
(a) location of EMG electrodes on the lower limbs for exoskeleton control: *1* — hip flexor muscle (musculus iliopsoas); *2* — hip extensor muscle (gluteus maximus); *3* — shin extensor muscle (musculus quadriceps femoris); *4* — shin flexor muscle (ischium-femoral muscles); (b) schematic diagram of proportional control algorithm

The developed device for translation of muscle tension into the exoskeleton commands is not limited by exoskeleton applications only. It allows implementation of various methods of functional diagnosis, control of assistive devices for rehabilitation (wheelchairs, electrostimulators, alarm signals, etc.); in gaming and training applications it can be used as an additional control device. One can use this variant of the mobile system to evaluate the muscle tone after training activity or when analyzing the tension force of separate muscles in real time, which is highly important in rehabilitation of patients with neurological pathologies.

Conclusion. The proposed device for electromyographic activity registration and the algorithms of estimating functional characteristics of pilot muscular system provide unique cooperative strategies of exoskeleton control. Thus, in the system of rehabilitation complex control, the evaluation of patient's own low limb muscle strains on the basis of EMG activity registration data can be implemented. In combination with the latest achievements in control theory based on the quantitative calculation of the control actions (torques in the device articulations) necessary for implementation of the required locomotion pattern, a dosed assistance becomes possible (the so-called assistance-as-need control approach). In other words, the control system stimulates the user to a more active participation in locomotion instead of repeating programmed movements as it is implemented in the majority of exoskeletons.

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Conflicts of Interest. The authors declare no conflicts of interests.

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