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KHVOSTIVSKYI MYKOLA
Ternopil Ivan Puluj National Technical University
https://orcid.org/0000-0002-2405-4930
e-mail: hvostivskyy@tntu.edu.ua
KOVALYK SERHII
Ternopil Ivan Puluj National Technical University
https://orcid.org/0000-0002-5334-1162
e-mail: sergyykovalyk1984@gmail.com

INTEGRATED MATHEMATICAL MODEL OF THE CONTROL SYSTEM FOR UPPER-LIMB BIOPROSTHESIS BASED ON EMG AND PIEZOELECTRIC SIGNALS

The article presents an integrated mathematical model of a control system for upper-limb bioprostheses that simultaneously incorporates electromyographic (EMG) signals as the user's intention channel and piezoelectric signals as the sensory feedback channel. Existing approaches to prosthetic control, such as proportional EMG amplitude-based methods or pattern recognition of muscle activity, have well-known limitations including instability during long-term use, lack of smoothness in motion, sensitivity to electrode displacement, and difficulties in clinical implementation of computationally intensive deep learning solutions. In contrast, the proposed model formalizes both EMG and piezo signals through their envelopes, extracted using the Hilbert transform, which significantly reduces the influence of noise, high-frequency artifacts, and random fluctuations, while preserving the physiological meaning of the signals. This approach allows achieving smoother, more stable, and reliable prosthetic motion control.

The system architecture integrates multiple modules: signal acquisition, preprocessing, envelope detection, control signal generation, DC motor actuation, and adaptive feedback. The EMG envelope reflects the integral level of muscle activation, providing direct representation of the user's intended effort, while the piezo envelope reflects the average contact force, enabling real-time adjustment of grip strength. Such integration reproduces the natural bio-inspired principle of the human neuromuscular system, where central motor commands are continuously corrected by tactile and proprioceptive sensory feedback. The mathematical formulation of the model captures the dynamics of both the electrical and mechanical parts of the actuator, enabling the analysis of motor stability, energy efficiency, and response under varying load conditions.

A closed-loop operational cycle is described, in which EMG serves as the driving input, whereas piezo feedback ensures adaptive regulation of force. If the grip is insufficient, the system automatically increases motor voltage; if excessive, it reduces actuation, thereby preventing object slippage, potential damage, or discomfort. The integrated model remains computationally efficient and can be readily implemented in MATLAB/Simulink environments for simulation, optimization, and clinical testing.

The presented work demonstrates that combining intention-driven EMG input with environment-responsive piezoelectric feedback creates a synergistic and adaptive control mechanism. This bioinspired approach enhances prosthesis performance by increasing movement precision, smoothness, and safety, while reducing dependency on manual recalibration or complex algorithms. The findings provide a foundation for future development of adaptive and intelligent prosthetic control strategies tailored to user-specific muscle patterns and varying real-world conditions. Ultimately, the model contributes to bridging the gap between artificial and physiological motor functions, thus advancing the field of assistive biomedical technologies.

Keywords: upper-limb prosthesis, EMG signal, piezo signal, mathematical modeling, sensory feedback, adaptive control, bioinspired system.

ХВОСТІВСЬКИЙ МИКОЛА
КОВАЛИК СЕРГІЙ
Тернопільський національний технічний університет імені Івана Пулюя

ІНТЕГРОВАНА МАТЕМАТИЧНА МОДЕЛЬ СИСТЕМИ КЕРУВАННЯ БІОПРОТЕЗОМ ВЕРХНІХ КІНЦІВОК ЗА ДАНИМИ ЕМГ-СИГНАЛІВ ТА П'ЄЗОСИГНАЛІВ

У статті представлено інтегровану математичну модель системи керування біопротезом верхніх кінцівок, що поєднує канали наміру користувача (ЕМГ-сигнали) та сенсорного зворотного зв'язку (п'єзосигнали). Актуальність дослідження зумовлена необхідністю підвищення точності, плавності та адаптивності рухів біопротеза, що безпосередньо впливає на його функціональність та зручність використання. Запропонована модель враховує фізіологічні особливості м'язової активності та механічної взаємодії із зовнішніми об'єктами, відтворюючи логіку природної нервово-м'язової системи людини.

ЕМГ-сигнали описано як стохастичний процес із подальшим виділенням огинаючої за допомогою Гільберт-перетворення, що дозволяє усунути високочастотні шуми та зберегти інформативність параметрів. П'єзосигнал, сформований у результаті п'єзоелектричного ефекту, використано для сенсорного контролю сили захвату; його огинаюча визначає інтегральний рівень тиску, що уможливлює стабілізацію хвату та запобігання висlизанню чи пошкодженню предметів. Інтеграція цих сигналів забезпечує баланс між наміром користувача та реакцією середовища, формуючи адаптивний зворотний зв'язок у замкненому контурі керування.

У роботі також подано математичний опис електричної та механічної динаміки двигуна біопротеза, зокрема залежності сили захвату та швидкості руху кінцівки від параметрів струму та кутової швидкості ротора. Це дозволяє відтворити природні біомеханічні властивості, зокрема зниження швидкості при зростанні навантаження. Алгоритм функціонування системи описано у вигляді замкненого циклу, що включає етапи реєстрації сигналів, генерації керуючих впливів, виконання руху та сенсорної корекції.

Запропонована модель створює основу для розробки адаптивних алгоритмів керування біопротезами, які можуть враховувати індивідуальні особливості користувачів та змінні умови експлуатації. Її практична реалізація у середовищі MATLAB/Simulink дозволяє проводити чисельні дослідження, оптимізацію та прогнозування роботи системи без потреби у великій кількості експериментів. Таким чином, результати дослідження відкривають перспективи підвищення функціональності біопротезів та наближення їх до фізіологічних аналогів.

***Ключові слова**: біопротез верхніх кінцівок, ЕМГ-сигнал, п'єзосигнал, математична модель, сенсорний зворотний зв'язок, інтегроване керування, адаптивна система.*

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Problem Statements. Analysis of Research and Publications

The development of modern upper limb bioprostheses requires the creation of control systems capable of ensuring not only the reproduction of basic motor functions, but also smoothness, accuracy and reliability of movements. The use of EMG signals as the main channel for reading the user's intentions has significant limitations: sensitivity to noise, electrode displacement and physiological changes, as well as the difficulty of achieving stable long-term control. The separate use of sensory feedback based on piezo sensors improves the quality of the capture, but is usually considered as an auxiliary module without integration into a single model [1]. Thus, there is a need to build an integrated mathematical model that would simultaneously take into account both the user's bioelectric signals and sensory information about the interaction of the prosthesis with objects, ensuring adaptability and stability of control.

In the scientific literature, several main approaches to controlling upper limb bioprostheses are distinguished. The traditional approach is proportional control based on the amplitude of the EMG signal (Parker, Englehart, Hudgins, 2006) [2]. This method is simple and reliable, but limited to one degree of freedom and sensitive to noise and muscle fatigue. Another direction is the recognition of EMG patterns (Englehart, Hudgins, 2003) [3], which are based on the time and frequency characteristics of the signal. They demonstrate high accuracy in laboratory conditions, but their effectiveness decreases during prolonged use due to electrode displacement and physiological changes, as well as due to the lack of smoothness in control. More modern is simultaneous proportional control, which is based on regression methods (Ameri, Kamavuako, Scheme, Englehart, Parker, 2018) [4]. It allows for simultaneous control of several degrees of freedom and provides more natural movements, but requires significant amounts of training data and fine-tuning of the hardware.

Special attention is paid to sensory feedback. The use of piezoelectric and thick-film sensors for force measurement and slip detection (Cranny et al., 2005; El-Sayed, Khalil, Al-Nazer, 2014) [5, 6] has proven its effectiveness in increasing grip stability, but most of these systems exist as auxiliary modules without integration into a mathematical control model. There are also works with impedance and adaptive controllers (Farina et al., 2016) [7], which take into account the mechanical properties of the interaction of the prosthesis with objects. They have proven themselves well in the field of robotics, but are rarely used in bioprostheses due to the complexity of practical implementation.

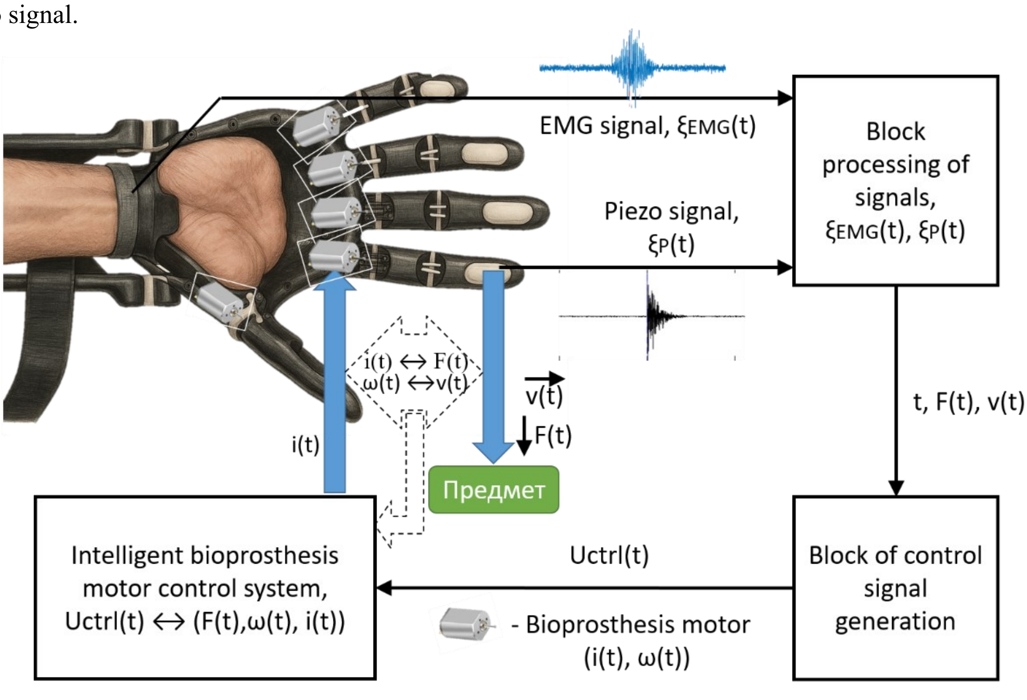
Thus, previous studies outline a number of limitations: lack of smoothness of movements in discrete classification, instability in long-term use, difficulty in implementing simultaneous control in clinical settings, and insufficient integration of sensory feedback. This determines the relevance of building an integrated mathematical model that simultaneously takes into account EMG signals and piezoelectric signals (piezo signals) in a single control loop.

Formulation of the article's objectives

The aim of the article is to develop an integrated mathematical model of the upper limb bioprosthesis control system, which simultaneously takes into account EMG signals (as a user intent channel), piezo signals (as a sensory feedback channel), and actuator dynamics. The implementation of such a model will allow to increase the accuracy, smoothness, and stability of movements, ensure the adaptability of the system to the individual characteristics of users, and create a basis for further optimization of control algorithms in digital modeling environments.

Structure of the bioprosthesis control system using EMG signals and piezo signals

Fig. 1 shows a block diagram of a bioprosthesis hand control system that uses a combination of EMG signal and piezo signal.



t – movement time; ω(t) – angular velocity; v(t) – speed of movement of the limb; F(t) – gripping force; i(t) – motor armature current

Fig. 1. Structure of the bioprosthesis control system using the example of index finger control

According to the structure (Fig. 1), the control is as follows. When the muscles are activated, EMG signals $\xi_{EMG}(t)$ are formed, which reflect the intensity of muscle fiber contraction. At the same time, during the interaction of the bioprosthesis with the object, a piezo signal $\xi_P(t)$ appears, which carries information about the contact and grip force.

Both signals are fed to the signal processing unit, where they are analyzed and the main parameters are extracted: movement time t, movement speed $v(t)$ and gripping/contact force $F(t)$. The obtained characteristics are transmitted to the control signal generation unit, which generates the corresponding control signal Ucntrl(t).

The intelligent control system of the bioprosthesis motor based on the signal Ucntrl(t) ensures the operation of the actuator - the electric motor. This allows the movement of the bioprosthesis to be realized with the required speed and gripping/contact force. At the same time, a feedback loop is formed that takes into account the parameters $F(t)$ and $v(t)$ for adaptive regulation of the control process.

Thus, the system combines EMG control, which directly reflects the user's intentions, and piezoelectric sensor coupling, which provides control of the force of interaction with objects. This allows for greater accuracy and reliability when performing movements with a bioprosthesis.

The development of a bioprosthesis control system requires not only the technical implementation of the hardware part, but also the creation of an adequate mathematical model that reflects the functioning of the entire system in dynamics. The mathematical model allows you to formalize the processes that occur during the acquisition and processing of biosignals (EMG signal, piezo signal), the formation of control influences, as well as the reaction of the bioprosthesis to external actions.

Therefore, the construction of a mathematical model of the bioprosthesis control system is a necessary condition for the creation of effective and reliable control algorithms. It provides the possibility of analytical study of the system, reduces the cost of experimental research and contributes to the improvement of the functional capabilities of bioprostheses.

Characteristics and mathematical representation of EMG signals

An EMG signal is generated as a result of the bioelectrical activity of muscle fibers during contraction [8]. Each action potential from an individual muscle fiber is weak and random, but the combined activity of multiple fibers generates a signal that can be recorded using electrodes.

The EMG signal has a stochastic nature and can be described mathematically as the sum of harmonic components with the addition of noise and artifacts:

$$\xi_{EMG}(t) = \sum_{i=1}^{N} A_i \sin(2\pi f_i t + \phi_i) + n_{EMG}(t), \tag{1}$$

where A_i – amplitudes, f_i – frequencies, φ_i – initial phases, a $n_{EMG}(t)$ – noise components.

This approach is scientifically sound, as it corresponds to:

– physiological nature of the signal (superposition of electrical activity of many fibers);
– spectral properties of the EMG signal (broadband and presence of dominant frequencies);
– mathematical convenience (possibility of spectral analysis, filtering, envelope separation).

Due to the high level of noise and rapid variability, the EMG signal cannot be directly used for direct control of the bioprosthesis as a control variable. The informative indicator is the amplitude of the signal, which reflects the force of muscle contraction. Therefore, the method of signal envelope extraction was applied, which ensures smoothness and reliability in controlling the bioprosthesis:

$$U_{EMG}(t) = \alpha E_{nv}\{\xi_{EMG}(t)\}, \tag{2}$$

where $E_{nv}\{\xi_{EMG}(t)\}$ – envelope calculation function, α – gain factor.

The Hilbert operator is used as a function for calculating the envelope of the EMG signal:

$$U_{EMG}(t) = \alpha\left|H\left(\xi_{EMG}(t)\right)\right|, \tag{3}$$

where $H(\cdot)$ – Hilbert transform operator;
α– muscle signal gain factor that scales the intensity of movement.

The Hilbert transform allows you to construct an analytical signal in which the real part is the input EMG signal itself, and the imaginary part is its Hilbert image [9, 10]. This form uniquely determines the instantaneous amplitude (envelope) and phase of the EMG signal. Unlike simple methods (for example, moving averaging or filtering), the Hilbert operator extracts the envelope without distorting the temporal structure of the EMG signal, i.e., it reflects changes in muscle strength or grip in real time. The Hilbert transform creates an EMG signal shifted by 90° in phase, which allows you to construct a mathematically stable envelope that does not depend on random noise peaks. This method works well for EMG signals, since it does not «lose» the physiological content, but rather extracts the main integral indicator – the level of activity or force.

In general, the envelope $U_{EMG}(t)$ reflects the integral level of muscle activity and correlates with the physiological force of contraction. That is why it is used as the main control parameter of the system: it can be directly scaled and fed to the controller input.

Justification for the use of the EMG signal envelope:

– High-frequency signal oscillations are less informative for control, while its amplitude dynamics are directly related to the strength and duration of muscle contraction.
– Using an envelope allows you to reduce the impact of noise and make the signal more stable.
– Physiologically, the envelope corresponds to the level of muscle activity and reflects the user's intention to exert a certain effort.

Thus, the EMG signal in the system acts as an input control signal that directly determines the user's command, and its envelope reflects the integrated level of muscle activity and correlates with the physiological force of contraction. That is why it is used as the main control parameter of the system: it can be directly scaled and fed to the controller input.

Characteristics and mathematical representation of piezo signals

The second important component is the piezoelectric signal, which arises from the piezoelectric effect – the ability of materials to generate an electrical potential in response to mechanical pressure. For a bioprosthetic system, this allows the measurement of the contact force between the prosthesis and the object.

The output voltage of a piezo sensor is directly proportional to the applied force:

$$\xi_P(t) = k_p F(t) + n_p(t), \tag{4}$$

where k_p – sensitivity coefficient of the piezo sensor, $F(t)$ – contact/grip strength, $n_p(t)$ – measurement noise.

A pure piezo signal $\xi_P(t)$ contains high-frequency oscillations caused by microvibrations, microslip of the object, and electrical noise. These oscillations are of little information for the control task, since the user is interested in the overall gripping force, not the instantaneous pulsations of the signal. The envelope reflects the integrated level of pressure/force and corresponds to the sensation of «grip force», which has a sensory analogue in the human nervous system (skin mechanoreceptors also respond to average pressure levels, not instantaneous spikes).

If a pure signal $\xi_P(t)$ is used for control, then random peaks and fluctuations enter the control loop and, accordingly, the system begins to oscillate or "readapt" without real need.

To calculate the envelope of the piezo signal, identically to the EMG signal, the Hilbert operator was applied:

$$U_P(t) = \beta E_{nv}\{\xi_P(t)\} = \beta\left|H(\xi_P(t))\right|, \tag{5}$$

where β – force feedback coefficient that regulates compensation for excessive force.

Thus, the piezo signal, in particular its envelope $U_P(t)$, directly describes the force interaction of the prosthesis with the environment, and therefore is an ideal source of feedback for stabilizing the grip in a bioprosthesis.

In a bioprosthesis, it is important to control the average grip force:

– if the signal envelope indicates insufficient force, the object may slip out;

– if the envelope indicates an excessive level, this may result in damage to the object or user discomfort.

Thus, in the mathematical model, the envelope of the piezo signal is a direct and reliable reflection of the mechanical interaction of the bioprosthesis with the environment, in particular, the envelope of the piezo signal in the control system allows us to isolate an informative low-frequency component that directly reflects the contact force. This is the value needed to regulate the grip force and the stability of the bioprosthesis. Using a «raw» signal, on the other hand, can lead to noise instability and incorrect adaptive reactions.

Integrated model of the bioprosthesis control system

The bioprosthesis control system must simultaneously consider input signals from EMG signals and piezo sensors to ensure both movement accuracy and stability of interaction with objects. Combining EMG signals and piezo signals allows building an adaptive bioprosthesis control system.

Taking into account two types of signals – EMG (user intent) and piezo (environmental reaction) – the mathematical model of the bioprosthesis control system takes the form:

$$U_{ctrl}(t) = \alpha E_{nv}\{\xi_{EMG}(t)\} - \beta E_{nv}\{\xi_P(t)\}, \tag{6}$$

or

$$U_{ctrl}(t) = \alpha U_{EMG}(t) - \beta U_P(t), \tag{7}$$

where $U_{ctrl}(t)$ – control signal for the bioprosthesis motor (determines voltage, current, speed and force);

α– muscle signal gain factor that scales the intensity of movement;

β – force feedback coefficient that regulates compensation for excessive force;

$U_p(t)$ – piezo signal envelope reflecting contact force.

The first component provides movement proportional to muscle activity, and the second one adjusts it depending on the grip force, preventing its excessive growth. Thanks to the parameter β, the system can automatically reduce or increase the force $F(t)$, ensuring accuracy and safety of actions.

Therefore, the system model reflects the balance between the user's intention (via the EMG signal) and the environment's reaction (via the piezo signal). The combination of EMG signals and piezo signals allows for high-accuracy motion reproduction while avoiding damage to objects or injury to the user.

Dynamics of the actuator (motor) of the control system (electrical part)

The actuator mechanism of a bioprosthesis is usually implemented on the basis of a brushless or brushless direct current motor (DC motor). The dynamics of the motor is described by a system of equations that combine electrical and mechanical processes.

Equation for armature current (for a DC motor):

$$L\frac{di(t)}{dt} + Ri(t) - K_e\omega(t) = U_{кер}(t), \tag{8}$$

where $i(t)$ – armature current; $\omega(t)$ – rotor angular velocity; L – winding inductance; R – winding resistance; K_e – back EMF coefficient; $U_{кер}(t)$ – control voltage generated by the control system.

Here $K_e\omega(t)$ describes the back EMF, which opposes the applied voltage and reduces the current at high speeds.

Dynamics of the actuator (motor) of the control system (mechanical part)

The equation of motion of the rotor according to Newton's second law [11]:

$$J\frac{d\omega(t)}{dt} + B\omega(t) = M(t) - M_{\text{load}}(t), \tag{9}$$

where J – rotor moment of inertia; B – coefficient of viscous friction;

$M(t)$ – electromagnetic torque of the motor; $M_{\text{load}}(t)$ – load moment from the gripping mechanism.

Motor torque is proportional to current:

$$M(t) = K_t i(t), \tag{10}$$

where K_t – engine torque constant.

If the moment is transmitted to the bioprosthesis finger mechanism through a transmission (reducer), then it is converted into force (output force per grip):

$$F(t) = k_f i(t), \tag{11}$$

where k_f – current to force conversion ratio (depends on the transmission design and geometry of the gripping mechanism).

Conversion of torque into force and limb velocity

In the control loop, it is advisable to take into account not only the contact force (via the piezo signal), but also the speed of finger movement. This allows:

– ensure smooth movement: the controller can limit speed when approaching an object, which reduces the risk of impact or slipping;

– optimize energy consumption: excessively high speed with low effort increases energy consumption, while speed regulation allows you to avoid overloads;

– Recreate natural biomechanics: in humans, the strength and speed of finger movement are also related: with strong compression, the speed decreases.

At the same time, the output gripping force $F(t)$, which is realized at the fingertip, is determined by the motor torque and the gearbox parameters:

$$F(t) = \frac{M(t)}{r} = \frac{K_t i(t)}{r}, \tag{13}$$

where r – equivalent radius of conversion of rotational motion of the rotor into translational/arc motion of the finger.

The movement of the finger of the bioprosthesis limb can be described through the linear velocity of the working link $v(t)$, which directly depends on the angular velocity of the electric motor rotor $\omega(t)$ and the gear ratio of the reducer. Thus, the linear velocity of the limb is directly proportional to the angular velocity of the motor and decreases with increasing load, which corresponds to the natural biomechanics of human movements [12]:

$$v(t) = r\omega(t), \tag{14}$$

Thus, the gripping force $F(t)$ and the finger movement speed $v(t)$ are directly related to the electrical parameters of the motor. The higher the armature current, the greater the gripping force; the higher the rotor angular velocity, the faster the finger moves. This reproduces the natural biomechanics of a person, where the movement speed decreases with increasing load.

Combining (electrical and mechanical equations) with the dependencies for the force $F(t)$ and finger velocity $v(t)$, we obtain the complete system:

$$\begin{cases} L\dfrac{di(t)}{dt} + Ri(t) - K_e\omega(t) = U_{ctrl}(t) \\ J\dfrac{d\omega(t)}{dt} + B\omega(t) = M(t) - M_{навантаж}(t) \\ F(t) = \dfrac{K_t i(t)}{r} \\ v(t) = r\omega(t) \end{cases}. \tag{15}$$

Thus, the system forms a closed control loop, where the EMG signal determines the movement command and the piezo signal provides adaptive feedback for stability and safety.

Scientific justification:

1. Biophysical correspondence: the armature current corresponds to the level of electrical activation, while the output force $F(t)$ and the speed of movement $v(t)$ reproduce the functional result in the form of movement and grip**.**
2. Adaptability: the control system adjusts the current $i(t)$ depending on the envelope EMG signals and piezo signals, which ensures a balance between the user's intention and feedback**.**
3. Stability: the model allows you to analyze the impact of loads and engine parameters on stability, avoid vibrations and overloads**.**

Algorithm of functioning and closed cycle of operation of the bioprosthesis control system model

The operation of the bioprosthesis control system in a closed loop is based on the integration of two main channels:

– user intent channel (EMG signal);

– sensory control channel (piezo signal from contact force sensor).

The algorithm of the system operation includes the following sequential stages:

– Generation of a control signal from the user. When muscles are activated, an EMG signal $\xi_{EMG}(t)$ is generated, which is recorded by electrodes. After processing and envelope separation, an informative indicator is formed $U_{EMG}(t)$, which reflects the level of muscle activation and is used as an input parameter for generating control action.

– Generating a command for the actuator. Based on this $U_{EMG}(t)$, a control voltage is generated, proportional to the force of the user's muscle contraction. It is fed to the bioprosthesis electric motor, ensuring the movement of the actuator (finger or hand).

– Performing a movement and interacting with an object. The motor creates a mechanical torque that is converted into a force $F(t)$ in the prosthesis' gripping mechanism at a given speed $v(t)$. In the event of contact with an object, an interaction force arises, which is recorded by a piezo sensor.

– Sensory feedback generation. The piezo signal $\xi_P(t)$, after the envelope is extracted $U_P(t)$, reflects the integral value of the grip/contact force $F(t)$. This signal is fed to the feedback unit and compared with the permissible levels. If necessary, the system additionally takes into account the speed of movement of the limb $v(t)$, which allows you to adjust the smoothness and safety of the prosthesis even before contact with the object.

– Adaptive correction. If the gripping force is insufficient, the system increases $U_{ctrl}(t)$, preventing the object from slipping. In case of excessive pressure, the system reduces the voltage on the motor, protecting the object from damage and the user from discomfort.

Thus, a closed cycle of the system operation is formed, which can be presented in the form of an algorithm in Fig. 2.

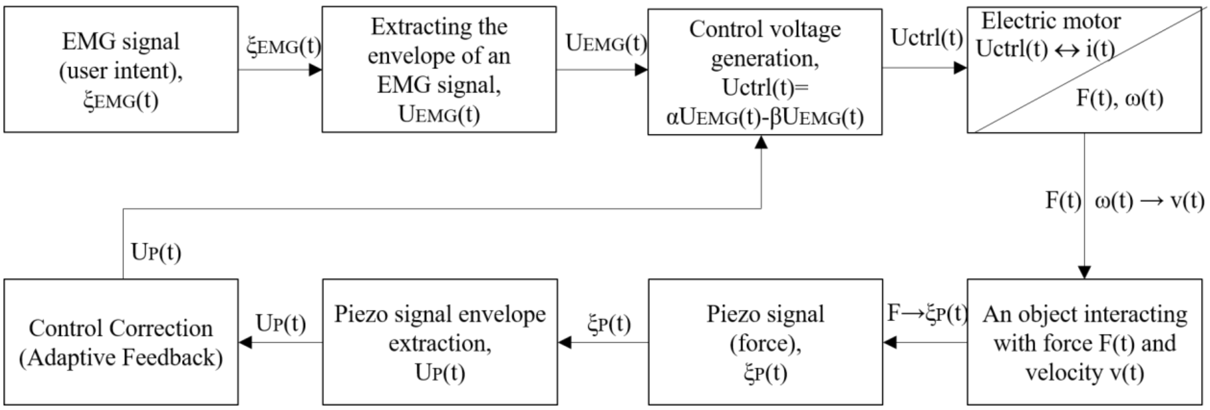


Fig. 2. Algorithm of functioning and closed loop model of the bioprosthesis control system

In this algorithm, the EMG signal acts as an intention channel, while the piezo signal performs the role of sensory control and stabilization. Such integration provides a balance between the desired action of the user and the safe execution of the movement by the bioprosthesis. As a result, the model combines biological logic: "intention" from the muscles + "sensory control" from touch, which is mathematically implemented through equations for the control voltage and motor dynamics.

Conclusions

The paper substantiates and builds an integrated mathematical model of the upper limb bioprosthesis control system, which combines the user's intention channels (EMG signal) and sensory feedback (piezo signal). Unlike traditional approaches, where EMG activation is used in isolation or sensory control functions as an additional module, the proposed model implements a holistic bioinspired regulation mechanism that reproduces the logic of the human neuromuscular system.

Formalization of EMG signals and piezo signals through their envelopes allowed to significantly reduce the sensitivity of the system to high-frequency noise, artifacts and random oscillations, while maintaining the informativeness of the control parameters. This approach provides not only smoothness and stability of movements, but also the possibility of scaling signals for the implementation of adaptive control. The model has proven its ability to adequately describe the interaction between electrical muscle activity, sensory feedback and the dynamics of the actuator (motor), which creates a basis for a deeper analysis of the stability, energy efficiency and accuracy of the bioprosthesis.

The results obtained demonstrate the prospects of an integrated approach to modeling bioprosthesis control systems. It allows not only to recreate the natural logic of human motor control, but also to form a platform for the implementation of adaptive and intelligent control algorithms that can take into account the individual characteristics of users and variable operating conditions. This opens up new opportunities for improving the functional characteristics of bioprostheses and bringing them closer to physiological analogues.

At the same time, taking into account the speed of limb movement along with the grip force allows for greater smoothness and naturalness of movements, which enhances the adaptability and energy efficiency of the bioprosthesis.

References

1. Dozorskyi, V., Martsenyuk, V., Dozorska, O., Dediv, L., Klymuk, N. (2024). The concept of developing the structure of a highly functional bionic hand prosthesis based on IoT technologies. Proceedings of the 1st International Workshop on Bioinformatics and Applied Information Technologies (BAIT'2024), 17-22. CEUR Workshop Proceedings, Vol. 3842. ISSN 1613-0073.

2. Parker, P., Englehart, K., Hudgins, B. (2006). Myoelectric signal processing for control of powered limb prostheses. Journal of Electromyography and Kinesiology, 16(6), 541–548. https://doi.org/10.1016/j.jelekin.2006.08.006.

3. Englehart, K., Hudgins, B. (2003). A robust, real-time control scheme for multifunction myoelectric control. IEEE Transactions on Biomedical Engineering, 50(7), 848–854. https://doi.org/10.1109/TBME.2003.813539

4. Ameri, A., Kamavuako, E. N., Scheme, E., Englehart, K., Parker, P. (2018). Real-time, simultaneous myoelectric control using force and position-based training paradigms. IEEE Transactions on Biomedical Engineering, 65(3), 647–657. https://doi.org/10.1109/TBME.2017.2704085.

5. Cranny, A., Cotton, D., Chappell, P. H., White, N. M., Beeby, S. P. (2005). Thick-film force, slip and temperature sensors for a prosthetic hand. Sensors and Actuators A: Physical, 123–124, 162–171. https://doi.org/10.1016/j.sna.2005.05.003.

6. El-Sayed, E., Khalil, M., Al-Nazer, A. (2014). Piezoelectric tactile sensor for prosthetic hand applications. Journal of Medical Engineering & Technology, 38(4), 197–202. https://doi.org/10.3109/03091902.2014.902513.

7. Farina, D., Vujaklija, I., Sartori, M., Kapelner, T., Negro, F., Jiang, N., Aszmann, O. C. (2016). Man/machine interface based on the discharge timings of spinal motor neurons after targeted muscle reinnervation. Nature Biomedical Engineering, 1(2), 0025. https://doi.org/10.1038/s41551-016-0025.

8. Geethanjali P. (2016). Myoelectric control of prosthetic hands: state-of-the-art review. Medical Devices: Evidence and Research. 9. 247-255. https://doi.org/10.2147/MDER.S91102.

9. Sharma, M. (2021). A comparative study of different EMG features for acoustics-based speech recognition. *Interspeech 2021*, 1–5. https://doi.org/10.21437/Interspeech.2021-1259.

10. Xie, H. (2006). Mean frequency derived via Hilbert-Huang transform with application to EMG signals. *Signal Processing, 86*(11), 3071–3078. https://doi.org/10.1016/j.sigpro.2006.03.015.

11. Ma, X., Liu, J., Zhao, L., Zhang, J. (2021). Dynamic behavior analysis of the winding rotor with electromagnetic-mechanical coupling. *Applied Sciences, 11*(17), 8124. https://doi.org/10.3390/app11178124.

12. Winter, D.A. (2009). *Biomechanics and motor control of human movement* (4th ed.). Hoboken, NJ: John Wiley & Sons. https://doi.org/10.1002/9780470549148.