UDC 616-71:004.9
DOI 10.36910/10.36910/6775-2313-5352-2025-27-1
Kovalyk S., Khvostivskyi M.
Ternopil Ivan Puluj National Technical University

METHOD AND ALGORITHM OF WINDOWED PROCESSING OF EMG AND PIEZOELECTRIC SIGNALS FOR THE FORMATION OF CONTROL ACTIONS IN BIOPROSTHESES

The paper presents a window-based method for processing biosignals to generate control actions in upper-limb bioprostheses operating in real time. The core of the method is the segmentation of EMG and piezoelectric signals into short time windows of 40-80 ms with partial overlap, ensuring continuous information updating and minimal system response latency (<50 ms). The EMG signal serves as the primary channel of user intent, while the piezoelectric signal functions as a sensory feedback channel. For each window, noise filtering, root mean square (RMS) calculation, envelope extraction using the Hilbert transform, and exponential smoothing are performed. The piezoelectric signal is introduced into the system with a temporal delay of 30-70 ms, replicating the natural sensorimotor loop «intention – action – contact – correction». Based on the smoothed EMG and delayed piezo signals, a control signal is generated and applied to the actuator motor, taking into account its electrical and mechanical dynamics. The proposed method combines windowed processing and sensory delay in a unified algorithm that enhances the stability, smoothness, and physiological compliance of control, suppresses random spikes, and ensures adaptability under varying conditions. Simulation results confirm the effectiveness of the proposed approach for accurate and reliable control of next-generation bioprostheses.
Key words: *EMG signal, piezoelectric signal, bioprosthesis, motor, windowed processing, sensory feedback, real-time operation, Hilbert transform, control signal, control stability, adaptive systems, Matlab.*

Problem statement. The control of modern upper-limb bioprostheses is a challenging task, as it must ensure natural movement, low reaction latency, and intuitive operation for the user. The primary source of control information is traditionally electromyographic (EMG) signals, which reflect the level of muscle activity, while additional sensory signals (force, piezoelectric, tactile) are used to implement closed-loop sensorimotor feedback [1-3]. However, reliable real-time biosignal processing remains an open and unresolved problem.

Analysis of the state of research. The first approaches to control were based on threshold algorithms, where the decision was made based on the excess of the EMG signal amplitude over a given threshold. Such methods were distinguished by their simplicity of implementation, but had low functionality and sensitivity to noise [4]. Further development is associated with pattern recognition methods (Pattern Recognition, PR), in which classifiers (LDA, SVM, neural networks) are used to identify gestures based on statistical and spectral features of EMG. This provided multifunctional control, but turned out to be insufficiently resistant to changes in the position of the electrodes, muscle fatigue, and individual differences of users [5].

To enhance the intuitiveness of control, regression-based approaches have been developed, allowing proportional control of force or movement speed. Despite the naturalness of this method, it requires stable features and remains sensitive to signal dynamics [5]. At the same time, researchers have proposed adaptive algorithms and online learning systems capable of adjusting classifier parameters in real time, which reduces the number of erroneous switches and shortens user reaction time [6].

Recently, particular attention has been given to feedback systems that integrate sensory signals (force, tactile, piezoelectric) into closed-loop control. This integration enhances grip force regulation and compensates for signal uncertainty, as confirmed by numerous experimental studies [7]. As a result, a class of hybrid methods has emerged, combining EMG as a command channel with sensory feedback within a unified algorithm. One such approach involves windowed processing of EMG and piezoelectric signals, incorporating a time delay in the sensory channel to model the natural sensorimotor loop and ensure smooth and stable operation of the prosthetic device.

Despite significant progress, most existing methods have limitations: high sensitivity to signal recording conditions, instability during prolonged use, insufficient response speed, or low smoothness of control. Therefore, the search for algorithms that achieve a balance between low latency, robustness to noise, and physiological plausibility of control remains a relevant and ongoing challenge.

Objective of the Study. The aim of this work is to develop and investigate a method and algorithm for windowed processing of EMG and piezoelectric signals to generate control actions for a prosthetic device, taking into account sensory feedback and its time delay. This approach is intended to enhance the stability and naturalness of control.

Results and Discussion. The upper-limb prosthesis control system operates in real time, implementing a data processing sequence within sliding time windows. Each window, with a duration of Δt (40–80 ms), contains discretized samples of the EMG and piezoelectric signals, which are accumulated in buffers with partial overlap.

After the completion of each window:

– noise filtering and signal normalization;

– calculation of their local features (envelope, root mean square value, and energy);

– generation of intermediate variables representing the level of muscle activity (EMG signal) and contact force (piezoelectric signal);

– synthesis of the control action taking into account the time delay of sensory feedback.

This approach ensures continuous information updating, minimal latency (<50 ms), and stable control without high-frequency oscillations.

The EMG signal $\xi_{EMG}(t)$ serves as the primary channel of the user's intent. Its amplitude fluctuations reflect the level of muscle contraction but also contain noise and random components.

To obtain a stable and controllable parameter, windowed integration is employed:

$$E_{EMG}(t_k)=\frac{1}{\Delta t}\int_{t_k-\Delta t}^{t_k}\left|\xi_{EMG}(\tau)\right|d\tau \,, \tag{1}$$

where Δt – window duration, t_k – update moment (every $\delta t = \Delta t/4\ldots\Delta t/2$).

Thus, a moving average (MA) amplitude is formed (1), providing a rapid estimate of the current muscle activity.

For a more accurate estimation of the envelope, the Hilbert transform is applied, yielding the analytic signal:

$$\tilde{\xi}_{EMG}(t)=\xi_{EMG}(t)+jH(\xi_{EMG}(t)), \tag{2}$$

$$E_{EMG}(t)=\left|\tilde{\xi}_{EMG}(t)\right|+\sqrt{\xi_{EMG}^2(t)+H^2(\xi_{EMG}(t))}\,, \tag{3}$$

The obtained envelope $E_{EMG}(t)$ (2-3) undergoes windowed smoothing using an exponential filter:

$$E_{EMG,win}(t_k)=(1-\lambda)E_{EMG,win}(t_{k-1})+\lambda E_{EMG}(t_k), \tag{4}$$

where $\lambda = \delta t/\Delta t$ determines the update rate.

The result is a smooth estimate of muscle activity that is updated in real time while preserving the physiological inertia of the biomechanical response.

The piezoelectric signal $\xi_P(t)$ reflects the interaction force between the prosthesis and the object. Its raw form contains both a useful low-frequency component (pressure) and high-frequency fluctuations (vibrations, micro-slips).

A similar windowed processing is applied to extract the informative component:

$$E_P(t_k)=\frac{1}{\Delta t}\int_{t_k-\Delta t}^{t_k}\left|\xi_P(\tau)d\tau\right|, \tag{5}$$

after which the envelope is constructed using the Hilbert transform:

$$E_{P,env}(t_k) = \left|\xi_P(\tau) + jH(\xi_P(\tau))\right| . \tag{6}$$

To stabilize the result (6), moving smoothing within a window of duration Δt is applied, similar to the EMG channel.

Since the piezoelectric signal reflects the environmental response, it always appears with a delay relative to the moment of muscle impulse generation.

Therefore, a time delay τ_d (30-70 ms) is introduced into the system to model the natural delay of human sensory feedback.

The delayed signal is described as:

$$E_{P,del}(t_k) = \xi_{P,env}(t_k - \tau_d) . \tag{7}$$

The choice of τ_d depends on the mechanical inertia of the prosthesis and the characteristics of the sensors.

– smaller τ_d: faster response but higher likelihood of oscillations;

– larger τ_d: more stable, but with reduced response speed.

Experiments have shown that the optimal value of τ_d=40-60 ms provides the best compromise between accuracy and stability.

After obtaining the smoothed values $E_{EMG,win}(t)$ (4) and $E_{P,del}(t)$ (7), a combined control signal $U_{ctrl}(t)$ is generated, which determines the actuation of the prosthetic motor.

It combines the user's active command (EMG signal) with the corrective action from sensory feedback (piezoelectric signal):

$$E_{ctrl}(t_k) = \alpha E_{EMG,win}(t_k) - \beta E_{P,del}(t_k), \tag{8}$$

where α – gain coefficient of the muscle channel, which determines sensitivity to the user's intent;

β – sensory correction coefficient, which defines the response level to contact force.

Thus:

– if the gripping force is insufficient (E_P is small) – the system increases U_{ctrl} and increases the force;

– if the force exceeds the permissible value, the piezo channel corrects the action by reducing the motor voltage

For smooth regulation, both coefficients in expression (8) can be adaptive ($\alpha(t)$, $\beta(t)$) and vary depending on the movement dynamics or the type of object.

The generated signal $U_{ctrl}(t)$ is applied to the actuator – a DC motor. Its electrical dynamics are described by the equation:

$$L\frac{di}{dt} + Ri(t) + K_e\omega(t) = U_{ctrl}(t), \tag{9}$$

where $i(t)$ – armature current;

$\omega(t)$ – rotor angular velocity;

L – winding inductance;

R – winding resistance;

K_e – back EMF coefficient

The electromagnetic torque $M(t)$ of the motor is a function of the current:

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

The rotor's mechanical dynamics are governed by the following equation:

$$J\frac{d\omega}{dt} + B\omega(t) = M(t) - M_{load}(t), \tag{11}$$

where J – moment of inertia, B – viscous friction coefficient, M_{load} – load torque from the gripping mechanism.

Conversion of torque into force and finger motion velocity:

$$F(t) = k_f i(t), \quad v(t) = k_v \omega(t), \tag{12}$$

where $F(t)$ – grip force, $v(t)$ – linear velocity of the limb.

These parameters in expression (12) are monitored in real time by piezoelectric sensors and influence the subsequent correction of the control signal $U_{ctrl}(t)$ (9).

In the closed-loop control system, the EMG signal serves as the direct command channel, whereas the piezoelectric signal functions as the sensory feedback channel with a time delay.

This structure implements a bioinspired principle: intention → motion → contact → sensory correction → stabilized movement.

In mathematical form, such a loop can be represented as:

$$\begin{cases} E_{EMG,win}(t) = f_1(\xi_{EMG}(t)), \\ E_{P,del}(t) = f_2(\xi_P(t - \tau_d)), \\ U_{ctrl}(t) = \alpha E_{EMG,win}(t) - \beta E_{P,del}(t) \\ i(t) = \dfrac{1}{L}\left[U_{ctrl}(t) - Ri(t) - K_e \omega(t)\right] \\ \omega(t) = \dfrac{1}{J}\left[K_t i(t) - B\omega(t) - M_{load}(t)\right]. \end{cases} \tag{13}$$

The resulting system of equations (13) describes the full dynamics of the prosthesis in real time, taking into account windowed processing, sensory delay, and electromechanical characteristics.

Advantages of the windowed approach for generating the control action:

– Increased stability: short windows attenuate noise and prevent motor overloading during accidental signal peaks.

– Smooth control: thanks to window overlap, the system updates U_{ctrl} smoothly, without abrupt changes in armature voltage or current.

– True adaptability: windowed processing provides flexible response even under changing contact or electrode conditions, without the need for complete recalculation of the filters.

– Physiological relevance: processing signals in time windows models natural human sensorimotor cycles (~50-100 ms), making control intuitively perceived by the user.

Taking into account all processing stages, the complete expression for the control action can be represented as:

$$U_{ctrl}(t_k) = \alpha\left[\frac{1}{\Delta t}\int_{t_k-\Delta t}^{t_k} |\xi_{EMG}(\tau)| d\tau\right] - \beta\left[\frac{1}{\Delta t}\int_{t_k-\Delta t-\tau_d}^{t_k-\tau_d} |\xi_P(\tau)| d\tau\right], \tag{14}$$

This equation (14) describes the real-time model of the bioprosthesis operation, in which the EMG signal determines the user's intended action, while the delayed piezoelectric signal provides its sensory correction.

Figure 1 shows the algorithm for windowed processing of EMG and piezoelectric signals with partial window overlap (Δt=40–80 ms) and exponential smoothing.

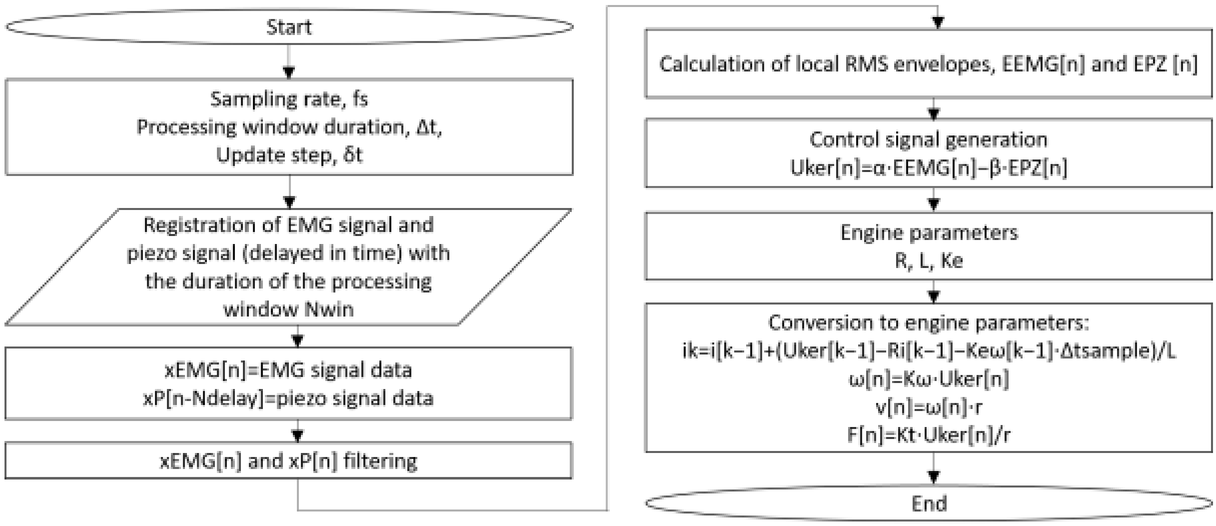

Figure 1 – Algorithm of windowed processing of EMG and piezoelectric signals for generating the control action of a bioprosthesis

The algorithm includes the stages of recording EMG and piezoelectric signals, their filtering, extraction of signal envelopes via the Hilbert transform, consideration of sensory delay in the piezoelectric channel, computation of the control signal, and accounting for the electromechanical dynamics of the prosthesis actuator. This sequence ensures continuous signal processing, minimal reaction delay, and stable real-time control.

The result of the study of the method in the Matlab environment is shown in Fig. 2 in the form of control signals for the bioprosthesis, in particular its motors.

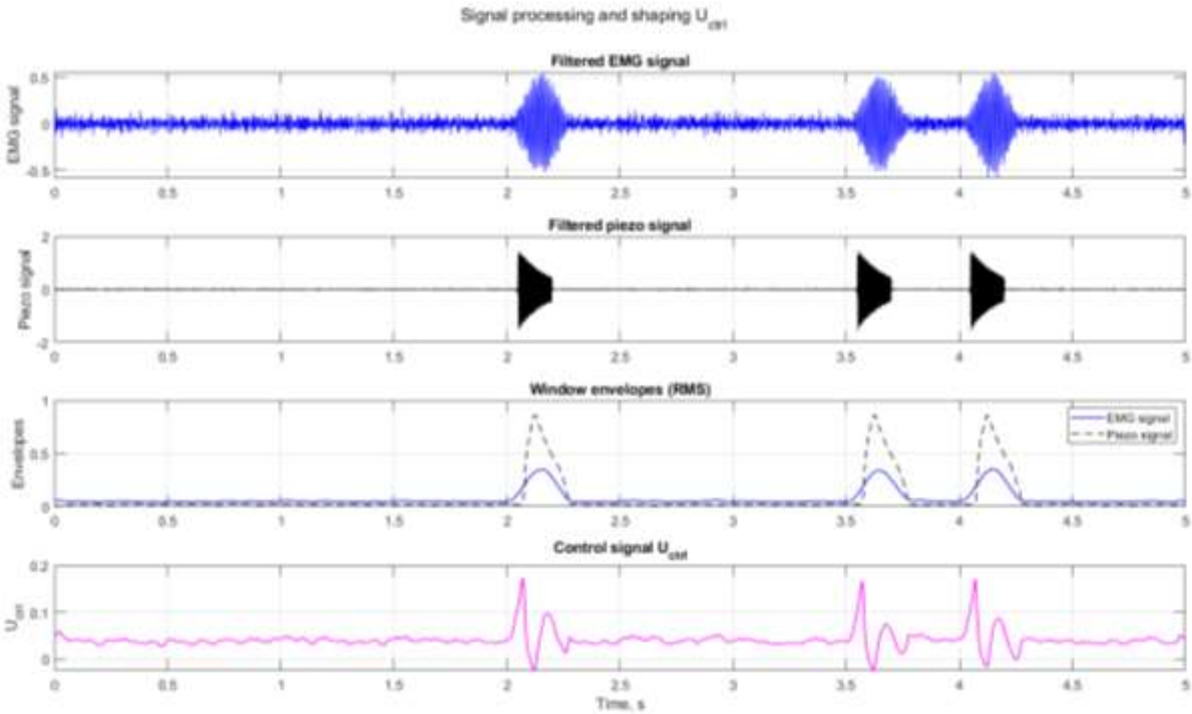

Figure 2 – Generated control signals of the bioprosthesis

The upper plots illustrate the filtered input EMG and piezoelectric signals, which have been segmented and smoothed in time windows. The lower plot shows the generated control signal Uctrl, reflecting both the user's muscle activation and the corrective influence of the piezoelectric signal. A smooth variation of the control signal is observed, without abrupt jumps or oscillations, indicating the effectiveness of the proposed windowed processing.

Figure 3 shows the temporal variation of the main parameters of the prosthesis actuator (rotor angular velocity, armature current, and grip/contact force) under the influence of the generated control signal.

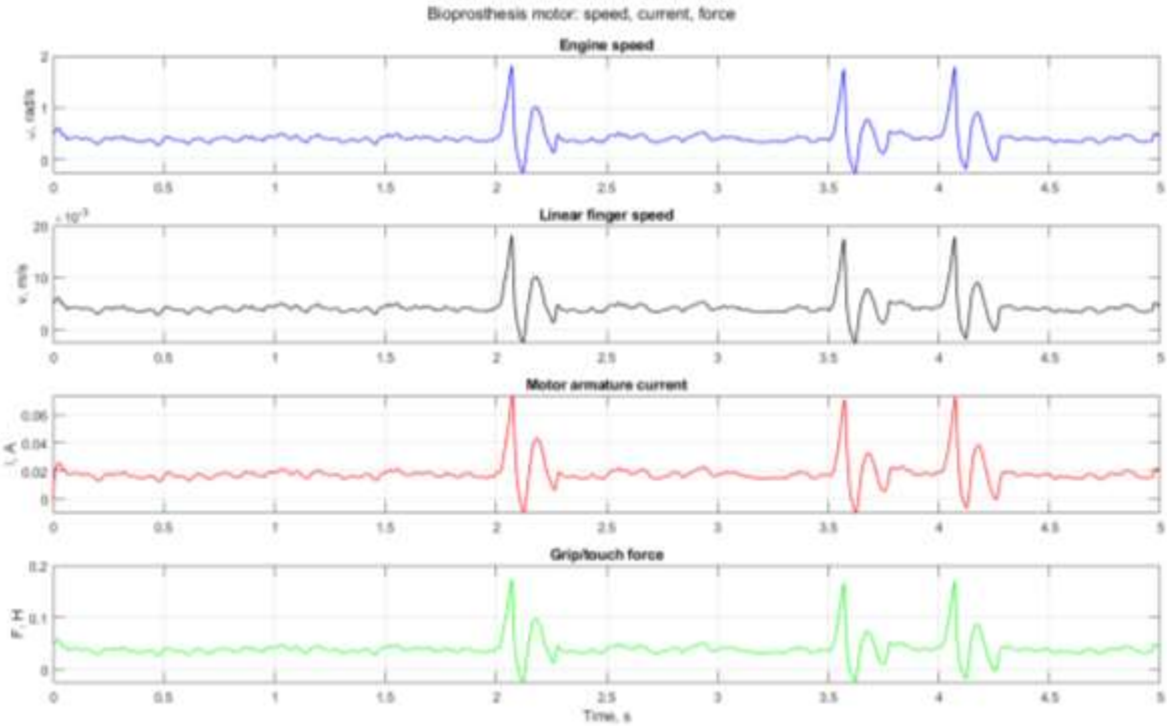

Figure 3 – Temporal variation of actuator parameters depending on the control signals

A typical inertial behavior is observed: rapid current fluctuations during transients subsequently transform into a smooth convergence of velocity and force to their steady-state values, indicating adequate interaction between the generated control signal and the actuator model. The presence of sensory correction via the control signal reduces overshoot and minimizes the steady-state force error, provided that the coefficients α, β, and the piezoelectric signal time delay are appropriately selected.

The plots demonstrate smooth actuator acceleration, absence of overshoot, and stabilization of the grip force upon reaching the target value. This confirms that using the EMG signal as the command channel and the piezoelectric signal as sensory feedback provides stable, accurate, and adaptive prosthesis control.

Conclusions. In this study, a method for windowed processing of EMG and piezoelectric signals was developed and investigated for generating control actions of upper-limb bioprostheses in real time. It was demonstrated that segmenting signals into short time windows with partial overlap ensures continuous information updating and minimal system reaction latency, while using the EMG signal as the command channel and the piezoelectric signal as the sensory feedback channel with a time delay allows reproduction of the natural sensorimotor loop 'intention – action – contact – correction.' The introduction of windowed smoothing and the Hilbert transform enhances the system's robustness against noise and accidental peaks, as well as ensures smooth and physiologically consistent control. Simulation results confirmed the effectiveness of the combined signal in providing precise control of the prosthesis actuator, taking into account its electromechanical dynamics. The findings indicate that the proposed approach offers advantages in stability, smoothness, and adaptability of control, and may serve as a basis for the development of next-generation bioprostheses. Future research directions include testing the method on real user biosignals, optimizing windowed processing parameters and sensory delay, and integrating machine learning algorithms to enhance adaptability and individualized control.

References

1. Oskoei M. A., Hu H. Myoelectric control systems – A survey. *Biomedical Signal Processing and Control*. 2007. Vol. 2, No. 4. P. 275-294. DOI: https://doi.org/10.1016/j.bspc.2007.07.009.

2. Dozorskyi V., Martsenyuk V., Dozorska O., Dediv L., Klymuk N. 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)*. 2024. Vol. 3842. P. 268–280. CEUR Workshop Proceedings. ISSN 1613-0073.

3. Dozorskyi V., Dediv L., Kovalyk S., Dozorska O., Dediv I. Design of the endoskeleton of a biocontrolled hand prosthesis. *Scientific Journal of TNTU*. 2024. Vol 115. №3. P. 100-111.

4. Arora A. S., Joshi D. Development of threshold based EMG prosthetic hand. *Journal of Vibroengineering*. 2007. Vol. 9, No. 3. P. 11–14. URL: https://www.jvejournals.com/article/1156.

5. Ghildiyal S., Mani G., Nersisson R. Electromyography pattern-recognition based prosthetic limb control using various machine learning techniques. *Journal of Medical Engineering & Technology*. 2022. Vol. 46, No. 5. P. 392–402. DOI: https://doi.org/10.1080/03091902.2022.2062064.

6. Edwards A. L., Dawson M. R., Hebert J. S., Sherstan C., Sutton R. S., Chan K. M., Pilarski P. M. Application of real-time machine learning to myoelectric prosthesis control: A case series in adaptive switching. *Prosthetics and Orthotics International*. 2016. Vol. 40, No. 5. P. 573-581. DOI: https://doi.org/10.1177/0309364615605373.

7. Tchimino J., Dideriksen J. L., Dosen S. EMG feedback outperforms force feedback in the presence of prosthesis control disturbance // Frontiers in Neuroscience. 2022. Vol. 16. Art. 952288. DOI: https://doi.org/10.3389/fnins.2022.952288.

Ковалик С. В., Хвостівський М. О.
Тернопільський національний технічний університет імені Івана Пулюя

МЕТОД ТА АЛГОРИТМ ВІКОННОЇ ОБРОБКИ ЕМГ-СИГНАЛІВ ТА П'ЄЗОСИГНАЛІВ ДЛЯ ФОРМУВАННЯ КЕРУЮЧОЇ ДІЇ БІОПРОТЕЗІВ

У статті наведено метод віконної обробки біосигналів для формування керуючих дій у біопротезах верхніх кінцівок, що функціонують у режимі реального часу. Основу методу становить сегментація ЕМГ-сигналів та п'єзосигналів у коротких часових вікнах тривалістю 40–80 мс з частковим перекриттям, що забезпечує безперервне оновлення інформації та мінімальну затримку реакції системи (<50 мс). ЕМГ-сигнал використовується як основний канал наміру користувача, а п'єзосигнал – як канал сенсорного зворотного зв'язку. Для кожного вікна виконується фільтрація шумів, розрахунок середньоквадратичних значень та огинаючих за допомогою Гільберт-перетворення, а також згладжування результатів експоненційним фільтром. П'єзосигнал вводиться у систему з часовою затримкою 30-70 мс, що відтворює природну сенсомоторну петлю «намір – дія – контакт – корекція». На основі згладжених ЕМГ-сигналів та затриманих п'єзосигналів формується керуючий сигнал, який подається на виконавчий двигун, враховуючи його електричну та механічну динаміку. Запропонований метод поєднує віконну обробку та сенсорну затримку у єдиному алгоритмі, що підвищує стабільність, плавність та фізіологічну відповідність керування, пригнічує випадкові піки та забезпечує адаптацію до змінних умов. Результати моделювання підтверджують ефективність запропонованого підходу для точного й надійного керування біопротезами нового покоління.

Ключові слова: *ЕМГ-сигнал, п'єзосигнал, біопротез, двигун, віконна обробка, сенсорний зворотний зв'язок, реальний час, Гільберт-перетворення, керуючий сигнал, стабільність керування, адаптивні системи, Matlab.*

Дата першого надходження статті до видання	Дата прийняття статті до друку	Дата оприлюднення
09.10.2025 р	12.11.2025 р.	25.12.2025 р.