Proceedings of ICEGEE 2026 Symposium: AI-Based Medicine and Biological Data Analysis
DOI: 10.54254/2753-8818/2026.AU31818

Myoelectric Sensor Technology for Intelligent Prosthesis and Wearable Human-Computer Interaction

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Abstract. With the ageing of the population and the increase in the number of people with limb disfunction, intelligent prosthetic and wearable human-computer interaction systems put forward higher requirements for highly reliable motor intention acquisition technology. As an important bioelectric signal reflecting the state of muscle activity, myoelectric signals have unique advantages in prosthetic control and rehabilitation assistance. This article focusses on the collection and sensing technology of myoelectric signals, and systematically sorts out the structural characteristics, signal performance and application scenarios of different schemes such as surface electro myoelectric sensors, intrusive myoelectric sensors, flexible wet electrodes and flexible dry electrodes. Through the comparative analysis of existing research results, the advantages and limitations of various electro myoelectric sensors in terms of signal quality, spatial selectivity, wearing comfort and system integration are pointed out, and the key challenges such as signal stability, crosstalk suppression and long-term wearing reliability are summarized. This article aims to provide a reference basis for the selection and optimization design of electro myoelectric sensors in intelligent prosthetics and wearable systems.

Keywords: Surface myoelectricity, myoelectric sensor, intelligent prosthesis, wearable system

1. Introduction

With the increasing ageing of the population, the frequent occurrence of traffic and industrial accidents, and the continuous increase in the number of patients with chronic diseases, limb disfunction has become one of the important problems facing the global public health sector. As key technologies to improve patients' quality of life and exercise ability, prosthetic limbs, rehabilitation aids and wearable robots have received wide attention for their intelligence and human-computer interaction performance. Against this background, how to accurately and stably obtain the movement intention of the human body and transform it into controllable mechanical action has become one of the core scientific and engineering problems in the development of intelligent prosthetic limbs and auxiliary systems. As an information carrier that directly reflects the state of human physiological activity, biological signals provide an important way to build a natural and efficient human-computer interface. Biosensors are the key components to realise biological signal perception and conversion. According to the types of signals collected, the current common biosensors mainly include electrocardiogram sensors (ECG) used to detect cardiac electrical activity, electroencephalographic sensors (EEG) used to record brain nerve activity, and muscle reception. Myoelectric sensors (EMG) of shrinkage activity, as well as mechanics and motion sensors based on pressure, acceleration or inertia measurement. Among them, electro myoelectric sensors show unique advantages in the fields of prosthetic control, rehabilitation training and human-computer interaction because they can establish direct information channels between the nervous system and the external mechanical system. According to whether it invades human tissue, electro myoelectric sensors can be divided into two categories: invasive and non-invasive. Among them, surface electro myoelectric sensors (sEMG) have become the key direction of current research and application because of their high safety, ease of use and easy integration.

The article conducts a comprehensive study on the acquisition and application of myoelectric signals, focusing on the characteristics and differences of different types of myoelectric sensors in terms of structural design, signal quality and application scenarios. This paper systematically sorts out the research progress of new sensing schemes such as surface electro myoelectric sensors, invasive myoelectric sensors, flexible wet electrodes and flexible dry electrodes, and discusses their advantages and challenges in wearable intelligent prosthesis and human-computer interaction systems, and provides reference for subsequent relevant system design and performance optimization.

2. Introduction to basic concepts

2.1. Wearable intelligent prosthetic limbs

Wearable intelligent prosthesis is a kind of auxiliary device that integrates biological sensing, embedded systems and intelligent control algorithms. Its core goal is to perceive the movement intentions of the human body in real time during the daily activities of users and transform them into natural and coordinated mechanical movements. Unlike traditional passive prostheses, intelligent prostheses continuously collect physiological and motor information from the human body through wearable sensors, such as myoelectric signals (EMG), inertial movement data (IMU) and foot mechanics information, so as to achieve a dynamic understanding of the user's movement status and exercise needs. Studies have shown that these sensing signals usually have small amplitudes, strong time-variability, and are highly dependent on the interaction between the human body, equipment and the environment. Therefore, in practical applications, they need to go through precise signal conditioning, feature modelling and intention analysis processes to achieve stable and reliable control output [1]. In the specific implementation process, wearable intelligent prostheses usually rely on a variety of sensors to work together to fully obtain key clues that reflect the intention of human movement. With the rapid development of wearable electronic technology and biomedical engineering, the collection and application of bioelectric signals has gradually expanded from traditional clinical monitoring scenarios to daily health management, rehabilitation assistance and human-computer interaction systems. Against this background, bioelectrical signals are not only used for state recording and diagnostic analysis, but also gradually become an important information channel connecting the human body with external equipment. For example, in wearable systems and intelligent auxiliary devices, bioelectric signals can be used as a key input to reflect the intention and physiological state of human movement, and to achieve more natural and intuitive interaction. From the perspective of engineering systems, the research and application of bioelectrical signals usually follow a complete processing process, including signal acquisition, signal preprocessing, characterization of information characteristics and analysis of signal meaning. Through this process, the original electrical signals are gradually transformed into information with practical physiological or functional significance, providing basic support for subsequent analysis, decision-making and control. This information acquisition and processing mode with bioelectrical signals as the core has become an important theoretical basis for modern biomedical electronic systems and intelligent wearable devices.

2.2. Bio-electricity signal

Bioelectrical signals, such as signals from muscles, heart and brain, are tiny voltage changes that occur during physical activity. These signals can generally be measured by skin or electrodes. Take EMG as an example, when muscles are active, these voltage changes will occur, which can be captured on the body surface through special sensors. The electromyogram signal is very weak, usually in the range of microvolts to millivolts, and the frequency is between tens of thousands of Hz. They can be interfered with by factors such as power cord noise, movement, and the degree of fit of the electrode to the skin, making it difficult to detect. ECG and EEG are weaker and noisier, so it is difficult to capture them clearly. With the rise of wearable technology, there is an increasing demand for better monitoring of these signals. Studies have shown that there are three main obstacles [2]. The first is how to properly handle the connection between the electrode and the skin. The second is to keep the amplification and filter circuits low-noise. The last is how to match these signals with the actual activities of the body.

2.3. Electromyographic signals and surface electromyographic signals

Electromyography (EMG) signal is a kind of bioelectric signal that reflects the characteristics of muscle electrical activity. Surface EMG (sEMG) is widely used in biomedical engineering due to its non-invasive and easy-to-deploy characteristics. Research fields such as process, motion analysis and human-computer interaction. The sEMG signal is collected by electrodes placed on the surface of the skin to record the potential changes generated by muscles during contraction and relaxation under the control of the nervous system. The superposition of these potential changes in time and space constitutes a myoelectric signal with the characteristics of randomness and time change. Its waveform and spectrum characteristics can reflect the activation state and functional activity of the muscle. Electromyogram (EMG) signals face several core challenges in signal acquisition and engineering application. Studies have shown that these challenges directly affect the reliability, repeatability and interpretability of myoelectric signals [3]. Because the surface myoelectric signal is extremely susceptible to a variety of pollution sources, including instrument noise, power interference, electrocardiogram interference, motion forgery and muscle crosstalk, different degrees and types of pollution will change the amplitude, spectrum distribution and timing characteristics of the signal, resulting in the EMG results of the same muscle under the same task. Lack of consistency between the same time or different channels

3. Classification of sensors for measuring electromyographic signals

3.1. Surface EMG electrodes

Surface EMG electrodes are a kind of non-invasive bioelectric sensor that obtains muscle electrical activity signals by attaching electrodes to the skin surface. Because of its high safety, comfort and flexible deployment, it is widely used in biomedical engineering, human-computer interaction and wearable systems. For its structural design and application performance, research has systematically explored the electrode size, geometric structure and placement strategy.

In terms of electrode placement, Young et al. systematically studied the influence of electrode size and orientation on the electrode displacement resistance of the surface electric pattern recognition system [4]. The study evaluated the impact of the electrode on the classification accuracy and real-time controllability when the electrodes are displaced in the parallel and vertical directions of muscle fibers by arranging bipolar surface electron electrical electrodes with different sizes of 1–9 cm² and different orientations along the direction of muscle fibers and transverse configuration across muscle groups. The results show that the longitudinal electrodes arranged along the direction of the muscle fiber are superior to the transverse electrodes under various displacement conditions, and the vertical displacement damage to the system performance is more significant. Moderately increasing the electrode size can reduce the sensitivity to displacement but will weaken the spatial selectivity. By combining longitudinal and transverse channels, the robustness of the system can be improved without increasing the number of electrodes. The study shows that the surface electro static electricity is highly dependent on the electrode orientation and geometric arrangement, which has important design guidance significance for wearable and prosthetic applications.

At the application level, Salomons et al. took the electromobility voice interface as an example, and compared the concentric bipolar structure with the bipolar single electrode pair with the bipolar surface myoelectric electrode [5]. The results show that in areas with dense muscle distribution such as the face and neck, the bipolar single electrode pair performs better in the classification task. The eight-channel bipolar surface myoelectric system constructed by it realizes the effective identification of phonetic muscle activity through fixed-point arrangement for pronunciation-related muscles, reflecting the potential of fine functional detection of surface myoelectricity under non-invasive conditions.

In general, surface electro myoelectric sensors have obvious advantages in terms of safety, comfort and system integration. They are suitable for wearable monitoring and human-computer interaction applications. However, in actual use, the electrode size and layout need to be reasonably designed and optimized according to specific tasks.

3.2. Invasive EMG sensors

Intrusive electro myoelectric sensors collect local, deep and highly specific electro myoelectric signals by implanting electrodes under the muscle tissue or the outer membrane of the muscle. Because the electrode position is fixed inside the muscle, its signal acquisition is less affected by skin displacement, sweat and external electromagnetic interference, so it shows higher signal-to-noise ratio and repeatability in long-term use. This characteristic gives invasive electro myoelectric sensors obvious advantages in high-performance applications such as multi-degree-of-freedom and fine control, but their applications usually rely on surgical implantation, putting forward higher requirements for clinical conditions and system maintenance.

In the study of prosthetic control, Zbinden et al. used implanted intramuscular electrodes as the signal source for motor intention decoding, combined invasive myoelectric sensors with deep learning algorithms, and realized the long-term stable connection between the electrode and the prosthesis system through the bone integration interface [6]. The research results show that compared with surface electro myoelectric signals, implanted intramuscular electrodes can record the local electrical activity of residual or reconstructed muscles more stably, thus improving the decoding performance of multiple degrees of freedom and simultaneous action in online control scenarios.

In a more representative clinical transformation study, Zbinden et al. proposed an electro-nerve-muscle reconstruction scheme combining intramuscular electrodes, extramacular membrane electrodes and nerve sleeve electrodes [7]. The method achieves long-term and stable myoelectric signal acquisition by isolating the peripheral nerve from the amputation and re-neutralizing it into the original muscle and free muscle transplant blocks and implanting the intramuscular electrode in the newly constructed muscle target. The follow-up results show that the system has maintained good electrical stability for more than two years, enabling patients to achieve intuitive prosthetic control of independent flexion and extension of five fingers.

In general, invasive myoelectric sensors have irreplaceable advantages in terms of spatial selectivity, deep muscle accessibility and signal stability. They are suitable for clinical prosthetic systems with high requirements for control performance, but their invasiveness and high medical costs limit their popularity in large-scale applications.

3.3. Flexible wet electrodes

In addition to the invasive mode, dry and wet electrodes are also an important classification in the detection of myoelectric signals. Flexible wet electrode is a kind of non-invasive surface electro myoelectric sensor that combines flexible substrate with an electrode-skin wetting interface such as gel or equivalent low-impedance material. It aims to improve wearing comfort and sports adaptability while maintaining the low contact impedance advantages of traditional wet electrodes. In recent years, relevant research has mainly promoted its development from the aspects of material system and structural design.

At the material level, Khan et al. used hydrogel as the electrode-skin interface material, integrated the ion-conductive network with high water content into the flexible substrate, and constructed a flexible wet electrode that can be attached to the skin [8]. The design uses the migration characteristics of ions in the hydrogel to form a stable ion-electron hybrid conductive channel between the skin and the electrode, thus significantly reducing the interface impedance and improving the acquisition quality of low-amplitude sEMG signals. Experiments show that this type of electrode can still maintain a high signal-to-noise ratio in long-term wearing and dynamic muscle activity monitoring. Its innovation lies in optimizing interface coupling through the material level, rather than relying on complex signal processing algorithms.

On this basis, Wang et al. further introduced functionalized polymer or composite gel materials, such as double network hydrogel or doped ionic liquid, to enhance the mechanical stability and conductivity of the electrode under tensile and bending conditions [9]. The flexible wet electrode array proposed by it can be used for multi-channel electromyography collection, which can effectively suppress the impedance fluctuations caused by electrode slippage during complex movement, and improve the problems of easy drying and failure of traditional wet electrodes.

In general, flexible wet electrodes have the advantages of low impedance, high signal quality and good skin adaptability in applications such as rehabilitation training, human-computer interaction and prosthetic control, but they still face challenges such as water-containing medium loss and high process complexity, which is an important development direction for high-precision sEMG collection.

3.4. Flexible dry electrodes

Flexible dry electrode is a kind of non-invasive surface myoelectric sensor that does not require conductive gel and can be directly attached to the skin surface to collect myoelectric signals. It aims to overcome the inconvenience and performance degradation of traditional wet electrodes in long-term wearing, wearable system integration and reuse. In recent years, relevant research has mainly promoted the development of flexible dry electrodes from the two levels of materials engineering and skin-electrode interface mechanism.

At the material level, Steenbergen et al. proposed a flexible dry surface electro myoelectric electrode based on PEDOT:PSS/PU conductive elastomer [10]. By evenly dispersing the conductive polymer PEDOT:PSS in a flexible polyurethane matrix, the electrode has both good electrical conductivity and mechanical flexibility. The experimental results show that the electrode can obtain a signal-to-noise ratio equivalent to or even higher than the traditional Ag/AgCl wet electrode in forearm electro myoelectric acquisition without the need for gel or complex skin preparation, and shows a smaller signal drift in long-term tests. This shows that the ion-electron hybrid conduction mechanism of the material itself can effectively improve the skin-electrode contact performance under dry conditions. It is characterized by the fact that the material itself constitutes a signal acquisition interface, thus improving the wearing comfort and reusability.

In terms of interface mechanism, Hassan et al.'s review system analyzed the impedance source and change law of dry electrodes in different bioelectric applications [11]. The study points out that the performance of flexible dry electrodes is not only affected by conductive materials, but also closely related to the surface structure, contact area, fit pressure and skin state of the electrode. It is proposed that the problem of increased dry interface impedance can be alleviated by conductive coating, nanofiller or structural design.

In general, flexible dry electrodes have the advantages of no need for gel, reusable, easy to integrate and good mechanical compliant. They are suitable for long-term electro myoelectric monitoring and wearable applications, but their stability still needs to be further optimised under dynamic exercise or dry skin conditions.

4. Challenge

In the future, surface electro myoelectric sensors will still face many challenges in practical applications. First, signal stability and consistency are still core issues. Changes in skin state, sweat secretion and relative displacement of electrodes will cause contact impedance fluctuations, affecting the reliability of long-term monitoring and cross-scene applications. Secondly, the problems of spatial selectivity and crosstalk are particularly prominent in areas with dense muscle distribution. How to accurately distinguish adjacent muscle activities under non-invasive conditions still needs to be further optimized in electrode structure and layout strategy. In addition, the balance between wearable integration and comfort is still challenging. Although high-density electrode arrays can improve the amount of information, they may increase the burden of wearing and system complexity. At the same time, the signal variability brought about by individual differences limits the applicability of general algorithms and puts forward higher requirements for adaptive modelling and personalized calibration. Finally, in practical engineering applications, how to achieve low power consumption, miniaturization and long-term reliable operation while ensuring performance is still an urgent problem for surface electro myoelectric sensors to move towards large-scale applications.

5. Conclusion

This paper focusses on the application of electromyoelectric signals in intelligent prostheses and wearable human-computer interaction systems, and systematically reviews different types of electromyoelectric sensors and their research progress. Through the analysis of surface myoelectric sensors, invasive myoelectric sensors, flexible wet electrodes and flexible dry electrodes, it can be seen that different sensors have their own advantages and limitations in terms of signal quality, spatial selectivity, wearing comfort and difficulty in system integration. With its non-invasive and good engineering achieability, surface electromyoelectric sensors are still the mainstream choice for current research and application, and invasive myoelectric sensors show irreplaceable potential in high-precision and multi-degree-of-freedom control scenarios. At the same time, the development of flexible electrode technology provides new solutions to improve long-term wearing stability and user comfort.

Based on existing research, it can be found that the performance of myoelectric signal acquisition is not only affected by the sensor type, but also closely related to the electrode structure design, arrangement strategy and skin-electrode interface characteristics. Future research needs to further take into account the comfort, miniaturisation and long-term stable operation needs of wearable systems while ensuring signal reliability. In addition, combining advanced signal processing methods and intelligent algorithms to improve the adaptability to individual differences and complex sports scenarios will be an important direction to promote the practical application of electromyoelectric drive systems. In general, the continuous in-depth research on myoelectric sensors and signal engineering will lay a solid foundation for the development of intelligent prosthetic limbs and human-computer interaction technology.

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