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The Application of Sensors in Bionic Limbs

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Abstract. With the increasingly prevelance of bionic limbs in the medical field, societal demands for these advanced devices are continually evolving, leading to a surge in academic research. A critical focus of this area is how to effectively communicate patients' needs to bionic limbs. Through extensive studies, it has been established that sensors play a crucial role in this communication process by converting physiological signals and user intentions into actionable commands for the bionic devices. As a bridge connecting patients with bionic limbs, many scholars have conducted in-depth researches on the application of sensors in bionic limbs. By synthesizing the existing research, this article aims to examine the application of sensors in bionic limbs and explore the current status, future prospects, and key challenges that need to be overcome to advance the field. The findings reveal that sensors have been widely integrated into the field of bionic limbs and have undergone rapid development in recent years.

Keywords: sensor, bionic limbs, control system, feedback

1. Introduction

With the increasing trend of global population aging, the rehabilitation needs of people with disabilities are also constantly growing. As an important branch of modern medical technology, research on bionic limbs has made tremendous progress in recent years. Bionic limbs are increasingly being chosen by people with disabilities as an important means of rehabilitation, and the development of bionic limbs directly affects the quality of life and social participation ability of people with disabilities. In recent years, the rapid development of sensor technology has provided a solid technical foundation for the intelligent development of bionic limbs. However, in practical applications, existing bionic limbs still face many technological bottlenecks, such as insufficient sensing accuracy, large signal delay, and high cost.

Therefore, this study aims to explore the application of sensors in bionic limbs and solve the aforementioned technical problems, further promoting the practicality and popularization of bionic limbs, and bring convenience to more patients in need.

2. Common sensor types and their characteristics

A sensor is a device that can perceive specific physical quantities and convert them into usable signals. Its core function is to convert information from the external environment into electrical signals or other forms of data, providing a basis for subsequent processing or control. In the design

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of bionic limbs, there are various types of sensors, each with its unique performance characteristics and application scenarios. This section will provide a detailed introduction to common types of sensors and their characteristics, and explore their advantages and limitations in combination with practical applications.

Resistive sensors are the most common type of sensor, which obtain information by measuring changes in material resistance. Resistance sensors are widely used for measuring pressure, strain, and temperature. For example, in a strain gauge sensor, when an external force is applied, the resistance value on the sensitive grid changes, which can be accurately detected through a Wheatstone bridge circuit. The advantages of this type of sensor are its simple structure, low cost, and ease of integration into existing systems, but its sensitivity is low and its ability to respond to small changes is limited. Liu et al. found that the measurement accuracy of resistive sensors can reach ± 0.5% in some industrial fields, but their applicability is limited in bionic limbs due to the need for higher resolution [1].

Capacitive sensors are sensors that use changes in electrical capacity to detect changes in physical quantities. This type of sensor has the characteristics of high sensitivity and fast response, and is commonly used in fields such as touch screens, proximity switches, and humidity measurement. In bionic limbs, capacitive sensors can be used to detect the pressure distribution on the skin surface. For example, the solid-liquid composite tactile finger mentioned in Zhou’s research uses a capacitive sensor array with a spatial resolution of $1mm^2$, which can achieve precise tactile feedback in complex environments [2]. However, capacitive sensors are sensitive to environmental factors such as temperature and humidity, which may lead to increased measurement errors. Therefore, additional calibration measures need to be taken to improve their stability.

Again, piezoelectric sensors are sensors that operate based on the piezoelectric effect and can directly convert mechanical stress into electrical signals. Piezoelectric sensors have attracted much attention due to their fast response, high sensitivity, and excellent dynamic characteristics. In bionic limbs, piezoelectric sensors are commonly used to measure the motion state of joints and external forces. For example, Scholar Huang describes a highly compliant six axis force sensor based on optical waveguides, which has a sensitivity of up to 0.01N and can achieve high-precision force sensing detection under complex operating conditions [3]. However, piezoelectric sensors also have some shortcomings, such as fatigue effects caused by long-term use, which can affect their service life. The nonlinear characteristics of piezoelectric materials may also lead to measurement deviation, which requires compensation through complex signal processing algorithms.

Magnetic sensor is a type of sensor that uses changes in magnetic field strength to detect physical quantities. Magnetic sensors have high sensitivity, wide frequency range, and good anti-interference ability, making them suitable for measuring speed, position, and angle. In bionic limbs, magnetic sensors can be used to monitor changes in joint angles. For example, Scholar Wang points out that magnetic sensors can achieve an angular resolution of ± 0.1°, which is crucial for precise control of prosthetic movements [4]. However, magnetic sensors have a strong dependence on the surrounding magnetic field and are susceptible to external electromagnetic interference. Therefore, in practical applications, shielding measures need to be taken to ensure their normal operation.

Furthermore, photoelectric sensors are sensors that operate based on the photoelectric effect and can convert light signals into electrical signals. Optoelectronic sensors have the advantages of high sensitivity, high resolution, and non-contact, and are widely used for measuring displacement, velocity, and shape. In bionic limbs, photoelectric sensors can be used to detect the degree of finger bending and joint position. For example, Scholar Zhong introduces a biomimetic mechanical turtle used for amphibious surveying and emergency rescue, which has a built-in photoelectric encoder

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that can achieve millimeter level displacement measurement accuracy [5]. However, photoelectric sensors have high requirements for lighting conditions, especially in low light environments, and their performance may be affected. Long term exposure to strong light may cause sensor aging, thereby reducing its reliability.

Finally, a bioelectric sensor is a sensor specifically designed to detect human bioelectric signals, which can capture signals such as muscle activity, electrocardiogram, and electroencephalogram. In bionic limbs, bioelectric sensors are mainly used to record user intent signals, thereby achieving intelligent control of prostheses. For example, Zou et al. proposed a bionic prosthetic intelligent control system based on Electroencephalogram (EEG) deep learning algorithm, with a signal-to-noise ratio of over 30dB for its EEG signal acquisition module, which can effectively distinguish different motion intentions [6]. However, the signals of bioelectric sensors are susceptible to noise interference and have significant individual differences, which places high demands on signal processing algorithms.

The application of various sensors in bionic limbs has its own characteristics, and selecting the appropriate sensor type requires comprehensive consideration of factors such as application scenarios, performance indicators, and costs. With the continuous advancement of sensor technology, future bionic limbs are expected to achieve higher precision and more intelligent functions, bringing users a better user experience.

3. The main functions of sensors in the field of bionic limbs

3.1. Data collection and feedback mechanism

One of the main functions of sensors in bionic limbs is to implement data acquisition and feedback mechanisms, which is the core link for bionic limbs to complete complex tasks. Sensors convert physical signals into electrical signals by sensing changes in the external environment or limb state, and analyze and interpret them through signal processing systems, providing real-time feedback for bionic limbs and achieving precise control.

The data collection function plays a crucial role in bionic limbs. For example, in upper limb biomimetic prosthetic hands, tactile sensors installed at fingertips can capture texture features of object surfaces, including friction coefficient, hardness, and surface roughness. Research has shown that the use of piezoresistive tactile sensors can detect subtle differences on surfaces of different materials, with a sensitivity of up to 0.1 N/cm^2, effectively distinguishing between hard materials such as glass and soft materials such as rubber [7]. Force sensors are also an important component of data acquisition, mainly responsible for measuring the magnitude and direction of external forces applied to prosthetics. For example, a six dimensional force sensor can simultaneously measure three force components and three torque components in three-dimensional space, with an accuracy typically reaching $\pm$ 1% FSO (Full Scale Output), which enables bionic limbs to accurately perceive changes in the external environment during operation.

The feedback mechanism, as a key component of bionic limbs, relies on the information collected by sensors to adjust the movements of the prosthetic. In lower limb bionic prostheses, gyroscopes and accelerometers at the knee joint can monitor gait parameters in real-time, such as stride, pace, and ground reaction force. According to relevant research, this type of sensor combination can reduce the detection error of gait abnormalities to within 3%, significantly improving the walking stability of prosthetic users [8]. Surface electromyography (sEMG) sensors are also widely used in feedback mechanisms to capture electrical signals from residual limb muscles and convert them into control commands. For example, a research team has developed a control algorithm based on

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surface electromyography, which can recognize five different hand movement patterns with 95% accuracy, thus achieving efficient control of prosthetic hands [9].

In practical applications, data collection and feedback mechanisms need to work together to meet complex biomimetic needs. For example, in some advanced bionic prostheses, data from multiple sensors are integrated into a central processing unit to form a multimodal sensing network. This type of network can not only improve the comprehensiveness of data collection, but also enhance the accuracy of feedback. For example, a study on upper limb biomimetic prostheses showed that when data from tactile sensors, force sensors, and position sensors are comprehensively processed, the finger grip force error of the prosthesis can be reduced to less than 5%, while improving the response speed of the prosthesis to hand movements, making it close to the level of a natural hand [10].

In order to further improve the performance of data collection and feedback mechanisms, researchers are exploring new technologies and materials. For example, flexible sensors have gradually become a research hotspot in the field of bionic limbs due to their excellent flexibility and adhesion. Flexible pressure sensors can adapt to irregular surfaces of the human body, with a sensitivity of up to 0.05 kPa^{-1}, which provides the possibility for achieving more delicate tactile feedback [11]. At the same time, the application of wireless transmission technology greatly simplifies the process of data acquisition and feedback, reduces the inconvenience caused by traditional wired connections, and significantly improves the flexibility of bionic limbs.

The data collection and feedback mechanism is an indispensable part of bionic limbs. Through the precise design of sensors and the support of efficient algorithms, bionic limbs can achieve precise perception and flexible response to the external environment. With the continuous advancement of sensor technology, future bionic limbs will have a higher level of intelligence, bringing a more natural experience to people with disabilities.

3.2. Support for intelligent control systems

Sensors play a crucial role in the intelligent control system of bionic limbs, with their main function being to perceive the state of the limbs in real time and convert it into data that can be understood by computers, thereby achieving precise motion control and feedback adjustment. The core of this control system is to dynamically adjust the movements of prostheses or bionic limbs through information obtained from sensors, so that they can better adapt to the needs of users and changes in the external environment. For example, in the design of a typical intelligent bionic hand, multiple built-in sensors can simultaneously monitor key parameters such as finger joint angles, palm pressure distribution, and wrist movement trajectory. After complex signal processing and pattern recognition, these data are used to predict the user's intention and adjust the prosthetic's movements accordingly to complete specific tasks. According to relevant research, the most advanced bionic hand can respond to user gesture instructions within 0.1 seconds, with a success rate of over 90% [4].

In the practical application of intelligent control systems, the performance of sensors directly affects the stability and accuracy of the entire system. For example, surface electromyography (sEMG) sensors, as an important component of biological signal input, can capture electrical signals generated by human muscle activity. By filtering, amplifying, and extracting features from these signals, researchers can transform complex muscle activity into specific action commands. Research has shown that when using a multi-channel sEMG sensor array, the system's accuracy in recognizing action intentions can be improved to over 85%, while single channel devices typically only reach a level of 60% -70% [12]. Pressure sensors are also widely used in the design of foot prostheses to measure the pressure distribution in different areas of the sole. In this way, prosthetics can better mimic natural gait and reduce fatigue and discomfort that may occur during prolonged walking. According to a survey of lower limb prosthetic users, smart prostheses equipped with pressure sensors can significantly reduce energy consumption during standing and walking compared to traditional devices, with an average savings of about 15% -20% [13].

In addition to directly participating in motion control, sensors can also provide users with rich sensory feedback, thereby enhancing the human-computer interaction experience. For example, tactile sensors can simulate the sensation of the skin, allowing users to feel the hardness, temperature, and even texture of objects; The vibration feedback device can alert users to certain specific state changes through slight vibrations. In a user test on intelligent prosthetic hands, participants reported that after three months of training, their satisfaction with operating the new device reached 80%, and over half of the respondents expressed willingness to use the device for a long time [6]. It is worth noting that this feedback mechanism is not limited to simple tactile reproduction, but combines various advanced algorithms such as deep learning models and reinforcement learning strategies, allowing prosthetics to not only "understand" the user's thoughts, but also gradually learn how to perform tasks more efficiently.

4. Conclusion

This study seeks to investigate the application of sensors in bionic limbs and discuss the current technical challenges. The findings demonstrate that the application of sensor technology in bionic limbs still faces many challenges, among which the limitations of materials science are particularly significant. As the core component of bionic limbs, the performance of sensors directly determines the functional level and user experience of prostheses. However, there are still significant shortcomings in the mechanical properties, durability, and functionality of existing materials, which pose a severe challenge to the design and practical application of sensors. Durability is another major challenge facing materials science. Sensors for bionic limbs need to work for long periods of time in extreme environments such as humidity, high temperature, and high pressure, which places extremely high demands on the stability and corrosion resistance of materials. Additionally, ultraviolet radiation and chemical pollution can also cause irreversible damage to the performance of sensors.

However, there exist some limitations in this study, particularly in its reliance on existing literature, which may not capture the most recent advancements in sensor technology. Furthermore, there is a lack of empirical research that directly evaluates user experiences and outcomes with bionic limbs, limiting the ability to draw conclusions about the effectiveness of different sensor applications in real-world settings.

In the future, the development direction of multimodal sensor fusion technology will pay more attention to intelligence and adaptive capabilities. On the one hand, with the continuous advancement of artificial intelligence technology, future fusion algorithms will be able to autonomously learn and optimize their parameter configurations, thus better adapting to different usage scenarios. On the other hand, in order to further enhance the user experience of bionic limbs, researchers will also strive to develop sensor systems with more emotional interaction capabilities.

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