Nanomaterial-Enabled Sensing for Coupling of Implantable Bcis and Prosthesis

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Abstract. Amputation caused by trauma, vascular diseases, etc., has created a global demand for high-performance prosthesis technology. Traditional electromyographic prostheses are limited by low signal fidelity and a lack of natural feedback, while implantable brain-computer interfaces still face bottlenecks such as insufficient signal stability and biocompatibility. Nanomaterials offer new possibilities to break through this dilemma. This article reviews the role of nanomaterial-enabled sensing technology in the collaborative control of implantable brain-computer interfaces and neural prostheses. The key mechanisms in improving electrochemical performance, matching mechanical flexibility, and regulating biological activity are analyzed emphatically. Through the representative studies of graphene, MXene, liquid metal, and biological hybrid interfaces, the significant advantages of nanostructures in reducing impedance, improving signal-to-noise ratio, and long-term stability are demonstrated, and the performance gain and closed-loop control potential in cross-scale systems are discussed. This paper summarizes that implanted electrodes can achieve a high signal-to-noise ratio, low delay, and multi-channel stable acquisition, but the problem of signal attenuation and biocompatibility is still prominent under long-term implantation conditions. In the future, collaborative optimization at the material and system levels is still needed. At the same time, this paper points out the emerging directions such as self-healing electrodes, bionic closed-loop systems, and organoid interfaces, which will promote brain-computer interfaces to be clinically feasible and natural interaction.

Keywords: Implantable brain-computer interfaces (BCI); Nanomaterials; Neural Prosthesis; Closed-loop control.

1. Introduction

With the superposition of factors such as trauma, diabetes, vascular diseases, and population aging, the number of amputees worldwide continues to grow. According to statistics from the World Health Organization and several epidemiological surveys, there are currently more than 57.7 million limb amputees worldwide, and more than 1 million new cases occur every year [1,2]. For these patients, a prosthesis is not only a tool to restore daily functions, but also a medium to rebuild self-identity and social participation.

However, clinical surveys in different regions show that the abandonment rate of traditional prostheses is still high, with an average abandonment rate of about 26% for body movement prostheses, 23% for electromyography prostheses, and even more than 50% for upper limb prostheses [3-5]. These data reflect the lack of comfort, responsiveness, and perceived interaction in traditional control methods, which makes it difficult for patients to achieve natural control.

In this context, an implantable brain-computer interface (BCI) is regarded as a potential solution to break through the bottleneck of traditional prosthesis control because it can directly decode the motor intention of the cerebral cortex. It has significant advantages in signal bandwidth and decoding accuracy, but long-term signal stability, biocompatibility, and implantation safety are still the main obstacles to clinical transformation [6]. In recent years, the development of flexible conductive nanomaterials has provided new ideas to solve these problems. The comprehensive improvement of its electrochemical performance, mechanical matching, and biological activity regulation significantly improves the interface signal quality and long-term stability, providing a better material basis for the implantable interface [6].

This paper focuses on the nano-sensing driven implantable brain-computer interface and collaborative control of neuroprosthesis, and reviews the recent research progress at the material and system levels. Through review and comparison, the mechanism of nanomaterials in the process and the potential for performance improvement were analyzed. To reveal the application value and future development direction of nanomaterials in promoting the clinical process of implantable BCI.

2. Synergistic Mechanism of Neuroprosthesis and Implantable BCI

The development of neuroprosthetic limbs is moving towards a higher degree of embodied integration. Traditional electromyography (EMG) prosthetics mostly rely on surface EMG signals as control inputs. However, sEMG is easily affected by electrode position, skin impedance, and residual muscle state, which is manifested as signal drift, reliability fluctuations, and limitations in the ability to decode complex movements [7]. Multiple reviews and surveys have shown that the phenomenon of giving up the use of prosthetic limbs due to comfort and functional limitations remains obvious, which reflects the insufficiency of traditional control methods in achieving natural interaction [4,5]. To improve the control effect, researchers have gradually integrated tactile and force feedback into a closed-loop system to enhance operational accuracy and the user's sense of presence [8].

In a closed-loop system, an implantable BCI undertakes the core function of intent decoding. Microelectrode arrays can directly record the spikes and local field potentials (LFP) of the motor cortex, thereby providing a higher information rate and richer control dimensions than non-invasive methods. Early human studies represented by the Utah 96-channel array have demonstrated that continuous three-dimensional grasping and transporting actions can be achieved through implantable recording, and high success rates have been obtained in goal-oriented tasks [9]. Clinical reports show that the goal completion rate of individual cases can reach approximately 90% [9]. With the advancement of hardware and algorithms, decoding performance has been continuously improving. Recently, researchers have achieved an online accuracy rate of approximately 90 characters per minute and 94% by decoding natural handwritten intents, providing a referenceable example for high-bandwidth intent reading [10].

Perceptual write-back is crucial for closed-loop performance. Micro-electrical stimulation (ICMS) of the somatosensory cortex in human subjects to provide tactile perception has been proven to significantly improve operational efficiency and natural sensations. In the relevant experiments, after supplementing tactile perception, the completion time of the subjects in the grasping and carrying tasks was significantly shortened. For example, in Flesher's experiment, the completion time was reduced from about 20.9 seconds to 10.2 seconds, and the success rate of operation and the stability of grasping the object were improved [8]. These results suggest that stable input recordings together with low-latency perceptual writeback determine the fluency of the closed-loop system.

At the system level, array size is as important as long-term stability. Since the early 96-channel arrays, the number of recorded channels has been extended to kilo-channel level technical lines, such as recent flexible high-channel platforms, which offer the possibility of capturing higher-dimensional neural representations [11,12]. At the same time, long-term follow-up studies suggest that the electrode signal quality will show a fast and slow change curve after implantation. Some studies still observe usable signals in several years of follow-up, but early degradation or short-term interruption events have also been recorded, emphasizing the importance of long-term biocompatibility and packaging process [13]. Therefore, the realization of cooperative control performance needs to find a balance between acquisition accuracy (high SNR, multi-channel), real-time decoding (low delay, high reliability), and multimodal feedback (perceived and low delay) [10,13,14]. Materials and interface engineering, such as flexible films and nanostructured surface modifications, are providing quantifiable improvement paths to reduce interfacial impedance and extend the functional life of electrodes, but more evidence-based data are still needed for long-term clinical validation of these technologies. In conclusion, the collaborative control of implantable BCI and neural prostheses requires that the technology start from materials and interfaces, and integrate decoding algorithms with clinical implementation. Only under the condition of collaborative optimization at the collection end, processing end, and feedback end can the closed-loop system move from laboratory demonstration to sustainable clinical application.

3. The Central Role of Nanomaterials in the Collaborative Control of Implantable BCI-Neuroprosthesis

3.1. Limitations of Traditional Materials

The performance of an implantable brain-computer interface system largely depends on the stability of the interface between the material and neural tissue. Traditional metal electrodes (such as Pt and Ir) have been widely used in early studies due to their high conductivity and mature preparation process, but their Young's modulus (about 160-200 GPa) is much higher than that of nerve tissue (100-10 kPa), resulting in a significant mechanical mismatch [15]. In the long-term implantation process, microscale displacement can induce tissue stress accumulation and inflammatory reaction, leading to the gradual thickening of the glial scar, the electrode impedance increases with time, and the signal of some channels is weakened [13]. The long-term follow-up study of Colachis et al. showed that the microelectrode array could still maintain effective recording within two years, but there was a trend of increasing impedance and decreasing number of active channels, suggesting that the signal stability was limited by chronic tissue reaction and interface aging [13]. To improve the interface properties, the conductive polymer PEDOT: PSS was introduced into the flexible neural interface. Its high charge injection capacity and compliant mechanical properties significantly reduced the interface impedance and maintained a stable electrochemical response in short-term experiments [16]. However, there is a risk of spalling and performance attenuation in a long-term in vivo environment [16]. It can be seen that the main bottleneck of traditional materials is mechanical mismatch, insufficient long-term stability, and the difficulty of inhibiting tissue reaction.

3.2. Roles and Cases of Nanomaterials

Table 1. Material Comparison in Brain-Computer Interface (Original)

Material Type	Impedance Characteristics	Mechanical Adaptation	Long-Term Stability	Biocompatibility & Functionalization	Representative Studies
Metals (Pt, Ir)	High impedance, low SNR	Ultra-high modulus (GPa scale), severe mismatch with brain tissue	Weeks to months	Prone to glial scarring, lack of functionalization	Utah array (clinical application)[9]
Polymers (PEDOT)	Significantly reduced impedance	Good flexibility, partial matching with tissue	Months decay	Drug or anti-inflammatory molecule loading capability	PEDOT: PSS coating study [15]
Nanocarbon (CNT/Graphene)	>50% impedance reduction, improved SNR	Ultra-thin flexible film, excellent matching	Months stable	Easy surface modification, enhanced cell compatibility	Graphene array study [6]
MXene	High conductivity, low impedance	Good flexibility, fabricable	Excellent with animals	Surface modifiable, supports neural adhesion	MXene electrode study [6]
Liquid Metals	Extremely low impedance, high conductivity	Stretchable, cyclic stability	Good animal data	Encapsulation required to prevent leakage, surface functionalizable	ACS Nano report [17]
Biohybrid Interfaces	Optimizable electrical performance	High modulus matching with tissue	Limited clinical evidence	Cell fusion and regeneration potential	Biohybrid interface study [18]

In order to clarify the differences in mechanical, electrochemical, and biological properties of different types of electrode materials, this paper systematically compares the main parameters of traditional metal electrodes, conductive polymers, and emerging nanomaterials (see Table 1).

In recent years, the advantages of nanomaterials in electrochemical, mechanical, and biological interface regulation have been gradually highlighted. The porous structure of graphene and carbon nanotubes significantly increases the effective contact area, reducing the interface impedance by more than 50% and increasing the signal-to-noise ratio by nearly two times [6]. Due to its high conductivity and rich surface functional groups, MXene material can achieve a higher charge injection limit (about 4.1 mC/cm^2) per unit area, which is three times that of traditional metal electrodes [6]. In the direction of flexibility, the ultra-thin polyimide substrate flexible electrode prepared by Guo et al. showed 35% tissue damage reduction in animal experiments [19]. Kwon et al. used liquid metal electrodes to achieve a signal retention rate of 90% in a deep brain stimulation model, maintaining stable conduction performance even after repeated bending [18]. These studies demonstrate the significant potential of flexible nanostructures to reduce mechanical irritation and improve long-term stability.

In addition to their physical properties, nanomaterials also present new possibilities for the regulation of biological activities. The bio-hybrid electrode proposed by Boufidis et al. makes use of biomolecular modification and cell co-culture technology to form steady-state integration of the electrode surface with glial cells, and the chronic immune response is significantly weakened [19]. In the long-term implantation experiment, the signal fluctuation of nanomaterials was lower than that of traditional metal electrodes, and the expression level of tissue inflammatory markers was decreased by 40%-60% [20,21]. This transition from inert materials to functional interfaces marks the evolution of neural interface materials from pure conduction to active regulation.

The role of nanomaterials is not limited to improving single performance, but to optimizing system performance at multiple levels through the "material-structure-function" collaborative design.

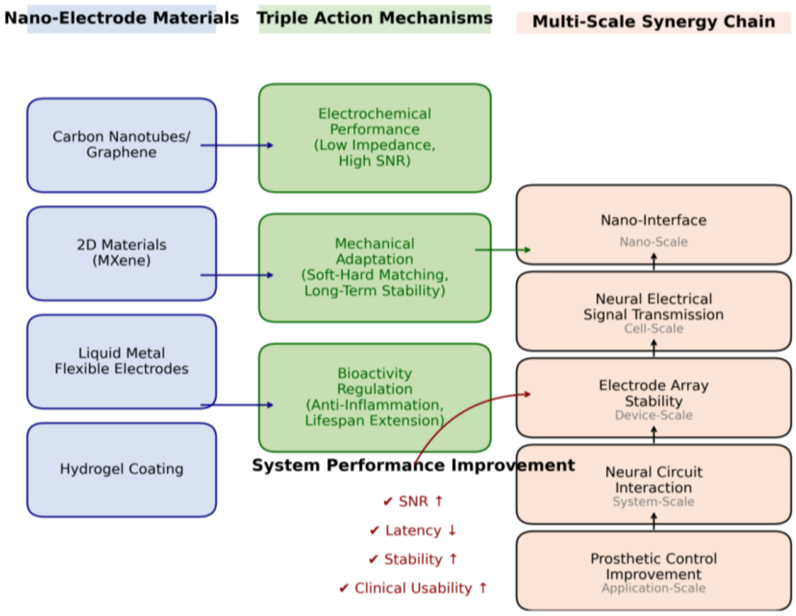

Fig. 1 Effect and Improvement Mechanism of Nanomaterials (Original)

Fig. 1 outlines this cross-scale chain of action, where nanoscale structures regulate electrochemical and mechanical properties at the interface to improve the quality and stability of neural signal acquisition. Through system integration and optimization, these improvements are further reflected in key metrics such as signal-to-noise ratio (SNR) improvement, latency reduction, and channel density increase, which ultimately translate into more natural motor control and clinical function recovery.

In closed-loop control experiments, the nanocomposite electrode significantly improved signal availability and response speed. The high SNR electrode resulted in a 20% reduction in the intent decoding error rate, and the system delay could be controlled within 100 ms [14]. Flesher et al. 's study showed that by providing tactile feedback through micro-electrical stimulation in the somatosensory cortex, the accuracy of subjects in the grasping task was increased to 93%, and the operating time was shortened by about 27% [8]. These results show that the flexible nanoelectrode not only improves the signal recording conditions but also provides a basis for realizing natural and intuitive closed-loop control.

However, the improvement of material properties has not fully solved the core problems of its clinical application. First, there is still uncertainty about long-term in vivo stability. Lv S et al. pointed out that the flexible electrode will still show impedance drift and coating micro-cracks after more than half a year of implantation, which may be related to tissue stress accumulation and interface micro-corrosion [22]. Secondly, large-scale fabrication and interbatch consistency are still difficult obstacles for nanostructured materials to overcome. Current fabrication processes often rely on fine coating and complex transfer steps, which are difficult to meet medical-grade production standards. Finally, the safety verification of long-term coexistence of materials and the nervous system is still in the early stage, and more multi-center and long-term clinical studies are needed to confirm the effectiveness and reliability.

3.3. The Future Development Trend of Nanomaterials

To solve these problems, research is gradually turning to composite materials with self-healing and intelligent response capabilities. The multi-layer nanocomposite electrode reported by Yang et al. can spontaneously recover conductivity after damage, with a recovery rate of conductivity of more than 95%, and significantly prolong the service life [23]. In addition, programmable surface modification technology enables materials to dynamically adjust their chemical properties in an inflammatory environment, thereby mitigating immune rejection and improving signal stability [23]. These strategies represent a transition from single performance optimization to systematic integration in nanomaterials research.

4. Conclusion

Taken together, the introduction of nanomaterials is opening up a new development path for the collaborative control of implantable brain-computer interfaces and neuroprostheses. Through the synergistic optimization at the electrochemical, mechanical, and biological activity levels, nanomaterials significantly improve the signal-to-noise ratio of the interface, reduce the impedance, and improve the mechanical matching between the electrode and the neural tissue, thereby providing a technical basis for high-fidelity signal acquisition and low-delay closed-loop feedback. Recent animal experiments and preliminary clinical results show that flexible nanostructured electrodes can maintain stable recordings on a scale of months to years, and significantly improve control accuracy and subjective embodiment when combined with multimodal feedback. These advances show that material innovation has become a key driving force to promote BCI from experimental verification to functional rehabilitation applications. However, there are still multiple challenges to achieving clinical usability, including long-term biocompatibility and package reliability. Future research should further strengthen cross-scale design and system integration, and explore self-healing and intelligent response to achieve the real integration of materials, algorithms, and clinical applications.

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This review systematically summarizes the key roles of nanomaterials in the coordinated control of implantable brain-computer interfaces and neuroprosthetics. It is comprehensive, clearly structured, and the analysis of representative materials is based on sound scientific evidence. It also provides valuable insights into future research directions. Overall, the review is of high quality, logically rigorous, and without significant issues; direct acceptance is recommended.							