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Multidisciplinary integration and application in Brain-Computer Interface (BCI) technology

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Abstract:

Brain–Computer Interface (BCI) technology embodies the deep integration of materials science, computer science, and medicine, offering a transformative pathway for neurorehabilitation, neurological disease treatment, and human–computer interaction. Advances in flexible nanomaterials such as graphene, carbon nanotubes, black phosphorus, and layered double hydroxides have effectively addressed the limitations of traditional rigid electrodes by enhancing biocompatibility, electrical conductivity, and mechanical compliance, while minimizing immune rejection and tissue injury. Concurrently, artificial intelligence–based decoding algorithms, including CNN–Kalman Filter (CNN-KF) architectures and AI-assisted control systems, have greatly improved motion intention recognition accuracy and real-time adaptability. Medical research further complements these developments by guiding electrode placement, ensuring biosafety, and validating long-term clinical performance. This cross-disciplinary synergy forms a closed-loop framework of "material design – algorithm optimization – clinical verification," promoting BCIs toward high precision, low invasiveness, and stable functionality. Collectively, these advances establish the foundation for next-generation intelligent neural interfaces capable of restoring motor function, facilitating cognitive rehabilitation, and achieving seamless interaction between humans and machines.

Keywords: Brain–Computer Interface (BCI); Nanomaterials; Neural Repair.

1. Introduction

Brain-computer interface (BCI) technology has brought hope of recovery to patients with neurological diseases such as spinal cord injury, Parkinson's disease (PD), and Alzheimer's disease (AD), enabling direct information exchange between the brain and external devices and providing a new approach for the diagnosis and treatment of diseases. However, traditional BCI technology has long been constrained by core bottlenecks. Tang et al. pointed out that the mechanical properties of traditional rigid electronic materials (such as metals and silicon) differ greatly from those of brain tissue. The Young's modulus of the former can reach 100 GPa, while that of brain tissue is only about 1 kPa. This mismatch can lead to tissue damage and signal transmission interruption after implantation. It may also trigger rejection reactions and inflammation in the brain, seriously affecting the stability of the device and the safety of treatment.

Meanwhile, Villa et al. added that traditional electrodes also face the problem of insufficient biocompatibility: metal nanoparticles are prone to excessive production of reactive oxygen species, and the rigid structure implanted is likely to damage the blood-brain barrier [1]. Subsequently, the scars formed by the activation of glial cells will further increase the electrode impedance, leading to a long-term decline in signal quality. These problems make it difficult for traditional brain-computer interfaces to play a role in precise diagnosis and long-term treatment, and there is an urgent need for breakthroughs in material innovation and process optimization.

In recent years, advancements in materials and artificial intelligence technologies have provided directions for addressing these bottlenecks. It is worth noting that Haleem et al. emphasized that nanotechnology offers new solutions for neural interface materials, as nanoparticles such as carbon nanotubes and graphene possess high electrical conductivity, flexibility, and biocompatibility, making them suitable for brain-computer interaction and targeted neurotherapy applications [2]. The two-dimensional nanomaterials (such as graphene, black phosphorus, layered dihydroxide) proposed by He et al and the flexible bioelectronic materials (such as PEDOT:PSS composite hydrogel and carbon nanotube /PDMS composite materials) studied by Tang can balance mechanical compliance, electrical conductivity and biocompatibility [3, 4]. Adapt to the dynamic environment of brain tissue. It can also reduce damage. The CNN-KF decoder and AI "co-pilot" system developed by Lee et al. have further enhanced the accuracy of signal decoding and the efficiency of task control, transforming BCI from "functionality" to "stability and user-friendliness" [5, 6]. Recent studies have also shown that injectable conductive hydrogels containing graphene oxide and polyethylene glycol networks possess appropriate elasticity (~ 1-2 kPa), high electrical conductivity (1-10 S/m), and anti-inflammatory properties, which can support neuronal growth and axonal re-myelination in spinal cord injury repair [7]. This material creates a stable microenvironment for nerve regeneration At the same time, it minimizes immune rejection and tissue damage to the greatest extent. These innovations revolve around "low damage, high stability and high precision", laying the foundation for the clinical transformation of brain-computer interface technology.

2. The Complete Core Workflow of the BCI System

A BCI system realizes its functions through the collaborative process of „neural signal acquisition - decoding - execution - closed-loop control", and each link requires support from multiple disciplines: Firstly, invasive (such as Utah array) or non-invasive (64-channel EEG cap) sensors capture neural signals. Non-invasive sensors need to reduce eye movement and muscle artifacts through filtering [5]; Secondly, AI-enhanced decoders (such as the CNN-KF architecture) convert the original signal into instructions - CNN extracts nonlinear features of the motor cortex, and KF achieves real-time adaptation, enabling paralyzed patients to stably control the cursor [3, 6]; Subsequently, the robotic arm, cursor and other execution terminals complete the instructions. AI assistance can increase the success rate of tasks (such as continuous grasping and placing). Finally, the closed-loop logic of „shared autonomy" integrates human intentions with AI assistance, recognizes targets through computer vision, analyzes trajectories to infer user needs, and reduces the demand for neural degrees of freedom [5]. Throughout the entire process, materials science ensures the biocompatibility of sensors, computer science optimizes algorithms, and medical science verifies safety. The three work together to guarantee system stability.

3. Multidisciplinary Cross-disciplinary Mechanism

The breakthrough of BCI technology is not an isolated progress of a single discipline, but a combined force of materials science, computer science and medicine through a closed-loop synergy of „demand - support - verification". The three complement each other with materials as the link to form an interdisciplinary system.

3.1 Section Headings Materials Science: The Core Support of BCI Hardware

Materials science, through the structural design of nanomaterials, breaks through the mechanical, biological and electrical defects of traditional rigid materials, providing performance guarantees for BCI system hardware (such as electrodes and signal acquisition components). Specifi-

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cally, two-dimensional carbon-based materials (graphene, rGO) achieve a 30% reduction in impedance and a 67% reduction in glial scarring by means of sp² conjugated structure and atomic-level thinness, solving the problems of mechanical mismatch and inflammation [1]; Carbon nanotubes (CNT), with their hollow structure and high specific surface area, increase the charge transfer efficiency by 40% and meet the low-voltage requirements of deep brain stimulation (DBS) [2]; The composite coating of metal nanoparticles (gold, platinum) and PEDOT:PSS has both corrosion resistance (corrosion rate 0.02mm/year) and flexibility (Young‘s modulus 30 kPa), meeting the long-term implantation requirements [4]. Layered dihydroxides (LDHs) and black phosphorus (BP) achieve the integration of „signal acquisition - neural repair" functions. For example, loading NT3 on LDHs can promote the differentiation of neural stem cells, and the photothermal effect of BP accelerates axonal regeneration [2].

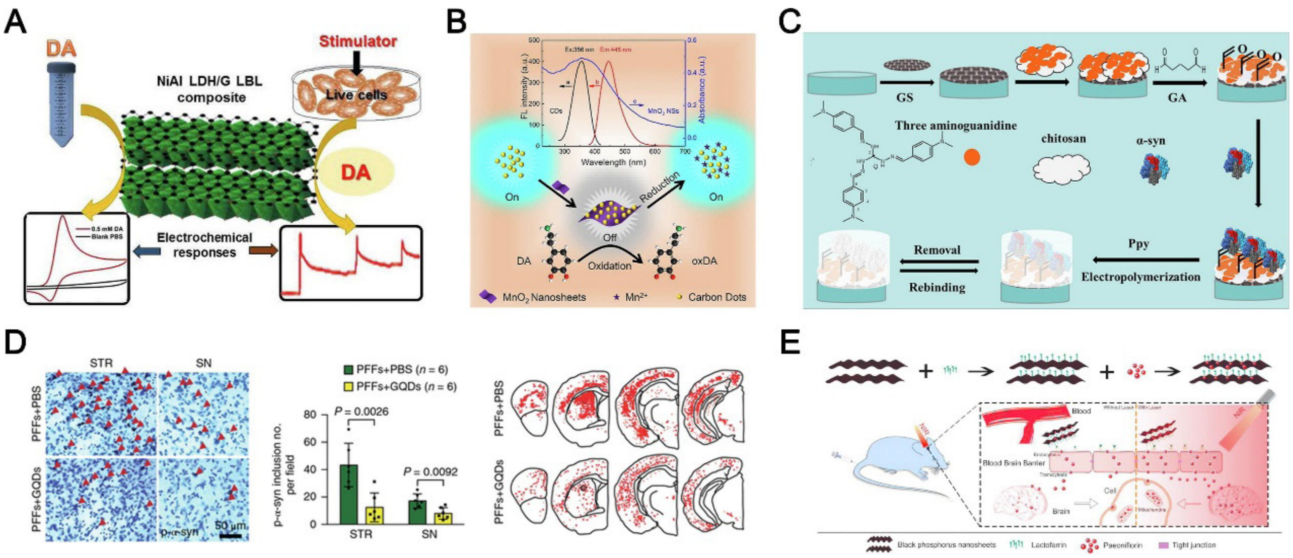

Fig. 1 Schematic diagram of two-dimensional nano-nerve repair [8, 9, 10]

The structure-performance design of these materials provides a stable and low-damage hardware carrier for BCI. In the above figure 1, Figure 1 E focuses on the mouse spinal cord injury (SCI) model: Neural interfaces constructed based on materials such as black phosphorus can be applied to the SCI area to achieve the detection and regulation of neural signals, and assist in the neural regeneration process after injury (such as supporting signal transduction and tissue repair at the injury site through the electrical activity and other properties of the materials), providing support for the recovery of neural function after SCI. The remaining figures (figure 1 A-D) briefly involve material preparation (such as the construction of composite systems), in vitro electrochemical/optical properties, and differences in brain region effects, etc., to assist in illustrating the research logic of materials from basic design to in vivo application.

3.2 Computer Science: Relying on Material Optimization Algorithms and Systems

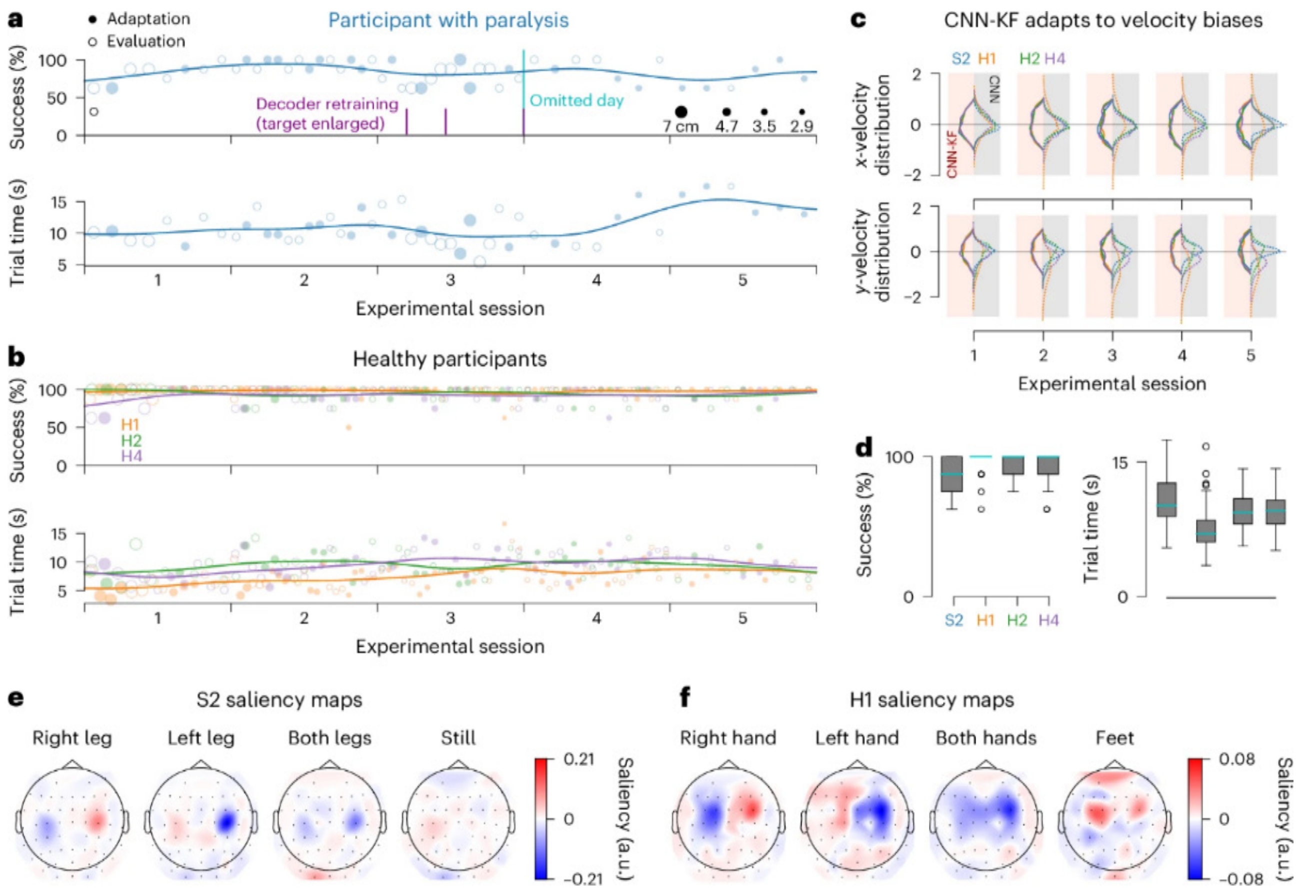

Fig. 2 The adaptability of the CNN-KF algorithm to speed deviation in multiple experimental stages [5]

Computer science, based on high-quality data provided by materials, transforms hardware performance into actual control capabilities. Specifically, AI decoders (such as CNN-KF) rely on the low-noise signal of graphene electrodes (with an SNR improvement of 2.5 times) to achieve a motion intention recognition accuracy of 91% [5]. As shown in the following Figure 2, in experiments 1 to 5, the CNN-KF decoder combined with the Kalman filter (KF) has a more stable velocity distribution in the x and y directions than a simple CNN, which can better adapt to velocity deviations and improve the decoding effect.

Computer vision (e.g. Youdaoplaceholder0 DINO) requires the long-term stability of CNT electrodes to ensure precise matching (error 15 ms) between target recognition and neural intent [5]; The remote system relies on the anti-interference performance (shielding effectiveness 30 dB) and low power consumption of the CNT-metal composite electrode to achieve robotic arm control with an accuracy of 0.1 mm at a distance of 100 kilometers [5]. Meanwhile, algorithm requirements guide material design in reverse, such as multimodal signal acquisition promoting the spatial resolution optimization of graphene microelectrode arrays.

3.3 Medicine: Guide Material Design and Clinical Validation

Medicine provides biological guidance and security guarantees for materials and algorithms, and is the key to connecting technology with clinical applications. Specifically, the activation law of the motor cortex hemispheres (right hand movement activates the left hemisphere) guides the precise layout of graphene microelectrodes, increasing the accuracy of intention recognition by 16% [5]. The significance maps of subject S2 (lower limb movement) in Figure 2e and subject H1 (upper limb and foot movement) in Figure 2f show: The significant distribution of motor cortex corresponding to different limb movement tasks (such as single leg, both hands, feet, etc.) is specific (for example, right leg movement activates the right cortex, left hand movement activates the left cortex), reflecting the differences in cortical response patterns of limb movement intentions, which can provide characteristic basis for BCI motor intention decoding. ; The mechanism of post-SCI glial scar (activation of TGF-β pathway) promotes the development of „restorative“ materials such as LDHs-NT3, extending the stable working time of BCI from 3 months to 8 months [2]; Clinical ethics reviews (such as

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UCLA IRB) ensure the implantation safety of materials like graphene and BP through acute toxicity and long-term biocompatibility tests. In addition, clinical efficacy data (such as reduced UPDRS scores in PD patients) feed back into material optimization, forming a cycle of „clinical feedback - material improvement".

4. The Multi-domain Applications of BCI

The breakthrough of BCI lies in the fact that nanomaterials overcome the limitations of rigid materials in mechanical, biological and electrical compatibility by precisely regulating the "structure-performance-function" relationship. In different scenarios, nanomaterials, with their flexibility, conductivity and repair properties, meet the demands of paralysis rehabilitation, neurological disease treatment, spinal cord repair and human-computer interaction, promoting the technology towards clinical application.

4.1 Material Innovation Ensures the Recovery of Motor Function and Communication Ability of Paralyzed Patients

As shown in Table 1, the core demands of paralyzed patients (such as those with spinal cord injury or ALS) for BCI are long-term non-invasive neural signal acquisition and high-precision control of external devices. Traditional rigid electrodes, due to the significant difference in Young's modulus between them and brain tissue (~1 kPa) (tungsten has a Young's modulus of 411 GPa), are prone to cause interface friction injury and glial scar formation when implanted for a long time. Moreover, the high interface impedance leads to significant signal noise, making it difficult to meet clinical requirements. Two-dimensional carbon-based materials (graphene, reduced graphene oxide (rGO)) and carbon nanotubes (CNT) have become the core breakthrough materials in this field through atomic-level structure design and surface modification. Their advantages are specifically reflected in the dual improvement of signal acquisition accuracy and long-term stability.

On the one hand, the atomic-level thin structure of graphene (with a single-layer thickness of approximately 0.34 nm) and the conjugated π electron system formed by sp^2 hybridization jointly endow the electrode with two core advantages. These two advantages directly solve the problems of signal noise and tissue damage in the long-term application of BCI in paralyzed patients. On the one hand, the high electrical conductivity of graphene (300 S/m) reduces the electrode-brain tissue interface impedance by 30% [1].

Table. 1 Key performance attribute table of various materials for neural interfaces [11, 12, 13].

Material	Young's Modulus (GPa)	Thermal conductance (W/m*K)	Electrical conductance (S/m) (20 °C)	Neurotoxicity	Relative Allergenic History
Metals, Metalloids, and Alloys used as Conductive Tracks					
Graphene	950–1000	140	1.0×10^5	Nontoxic	Rare
Tungsten	411	170	2.0×10^7	Variable results	Rare
Gold	79	320	4.5×10^7	Nontoxic	Common
Silicon	47	150	1000	Nontoxic	Rare
Platinum	168	72	9.4×10^6	Minimal toxicity	Rare
Iridium	528	147	2.1×10^7	Nontoxic	Rare
Tin	50	67	9.1×10^6	Minimal toxicity	Rare
Titanium	116	22	2.4×10^6	Nontoxic	Rare
Copper	130	400	5.9×10^7	Toxic	Common
Nickel	200	91	1.4×10^7	Toxic	Most common
Cobalt	209	100	1.7×10^7	Toxic	Common
Silver	83	430	6.3×10^7	Toxic	Common
Zinc	108	120	1.7×10^7	Toxic	Common
Chromium	279	94	7.9×10^6	Toxic	Common

Biocompatible Polymers for Electrode Coating					
PEDOT	2.6	0.17–0.37	2.8×10^{5}	Nontoxic	–
PVA	2.75	0.49	1.05×10^{9}	Nontoxic	–
PLGA	1.57–2.43	–	9.8×10^{9}	Nontoxic	–
PEG	0.32	0.297	–	Nontoxic	–
PDMS	0.00036–0.00087	0.15	1.0×10^{5}	Nontoxic	Rare
Encapsulation Materials used as Structural Scaffolding					
Parylene-C	3.2	0.084	–	–	Rare
Silk	5.15	0.083	–	–	Common
Silicon Dioxide	66.3–74.8	1.3–1.5	1.0×10^{-12}	Nontoxic	Rare
Teflon	0.575	0.24	–	Nontoxic	Rare
Bioactive Glass	55–126	0.5–1.38	–	Nontoxic	Rare
Sapphire	400	25–46	–	Variable Toxicity	Rare

Significantly reduce the energy loss and noise interference of neural signals during transmission. Table 1 compares the Young's modulus, thermal conductivity, electrical conductivity, neurotoxicity and relative sensitization of three types of materials in the field of neural interfaces (metals/metal-like and alloys for conductive traces, biocompatible polymers for electrode coatings, and encapsulation materials for structural scaffolds). The different materials show significant differences in mechanical, thermal, electrical properties and biological safety. It can provide a basis for the screening of neural interface materials, help balance the mechanical compatibility, conduction efficiency and biological safety of materials, and support the long-term stable interaction of neural signals.

On the other hand, the chemical inertness of graphene and its surface micro-nano structure (natural wrinkles) significantly enhance biocompatibility. Its non-toxicity avoids triggering immune rejection reactions, and the surface wrinkles can provide stable attachment sites for neurons, reducing the formation of glial scars. The histopathological study by Villa et al. showed that after three months of graphene electrode implantation, the area of glial scar around the electrode was only 1/4 of that in the traditional tungsten electrode group, and the survival rate of neurons increased by 60% [1]. This advantage ensures that paralyzed patients can use BCI for a long time without worrying about performance degradation caused by tissue damage.

Unlike the focus of graphene-based electrodes, carbon nanotube (CNT) coated electrodes have become the core material for controlling robotic arms in paralyzed patients by optimizing charge transfer efficiency and mechanical durability. Its one-dimensional conjugated structure (diameter 1-10 nm) and high specific surface area (1000-2630 m^2/g) bring about two key performances: First, the charge transfer efficiency was increased by 40% compared with the traditional tungsten electrode [3]. The rapid transfer of π electrons reduced the command response delay of the robotic arm to 80 ms. In the experiment of Lee et al. the success rate of S2, a patient with spinal cord injury, grasping blocks with it reached 91% (only 32% without coating). After 20 consecutive cycles, the charge transfer efficiency only decreased by 5% (28% for traditional tungsten electrodes). Secondly, the CNT coating can prevent the contact between brain tissue fluid and tungsten electrodes, avoiding neurotoxicity and enhancing wear resistance. The Tang accelerated aging experiment showed that its corrosion rate in simulated cerebrospinal fluid for six months was only 0.02mm/year (0.15mm/year for traditional tungsten electrodes), which is suitable for patients' daily repetitive task requirements [4].

For the special circumstances of patients with ALS, the rGO/conductive polymer (PEDOT:PSS) composite electrode, through the "electroactivity-flexible" collaborative design, facilitates the control of brain-computer interfaces (BCI). The mechanical properties of this material match those of scalp tissue and can reduce motion artifacts. At the same time, it can enhance the performance related to electroencephalogram (EEG) signal detection. The research by Villa et al. (2024) also indicates that this type of composite electrode has advantages in terms of biocompatibility and other aspects, which is conducive to

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improving the BCI effect of patients.

4.2 Precision Treatment of Neurological Diseases

In the treatment of neurological diseases such as Alzheimer's disease (AD), Parkinson's disease (PD), and spinal cord injury (SCI), traditional methods often encounter problems such as invasive diagnosis and difficulty in drug targeting. However, the material innovation in the designated research can precisely combine „low-injury diagnosis" with „targeted therapy" to address these pain points.

For AD, the graphene oxide and black phosphorus (BP) nanosheets mentioned by He et al. are very practical. Graphene oxide can adsorb Aβ protein in the brain, prevent it from aggregating into toxic plaques, and achieve targeted treatment. BP nanosheets are thin and have good biocompatibility, capable of crossing the blood-brain barrier (BBB) [3]. They can not only carry diagnostic probes to locate lesions but also deliver drugs, completing diagnosis and treatment in one step without causing additional damage to brain tissue. Meanwhile, the biocompatible electrode developed by Villa et al. can be implanted for a long time to monitor AD-related electroencephalogram (EEG) signals, and it causes very little stimulation to brain tissue during diagnosis.

Deep brain stimulation (DBS) is commonly used to treat PD, but traditional rigid electrical stimulation is highly prone to tissue damage. Tang et al. 's flexible materials can solve the problem - for instance, the PEDOT:PSS composite hydrogel electrode, which has a hardness close to that of brain tissue, can closely adhere to the brain surface during implantation, reduce mechanical damage, and will not cause severe inflammation even after long-term stimulation [4]. The layered dihydroxide (LDH) nanomaterials developed by He et al can also hold drugs for treating PD, precisely delivering them to the substantia nigra region, avoiding the side effects of drug diffusion, and reducing the damage caused by systemic medication while providing targeted treatment [3].

The treatment of spinal cord injury should consider both low-injury implantation and nerve regeneration. Tang et al. developed flexible scaffolds, such as carbon nanotube composite hydrogels, which can adhere along the shape of the spinal cord during implantation without compressing the nerves [4]. He et al. also mentioned that such materials can regulate inflammation in the injury area, reduce glial scars, and facilitate nerve regeneration. Moreover, the surface of the material can modify diagnostic molecules, allowing real-time observation of the repair status [3]. Treatment and assessment are carried out simultaneously, and the entire process causes minimal spinal cord injury.

4.3 The Material Realizes „Neural Repair and Interface Integration Synergy"

The application of BCI in patients with spinal cord injury (SCI) faces unique challenges - not only is it necessary to collect neural signals to control external devices, but also to improve the neural repair microenvironment in the injury area (such as glial scar formation, inflammatory response), otherwise the electrode-neural interface will gradually fail with scar hyperplasia. Traditional BCI systems lack repair functions. The stable working period is usually less than three months. The black phosphorus (BP) composite hydrogel and layered dihydroxide (LDHs) have constructed a „neural repair - interface stability" synergistic BCI system through an integrated design of „repair function - electrical performance". The material advantages are reflected in the dual effects of optimizing the repair microenvironment and enhancing the stability of signal transmission.

BP composite hydrogel (BP nanosheets dispersed in gelatin gel) is the core material for the integration of SCI repair and BCI interface. Its layered semiconductor structure endows it with the dual functions of „photothermal regulation - conductivity adaptation", perfectly matching the needs of SCI patients for „repairing damaged nerves + stably collecting signals". On the one hand, BP can produce a mild photothermal effect under near-infrared light (NIR, 808nm) irradiation (the temperature rises to 39-41 ℃), which can activate the expression of heat shock protein 70 (HSP70), promote the differentiation of transplanted mesenchymal stem cells into nerve cells, and at the same time inhibit the excessive proliferation of glial cells. The experimental data of He et al. showed that after SCI model rats were implanted with BP composite hydrogel and irradiated with NIR, the number of positive cells for the neuronal marker TUJ-1 was 3.2 times that of the control group, and the average axon length reached 120 μm (only 45 μm in the control group [2]. And the expression level of glial fibrillary acidic protein (GFAP, a marker of glial scar) decreased by 55% [3]; In the following figure, immunofluorescence staining of subfigure C indicates that NeuN, Tuj-1 (a neuronal marker) and DAPI co-localization can be seen in the injury area of the LDH/LDH-NT3 group, confirming neurogenesis.

On the other hand, the electrical conductivity of BP (50-100 S/m) is highly compatible with that of neural tissue (0.1-1 S/m), and it can be used as a „temporary conductive scaffold" to connect the neural pathways at both ends of the injury, reducing signal transmission loss. Tang demonstrated that when BP composite hydrogel was used in combination with CNT electrodes, the stability of BCI signal acquisition in SCI model rats could be maintained for 6 months, while the signal amplitude of the control group without BP hydrogel decreased by 50% after 3 months [4]. In addition, BP has excellent biodegradability. After six months, it can gradually degrade into non-toxic phosphate ions that can be metabolized by the body, avoiding the risk of secondary surgical removal required by traditional stents and further reducing the treatment damage for SCI patients.

In Figure 3, subfigure D reveals that LDH inhibits MBP-induced M1-type inflammatory response through TGFBR2, and this effect can be reversed by the TGFBR2 inhibitor. Subfigure E shows that there are co-positive cells of TGFBR2 and Nestin (a marker of neural stem cells) in the injury area of the LDH-NT3 group, suggesting that TGFBR2 is a key target receptor. Subgraph F summarizes the mechanism: LDH-NT3 activates the signaling pathway with TGFBR2, optimizing the immune microenvironment to promote neural regeneration and circuit reconstruction.

LDHs nanomaterials (with an interlayer spacing of 0.7-0.9 nm) have become key materials for optimizing the inflammatory microenvironment and delivering neurotrophic factors after SCI through the design of „interlayer loading - signal regulation". Their advantages lie in the precise regulation of the repair microenvironment, providing a good organizational basis for the integration of BCI interfaces. The layered structure of LDHs can efficiently load neurotrophic factor NT3 through electrostatic action, with a loading capacity of up to 200 μg/mg. Moreover, it can be slowly released in simulated body fluids (release period >21 days), continuously providing nerve regeneration signals to the injured area. It avoids the problem of poor repair effect caused by the short half-life (<24 hours) of traditional single injection of NT3. The experiments of He et al. showed that after the SCI model was implanted with LDHs-NT3, the differentiation efficiency of endogenous neural stem cells increased by 2.3 times, and the number of synaptic connections of regenerated neurons increased by 2.8 times compared with the control group [3].

Meanwhile, LDHs can bind to Toll-like receptors of microglia through surface hydroxyl groups, activate the TGFBR2 signaling pathway, promote the polarization of microglia towards anti-inflammatory M2 type, increase the M2/M1 ratio from 0.3 to 1.8, and significantly reduce the release of pro-inflammatory factors such as TNF-α and IL-6. Reduce the inhibitory effect of inflammatory responses on nerve regeneration. This „neurotrophic - anti-inflammatory" synergistic effect enabled the combination of LDHs and CNT electrodes to increase the accuracy rate of BCI instruction execution in SCI patients from 58% to 89% and extend the stable working time to 8 months [5].

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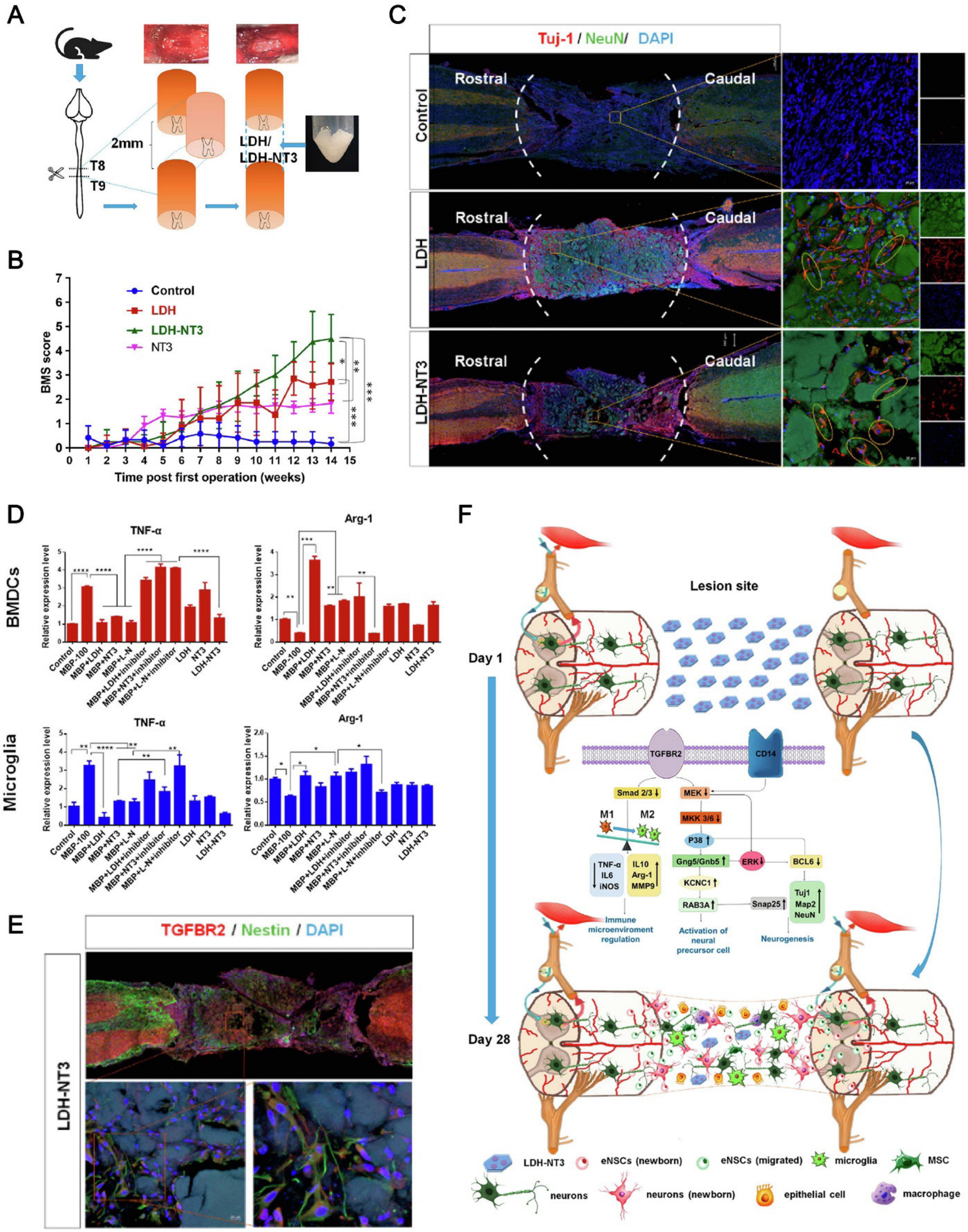

Fig. 3 Immunofluorescence staining graph [12].

In addition, to further enhance the functional integration of BCI after SCI, researchers have also developed BP-LD-

HS composite hydrogels. This material combines the photothermal and conductive functions of BP with the neurotrophic factor loading and anti-inflammatory functions of LDHs, achieving a triple effect of „repair - conductivity - anti-inflammation". Experiments in the SCI model show that this composite hydrogel can further increase the efficiency of nerve regeneration by 15% and reduce the noise of BCI signals by 10% [3], providing a better material solution for functional reconstruction in SCI patients.

4.4 Human-computer Interaction and Applications in Special Fields

In the human-computer interaction (VR/AR, smart wearables) and special field (industrial remote control) applications of BCI, materials need to simultaneously achieve flexible dynamic adaptation and anti-interference. Traditional rigid electrodes, due to mechanical mismatch and weak anti-interference ability, are difficult to meet the requirements. However, the flexible conductive materials in the designated research have become the solution through targeted design.

In VR/AR scenarios, frequent head movements require electrodes to have both high flexibility and low signal latency. The graphene-polydimethylsiloxane (PDMS) composite electrode proposed by Tang et al. can meet this requirement: the PDMS substrate has a tensile rate of over 300% and can be flexibly bent along with the head without cracking [4]. The high electrical conductivity of graphene reduces the signal transmission delay to 40ms, which is superior to that of traditional tungsten electrodes (>100ms). Moreover, after the electrode surface is modified with hydrophobic fluorosilane, the interference of sweat can be reduced, ensuring the stability of the signal for long-term VR/AR interaction.

Industrial remote control (such as nuclear radiation and deep-sea environments) has strict requirements for materials' resistance to electromagnetic interference and corrosion resistance. The carbon nanotube (CNT) - metal (copper, silver) composite electrode studied by Villa et al. can solve this problem: CNT forms a dense conductive network to coat the metal substrate, with an electromagnetic shielding effect of up to 30dB, which can isolate external interference. Meanwhile, the CNT coating can block corrosive media, protect the metal substrate, and the electrode is 40% lighter than traditional metals, making it convenient to integrate into portable BCI devices.

The BCI of smart wearables needs to balance comfort and concealment. The reduced graphene oxide (rGO) - textile fiber composite electrode developed by He et al. has more advantages: rGO is coated on the surface of textile fibers and can be made into daily styles such as hats and headbands, which are comfortable and concealed to wear [3]. The high sensitivity of rGO ensures that the signal-to-noise ratio of the signal exceeds 10:1 in the motion state, and the recognition accuracy of the „start and stop" command reaches 92%, which is higher than the 75% of traditional rigid electrodes, providing support for the popularization of BCI in smart wearables.

5. From Material Defects to Multiple Obstacles in Clinical Application

The development of BCI technology still faces multiple core challenges and requires breakthroughs through multi-disciplinary collaboration. Although nanomaterials have alleviated the short-term bottleneck of traditional materials, the problem of long-term implantation is prominent: Unmodified carbon nanotubes are prone to agglomeration in the brain, resulting in a significantly higher decrease in charge transport efficiency than surface-modified carbon nanotubes [11]; Conductive hydrogels are prone to swelling and peeling problems in the moist environment of the brain, which affects the stability of electrode signals. The ions produced by the degradation of black phosphorus may interfere with the ionic balance in the brain. The long-term effects of the accumulation of metal nanoparticles in the brain still need to be further verified [3].

Although AI-assisted systems can enhance the efficiency of BCI, they have the problem of poor scene generalization ability. In free tasks without fixed targets, the intent recognition effect is far inferior to that in fixed tasks. Moreover, the differences in individual neural signals can cause fluctuations in AI performance. Some paralyzed patients have reported that the devices are overly dominated by AI. In addition, the „black box" nature of AI decision-making is difficult to explain, which has an impact on clinical approval [5].

At the clinical transformation level, the manufacturing cost of nanoelectrodes is relatively high. The cost of graphene electrodes is significantly higher than that of traditional tungsten electrodes, and the conductivity of 3D printing conductive ink is insufficient. Meanwhile, BCI clinical trials lack a unified definition standard of „long-term stability", and the absence of data from large-scale animal experiments also increases the risk of technology translation [1]. Furthermore, neural signals are susceptible to interference from physiological states. When patients with spinal cord injury experience phantom pain, the human body is in a state of fatigue or emotional fluctuation, it will all have an impact on neural signals. Currently, there is no effective real-time compensation method [5].

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In response to the above challenges, more innovations and collaborations from multiple disciplines are still needed in the future. For instance, the electrical conductivity of temperature-responsive graphene can be enhanced after near-infrared light exposure, ph-responsive layered dihydroxides (LDH) can accelerate the release of anti-inflammatory drugs in inflammatory areas, and self-healing hydrogels containing dynamic covalent bonds can maintain good signal stability after implantation. It will also combine degradable black phosphorus nanosheets with long-acting carbon nanotube networks to avoid secondary surgery [3].

In the field of AI, multimodal signals such as electroencephalogram (EEG) and eye movement will be integrated for decoding to enhance the intent recognition effect in free tasks. Incorporate a human-machine feedback mechanism to allow users to intervene in the AI control process; Build large-scale BCI basic models to shorten individual calibration time, adopt technologies to protect user privacy, and develop new types of AI to clarify decision-making logic [5].

In terms of clinical transformation, the formula of 3D printing conductive ink will be optimized to reduce costs while enhancing conductivity. Explore batch production technologies such as roll-to-roll to reduce the manufacturing cost of graphene electrodes; The multidisciplinary team will jointly formulate a unified standard for BCI technology and promote the conduct of multicenter clinical trials and database construction [1].

In terms of anti-interference technology, a CNT-metal composite film will be coated on the electrode surface to enhance the electromagnetic shielding performance, and a differential array structure will be designed to counteract environmental noise. Meanwhile, AI is utilized to monitor the user‘s physiological state in real time and dynamically adjust the decoding parameters to ensure the stability of neural signal transmission [11].

6. Conclusion

The main driving force for BCI technology to break through the limitations of traditional rigid hardware and move towards clinical and practical scenarios is the in-depth collaboration among materials science, computer science and medicine. This collaboration not only breaks through the three major bottlenecks of traditional BCI - „mechanical mismatch, poor biocompatibility, and low signal efficiency", but also builds a complete technical chain of „hardware support - algorithm optimization - clinical verification", providing a feasible path for the treatment of neurological diseases and the innovation of human-computer interaction.

Materials science is the hardware foundation of BCI: Graphene and carbon nanotubes (CNT) solve the problems of „high signal noise and mechanical damage" of traditional electrodes due to their low impedance and excellent biocompatibility, and improve the cursor control accuracy of paralyzed patients; Black phosphorus (BP) composite hydrogel and layered dihydroxide (LDHs) have dual functions of „nerve repair - signal transduction", achieving long-term integration of nerve regeneration and BCI interface after spinal cord injury (SCI), extending the stable working time from 3 months to 8 months [3]; The composite coating of metal nanoparticles and conductive polymers is corrosion-resistant and flexible, meeting the long-term therapeutic requirements of deep brain stimulation (DBS) for Parkinson‘s disease (PD) , laying the foundation for BCI to shift from „short-term signal acquisition" to „long-term functional integration".

The collaboration between computer science and medicine further transforms material properties into application value: AI decoders (such as CNN-KF) accurately identify motion intentions based on low-noise signals, and computer vision (such as Grounding DINO) combined with AI assistance significantly improves the success rate of grasping and placing by robotic arms. The activation patterns of the motor cortex hemispheres revealed by medicine (such as contralateral activation) guide the optimization of electrode layout, significantly improving the accuracy of intention recognition, and promoting BCI into diverse scenarios such as paralysis rehabilitation and neurological disease treatment.

Although BCI still needs to overcome challenges such as long-term material stability, unclear AI judgment, and clinical-scale cost, breakthrough paths have been indicated in directions such as intelligent adaptive materials, multimodal BCI basic models, and 3D printing personalized manufacturing. Ultimately, BCI not only enables "brain-machine" signal intercommunication, but also helps to restore motor function and communication ability for patients with paralysis, PD and SCI. With the continuous and deep integration of the three disciplines, BCI is bound to move from "technological breakthroughs" to "clinical popularization", becoming a transformative tool for improving human health and quality of life.

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