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Application of Non-Invasive Brain-Computer Interfaces in Spinal Cord Injury Rehabilitation

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Abstract: *Spinal cord injury (SCI) is a highly disabling central nervous system injury. Traditional treatments such as early surgical decompression and pharmacological interventions have limited efficacy. Most patients still suffer from sensory and motor dysfunction below the injury level, severely impacting their quality of life. In recent years, brain-computer interface (BCI) technology has advanced rapidly, offering new possibilities for SCI rehabilitation. BCI works by acquiring and decoding brain signals and converting them into control commands to drive external devices or directly perform neuromodulation, thereby enabling motor function restoration, sensory feedback, and psychological regulation. This article systematically reviews the classification of BCIs, focusing on the main types of non-invasive BCIs. It elaborates on their application progress and evidence in upper/lower limb motor function rehabilitation, sensory recovery, psychological state improvement, and pain management for SCI patients. By integrating recent clinical studies, systematic reviews, and meta-analyses, the article points out that non-invasive BCIs show significant potential in SCI rehabilitation but still face challenges such as signal quality, individual variability, long-term safety, and clinical dissemination. Finally, this article prospects future research directions, including algorithm optimization, multimodal fusion, personalized rehabilitation protocols, and the expansion of home-based application scenarios.*

Keywords: *Brain-Computer Interface; Spinal Cord Injury; Rehabilitation; Non-Invasive*

1. Introduction

Spinal cord injury (SCI) refers to damage to the structure and function of the spinal cord caused by trauma or disease. Epidemiological data indicate that the global number of SCI patients exceeds 20 million, with approximately 250,000–500,000 new cases reported annually[1,2]. The primary clinical manifestations of SCI are abnormal motor and sensory functions below the injury level, often accompanied by a series of secondary complications, including neuropathic pain, autonomic dysreflexia, bladder and bowel dysfunction, and psychological issues such as anxiety and depression[3,4]. These multiple impairments not only severely compromise patients' physical and mental health and significantly reduce their quality of life but also impose a sustained and substantial economic burden on families and the social healthcare system [5,6].

Current clinical treatments for SCI mainly include surgical decompression in the acute phase, medication, hyperbaric oxygen, hypothermia, pulsed electrical stimulation, and rehabilitative therapy [7,8]. However, these methods have limited effects in promoting nerve regeneration and rebuilding neural pathways. Most patients remain dependent on wheelchairs for life with severely compromised self-care abilities [9]. Therefore, developing rehabilitation technologies that can promote neuroplasticity and reconstruct sensorimotor pathways has become a research focus.

Brain-computer interface (BCI) is a cutting-edge technology at the intersection of neuroscience, bioengineering, and rehabilitation medicine, aiming to establish a direct information exchange pathway between the brain and external devices [10,11]. This technology acquires and decodes brain activity signals, converts them into control commands, and thereby drives external assistive devices or neuromodulation systems to promote limb movement and enhance neuroplasticity, offering a new approach for reconstructing motor and sensory pathways after SCI [12]. In recent years, with improvements in signal acquisition technology, optimization of decoding algorithms, and refinement of feedback devices, research on BCI in SCI rehabilitation has deepened, demonstrating broad clinical application potential[13]. This article aims to systematically review the classification, working principles, current applications, and future directions of BCI technology, particularly non-invasive BCI, in SCI rehabilitation, to provide references for clinical practice and research.

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2. Classification and Working Principles of Brain-Computer Interfaces

2.1 Basic Components of a BCI System

A complete brain-computer interface system typically comprises three core stages: signal acquisition, processing and decoding, and output feedback[14]. First, the system acquires raw signals of neural electrical activity or metabolic changes in the brain via electrodes or sensors. Subsequently, signals are filtered, denoised, have features extracted and classified to identify the user's movement intention or cognitive state. Finally, the decoded commands are translated into control signals to drive external devices such as exoskeletons, electrical stimulators, or wheelchairs, combined with visual, tactile, or auditory feedback to form a closed-loop training system [15].

2.2 Classification by Signal Acquisition Method

Based on the proximity of the signal acquisition device to the brain, BCIs can be classified into invasive, semi-invasive, and non-invasive types[16], as shown in Table 1.

Table 1 Summary of BCI Technology Categories and Their Key Characteristics

Type	Representative Technologies	Signal Source	Advantages	Disadvantages
Invasive	Electrocorticography (ECoG), Intracortical Microelectrode Arrays (ICMA)	Direct recording from cortical surface or neuronal firing	High signal-to-noise ratio, high spatial resolution, stable signals	Requires surgical implantation, risk of infection, poor long-term stability, ethical restrictions
Semi-invasive	Epidural/Subdural Electrodes	Recording near the cortical surface	Less traumatic than invasive, relatively good signal quality	Still requires surgery, long-term biocompatibility issues
Non-invasive	Electroencephalography (EEG), Functional Near-Infrared Spectroscopy (fNIRS), Magnetoencephalography (MEG), Functional Magnetic Resonance Imaging (fMRI), Functional Transcranial Doppler Sonography (fTCD)	Indirect recording from scalp or outside the skull	Safe and non-invasive, easy to wear, suitable for long-term and home use	Signals susceptible to noise interference, lower spatial resolution, significant individual variability

2.3 Main Types of Non-Invasive BCIs

Non-invasive brain-computer interfaces primarily include electroencephalography (EEG), functional near-infrared spectroscopy (fNIRS), magnetoencephalography (MEG), functional magnetic resonance imaging (fMRI), and functional transcranial Doppler sonography (fTCD)[17].

Among these, EEG records synaptic postsynaptic potential changes of cortical neurons via scalp electrodes, offering millisecond-level high temporal resolution. The equipment is portable and low-cost, making it suitable for real-time feedback training. However, EEG signals are easily contaminated by artifacts such as electromyography (EMG) and eye movements, and spatial resolution is limited. fNIRS uses near-infrared light to detect changes in hemoglobin concentration in the cerebral cortex, offering strong resistance to interference and suitability for monitoring in motor environments. However, its temporal resolution is lower than EEG, and its spatial scope is limited to cortical regions [18]. MEG records magnetic field signals generated by neuronal currents, offering excellent temporal and spatial resolution and being less susceptible to interference from scalp tissue. However, the equipment is expensive and bulky, primarily used in research rather than daily rehabilitation. fMRI reflects brain activity based on blood-oxygen-level-dependent (BOLD) signals, offering extremely high spatial resolution but low temporal resolution. The equipment is costly and not suitable for real-time interaction.

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fTCD measures blood flow velocity in major cerebral arteries using ultrasound Doppler, offering good portability but very low spatial resolution, reflecting only hemispheric-level perfusion changes. Its clinical application is currently relatively limited.

Currently, EEG, due to its high safety, low cost, portability, ease of use, and adaptability to various experimental paradigms, has become the most widely used technology in non-invasive BCI applications[19,20].

3. Application of Non-Invasive BCI in SCI Rehabilitation

3.1 Upper Limb Motor Function Rehabilitation

The loss of upper limb function, particularly fine motor skills of the hand, severely restricts the ability of individuals with spinal cord injury to perform activities of daily living. Currently, non-invasive brain-computer interfaces are primarily combined with exoskeleton robots or functional electrical stimulation to promote the recovery of upper limb motor function. Among these approaches, EEG-based BCIs decode the patient's movement intentions to drive exoskeleton robots in assisting with actions such as extension and grasping[21-23]. It is worth noting that, beyond the aforementioned mechanically assisted pathways, the neuroregulatory approach combining BCI with functional electrical stimulation demonstrates unique potential in inducing neuroplasticity and facilitating functional reconstruction. Research by Jovanovic et al. [24] demonstrated that BCI-FES intervention is safe, feasible, and can improve functional independence and upper limb motor function in subacute cervical SCI patients. Furthermore, Cantillo-Negrete et al.[25] conducted 12 sessions of BCI-FES intervention in chronic cervical SCI patients, resulting in significant improvements in upper limb motor function and life independence. The study by Kumari et al.[26] innovatively used BCI-FES as a "motor preparation" tool, aiming to activate the sensorimotor cortex before physical therapy to maximize the benefits of subsequent rehabilitation. The underlying mechanism is that BCI-FES forms a closed-loop training of "motor intention → electrically stimulated actual movement → sensory feedback." By strengthening the connection between the motor cortex and residual spinal pathways, it effectively promotes neuroplasticity and motor function remodeling.

3.2 Lower Limb Motor Function Rehabilitation

The core goal of lower limb motor function rehabilitation is to restore patients' standing and walking abilities. Non-invasive brain-computer interfaces (BCIs) are often combined with lower limb exoskeleton robots, virtual reality (VR), and functional electrical stimulation (FES) to achieve this goal. Clinical studies have shown that electroencephalography (EEG)-based motor imagery BCI can decode patients' cortical movement intentions to drive lower limb exoskeletons for active gait training, enhancing neuroplasticity and promoting motor recovery. Cui et al.[27] conducted a rehabilitation training study using BCI-controlled lower limb robots. After 3-7 weeks of short-term training, the lower limb key muscle strength scores of 7 SCI patients improved by an average of 2.6 points, and activities of daily living scores improved by an average of 16.9 points. A randomized controlled trial by Hu et al. [28] further confirmed that 4 weeks of BCI-controlled exoskeleton training significantly improved lower limb motor function and walking ability in SCI patients. Portuguese researchers [29] provided a multi-sensory integrated VR-BCI rehabilitation program for a patient with complete SCI. After 14 months of trials, the patient not only experienced reduced pain but also exhibited induced rhythmic lower limb movements. Research by King et al.[30] first demonstrated that paraplegic patients using a non-invasive BCI-FES system could progress from virtual environment training to overground suspension testing and finally achieve conscious ground walking. Building on this, Selfslagh et al. [31] further proved that BCI-FES technology can not only enable ground walking but also achieve partial neurological functional recovery. The core mechanism of non-invasive BCI-driven lower limb functional rehabilitation systems lies in constructing a "cortex-device-body" closed-loop neuromodulation pathway: the system decodes motor imagery (MI)-related cortical activity via EEG, translates movement intentions into control commands to drive the lower limb exoskeleton to perform gait movements, while combining FES to electrophysiologically activate target muscles, forming a closed loop of "central command - peripheral execution - sensory feedback."

3.3 Sensory Function Recovery

After spinal cord injury, sensory functions below the injury level, such as touch, proprioception, and

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visceral sensation, are often severely impaired, leading to disruption of sensorimotor integration circuits and hindering functional recovery. Non-invasive brain-computer interfaces provide an innovative approach to address this issue by employing sensory substitution or closed-loop sensory feedback strategies to partially reconstruct the impaired sensory input. Clinical studies indicate that such BCI-based sensory interventions are effective. Shokur et al.[32] conducted a 28-month study involving 7 chronic complete SCI patients undergoing BCI-controlled exoskeleton gait training supplemented with real-time visual-tactile feedback. After training, all patients showed improvement in trunk and lower limb proprioception. Additionally, visceral sensory functions such as urinary/fecal control and sexual function significantly improved. A randomized controlled trial by Nicolelis et al. [33] demonstrated that non-invasive BCI combined with tactile feedback and motor training significantly promoted sensory function recovery in chronic complete SCI patients, evidenced by improvements in touch, pain sensation, proprioception, and vibration sense. The possible mechanisms for non-invasive BCI promoting sensory function recovery include promoting neuroplasticity, providing closed-loop sensory feedback, activating residual sensory pathways, and strengthening sensory input and integration [34]. These mechanisms work together to drive the functional reconstruction and recovery of sensory pathways.

3.4 Pain Management and Psychological State Improvement

SCI patients often suffer from secondary central neuropathic pain, anxiety, and depression due to neurological dysfunction. These complications not only directly reduce patients' quality of life but also severely undermine their motivation and participation in rehabilitation training. Non-invasive brain-computer interfaces offer a new intervention pathway. The core mechanism involves using closed-loop neurofeedback training to actively regulate patients' brain activity patterns associated with pain and emotion, thereby alleviating symptoms and improving psychological state [35]. In this process, the improvement of psychological state and neurological recovery mutually reinforce each other, forming a virtuous cycle that promotes overall rehabilitation.

Clinical research provides empirical support. In terms of pain management, the home-based self-managed BCI system developed by Al-Taleb et al. [36] led to significant pain reduction in 12 out of 15 patients. It offers a safe, non-invasive, self-controlled alternative or complementary treatment option for patients with chronic central neuropathic pain who respond poorly to medication or are troubled by side effects. Pais-Vieira et al. [29] further combined EEG with virtual reality for immersive motor imagery training and observed a continuous decrease in pain levels over time. A case report by Yoshida et al. [37] suggested that sensorimotor rhythm-based BCI training might alleviate neuropathic pain by enhancing event-related desynchronization in the sensorimotor cortex to modulate cortical excitability. Research by Hasan et al. [38] based on EEG further elucidated that SCI and neuropathic pain have distinct impacts on brain functional connectivity. Specifically, abnormal frontal-parietal network connectivity in the theta band and increased global efficiency are specific markers for pain, whereas reduced sensorimotor network connectivity in the beta/gamma bands primarily reflects the injury effect. These findings not only deepen the understanding of the neural mechanisms of pain but also lay the foundation for developing brain network-based precise diagnostics. Regarding psychological improvement, research by Sitaram et al. [39] showed that non-invasive EEG-BCI combined with real-time neurofeedback can effectively regulate neural activity in the prefrontal cortex and limbic system, thereby alleviating symptoms of depression and anxiety. A review by Dobbins et al. [40] indicated that EEG-based neurofeedback can reduce depressive symptoms in patients.

4. Current Limitations and Future Prospects

Although non-invasive BCI shows broad prospects in SCI rehabilitation, its clinical application is still exploratory, facing the following main challenges:

4.1 Signal Quality and Decoding Accuracy

EEG signals are susceptible to artifacts such as EMG and eye movements, exhibit significant individual variability, and traditional decoding methods have limited performance when dealing with complex, non-linear EEG features. To improve signal quality and user experience, electrode technology is evolving from traditional wet electrodes towards dry and semi-dry electrodes, enhancing wearability and comfort while ensuring signal stability[41]. In signal analysis, deep learning technology has recently shown significant advantages. Its models can automatically extract high-level spatiotemporal features directly from raw or multi-channel EEG signals, avoiding complex manual feature engineering, thereby improving classification accuracy and system robustness [42]. Furthermore, transfer learning, an important branch of deep learning, can transfer knowledge from existing models to new users or tasks, effectively reducing calibration workload, which is particularly suitable for rehabilitation scenarios involving SCI patients [43]. In terms of multimodal fusion, EEG-fNIRS hybrid systems combine the high temporal resolution of EEG with the good spatial specificity of fNIRS, further enhancing the decoding performance of brain activity [44]. Future research should focus on biocompatible nanomaterial electrodes, adaptive deep learning algorithms, and multimodal information fusion to further improve the decoding performance and practicality of BCI systems in complex rehabilitation environments [45,46].

4.2 Limited Scope of Functional Recovery

Non-invasive BCI primarily assists movement by controlling external devices like exoskeleton robots or wheelchairs, or promotes neuroplasticity combined with electrical stimulation, but it cannot directly repair damaged spinal cord neural pathways. For complete paralysis caused by severe SCI, the degree of functional recovery remains relatively limited.

4.3 User Fatigue and Attention Demands

Patients using non-invasive BCI need to maintain focused attention for extended periods, which can easily lead to fatigue, subsequently affecting signal quality and control stability. Long-term use may burden the patient's psychological and physiological state, reducing treatment compliance.

4.4 Level of Clinical Evidence

Current clinical research on BCI in SCI rehabilitation predominantly consists of small-sample pilot studies or self-controlled before-and-after designs, with a lack of high-quality randomized controlled trials (RCTs). In the future, it is necessary to conduct prospective, multi-center, large-sample RCTs with long-term follow-up, while promoting the unification and standardization of assessment metrics [47].

4.5 Multidisciplinary Collaboration and Ethical Considerations

The development and application of an effective BCI-based rehabilitation system inherently involve multiple disciplines, including neuroscience, rehabilitation medicine, engineering disciplines, and psychology. Fostering close and structured collaboration among experts from these fields is crucial for translating technological innovations into clinically viable and user-centered solutions. Concurrently, the implementation of BCI technology raises several significant ethical issues that must be proactively addressed. Key concerns include ensuring patient data privacy and security, safeguarding the physical and mental well-being of users throughout the intervention, obtaining comprehensive and ongoing informed consent, and thoughtfully managing the potential for long-term technology dependency [48].

5. Conclusion

Non-invasive brain-computer interface, as a safe and feasible novel rehabilitation technology, demonstrates significant potential in motor function restoration, sensory recovery, psychological regulation, and pain management for spinal cord injury patients. Particularly, EEG-based BCI systems have seen preliminary application in clinical and home settings due to their non-invasive nature, portability, and real-time feedback. Current research confirms that BCI can help SCI patients recover partial function and improve their quality of life through various mechanisms, including promoting neuroplasticity, reconstructing sensorimotor closed loops, and modulating brain network activity.

However, this field still faces multiple challenges, including signal decoding accuracy, individual variability, validation of long-term efficacy, and clinical translation. Future research should focus on algorithm optimization, multimodal fusion, design of personalized rehabilitation protocols, and large-scale clinical validation. With the continuous maturation of technology and deepening interdisciplinary collaboration, non-invasive BCI is expected to become an important component of the comprehensive SCI rehabilitation system, providing innovative momentum for achieving the multi-level rehabilitation goals of "neural repair - functional compensation - social integration."

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