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# A Review of Brain-Computer Interfaces in Neurorehabilitation and Nursing Care for Patients with Paraplegia

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## Abstract

Paraplegia, most commonly caused by spinal cord injury (SCI), results in motor, sensory, and autonomic dysfunction below the level of injury. Traditional rehabilitation primarily relies on passive training, which has limited effects on central neural remodeling. As a cutting-edge neuromodulation technology, brain-computer interfaces (BCIs) can bypass the damaged spinal cord and directly translate brain signals into commands for external devices, offering a new pathway for functional reconstruction. Focusing on the neurorehabilitation and nursing perspectives of patients with paraplegia, this review systematically summarizes the definition, principles, classification, and clinical value of non-invasive EEG-BCI and invasive implantable BCI. It outlines stratified rehabilitation strategies for patients with different injury severities and constructs a comprehensive nursing model that includes pre-rehabilitation assessment, intra-training monitoring, complication prevention, psychological intervention, and home-based continuing care. Current evidence indicates that BCIs can effectively activate neuroplasticity, relieve spasticity, and improve motor intention and activities of daily living. Professional nursing is critical for ensuring safety, adherence, and long-term outcomes. This review also discusses current research limitations and proposes future directions to inform clinical practice and academic research.

## Keywords

brain-computer interface, paraplegia, spinal cord injury, neurorehabilitation, rehabilitation nursing

## 1. Introduction

Paraplegia resulting from spinal cord injury is characterized by high disability rates, numerous complications, and a significant psychological burden. Patients often experience loss of motor function, muscle spasticity, bowel and bladder dysfunction, anxiety, and depression, all of which severely impact their quality of life. Traditional rehabilitation primarily involves passive training and complication prevention, which has limited effectiveness in rebuilding neural pathways between the brain and paralyzed limbs [1]. With advances in neural engineering and rehabilitation medicine, brain-computer interfaces (BCIs) have emerged as a promising approach that bypasses the spinal cord's conduction limitations by directly capturing and decoding brain signals to control external devices [1]. This offers new possibilities for motor compensation and functional reconstruction in patients with severe neurological dysfunction.

Most current BCI research focuses on technical principles, signal algorithms, and clinical efficacy, with few systematic reviews from a nursing perspective [2]. Nurses, as direct implementers and safety managers of BCI rehabilitation, play an irreplaceable role in patient assessment, education and guidance, training coordination, risk monitoring, psychological support, and home-based instruction [3]. Therefore, reviewing the application of BCIs in paraplegic neurorehabilitation and associated nursing care holds significant theoretical and clinical importance.

This review clarifies BCI classification, mechanisms, and rehabilitation value, summarizes stratified rehabilitation strategies for paraplegic patients, constructs a comprehensive BCI nursing model, and analyzes research limitations and future directions. It first elaborates BCI definition, classification, and neuroplasticity mechanisms to lay a theoretical foundation; second, summarizes stratified rehabilitation strategies based on clinical evidence for patients with different injury degrees; third, builds a nursing model covering assessment, monitoring, complication prevention, psychological intervention, and continuous care; finally, discusses limitations in signal quality, nursing standardization, and evidence level, and proposes future directions. This review provides a reference for BCI clinical translation, rehabilitation nursing standardization, and precise rehabilitation system construction.

## 2. Theoretical Foundations

### 2.1 Definition and Classification of BCIs

A brain-computer interface is a neuromodulation technology that establishes direct communication between the brain and an external device, based on operant conditioning and neuroplasticity [1]. BCIs are primarily divided into two categories. Non-invasive BCIs use scalp electroencephalography (EEG) as the signal source, require no surgery, are safe, convenient, and have good adherence, making them suitable for both clinical and home-based rehabilitation; however, their signals are susceptible to interference and have low spatial resolution. Invasive BCIs involve surgically implanting electrodes into the cerebral cortex, providing highly stable and accurate signals but carrying risks of surgical trauma, bleeding, infection, and electrode displacement.

From the perspective of patient suitability, individuals with incomplete paraplegia or poor physical condition who cannot tolerate surgery are better suited for non-invasive BCIs for home rehabilitation and simple assistive device control. Those with high-level complete paraplegia, poor non-invasive signal quality, and good surgical tolerance may benefit from invasive BCIs for precise control of prostheses and wheelchairs. Nursing care for invasive BCI includes thorough preoperative assessment, psychological support, scalp preparation, postoperative vital sign monitoring, wound inspection, prevention of electrode displacement due to impact, infection and thrombosis prevention, and subsequent rehabilitation training with caregiver education for home monitoring [3].

### 2.2 Neuroplasticity Mechanisms

Neuroplasticity refers to the structural and functional remodeling of the nervous system after injury. It is the core biological basis for functional recovery after SCI and the theoretical premise for BCI efficacy [4]. During training, operant conditioning is applied: the patient actively modulates brain signals through mental intention; successful device recognition provides immediate reward feedback. Through repeated reinforcement training, a stable brain-device conditioning reflex is gradually established.

BCI neurorehabilitation operates through two phases: short-term compensation and long-term plasticity. Short-term compensation involves capturing and decoding motor intentions, using motor imagery to control rehabilitation equipment, and providing audiovisual feedback to temporarily replace damaged neural pathways, thereby compensating for motor deficits. Long-term plasticity is achieved through repeated closed-loop training that enhances cortical excitability and remodels sensorimotor circuits. This closed-loop system compensates for disrupted neural transmission and simultaneously promotes activity-dependent plasticity, thereby supporting functional reorganization within the CNS [4]. This process inhibits pathological pyramidal tract discharges, reduces excessive activation of spinal anterior horn neurons, and rebalances neuromuscular control between agonists and antagonists, thereby reducing muscle hypertonia and spasticity, and achieving sustained functional improvement through cortical reorganization.

### 2.3 Nursing Theory Framework

Clinical nursing for BCI rehabilitation is supported by four theoretical pillars: holistic nursing, rehabilitation nursing, stratified management, and continuing care [3]. Holistic nursing addresses both physical and psychological assessments, focusing on the relationship between patient anxiety, overall status, and EEG signal stability. Rehabilitation nursing follows neurological rehabilitation standards, managing positioning, spasticity observation, and adverse reactions during BCI training. Stratified management differentiates BCI training duration, protocol parameters, and bedside monitoring frequency according to ASIA impairment scale grades. Continuing care bridges in-hospital training with home rehabilitation, including remote BCI follow-up, home device usage guidance, and long-term functional monitoring [5]. BCI nursing is patient-centered, encompassing assessment, intervention, monitoring, and follow-up, addressing individual variability, training tolerance, psychological stress, long-term adherence, and safety risks to ensure safe, effective, and sustainable rehabilitation.

## 3. Literature Review

### 3.1 Clinical Efficacy Evidence

Early BCI research focused on signal decoding and animal experiments, demonstrating the feasibility of brain-controlled devices. Over the past decade, clinical studies have rapidly increased, focusing on conditions such as SCI, stroke, and amyotrophic lateral sclerosis. A large body of evidence confirms that non-invasive EEG-BCI can improve motor control, spasticity, and activities of daily living in patients with incomplete paraplegia. Combining BCI with functional electrical stimulation, rehabilitation exoskeletons, or virtual reality can further enhance rehabilitation outcomes [6].

Clinical studies of invasive BCI have shown that implanted cortical electrodes enable patients with complete paraplegia to control robotic hands, wheelchairs, and perform fine motor tasks, demonstrating that BCI can effectively bypass the injured spinal cord to achieve functional output [1]. However, due to surgical risks, device costs, and ethical constraints, invasive BCI is not yet widely applicable clinically. From a nursing perspective, standardized perioperative nursing can optimize wound management, reduce postoperative infections, and mitigate some surgical risks, though high costs and ethical concerns require ongoing material innovation and technical advancement.

### 3.2 Current Status and Challenges in Rehabilitation Nursing

Literature on BCI rehabilitation nursing remains limited but is growing annually. Existing studies confirm that comprehensive, standardized nursing throughout the care continuum can support rehabilitation outcomes in several ways: (1) Preoperative phase: comprehensive assessment to screen suitable candidates and exclude contraindications, combined with health education and individualized psychological intervention to reduce anxiety and improve treatment adherence. (2) In-hospital training: real-time EEG signal monitoring, proper positioning, and skin protection to reduce electrode pressure and damage, ensuring signal acquisition and training quality. (3) Post-implant care for invasive BCI: standardized wound dressing changes (every 2-3 days routinely, or immediately if exudate or bleeding is present), continuous monitoring for redness, swelling, exudate, local warmth, and systemic fever, with anti-infective measures to prevent implantation site complications. (4) Home follow-up: systematic home device usage guidance and regular remote follow-up to consolidate long-term rehabilitation outcomes.

### 3.3 Influencing Factors and Evaluation Systems

Multiple studies indicate that injury severity, disease duration, and rehabilitation adherence are important factors influencing BCI outcomes. Patients with incomplete injury, shorter disease duration, and good adherence tend to benefit more significantly [7]. In patients with recent injury, central neuroplasticity has not yet declined, aberrant neural circuits have not fully formed, and residual neural pathways can be effectively remodeled through closed-loop BCI training. In contrast, those with long disease duration often develop maladaptive neural reorganization, muscle spasticity, joint contractures, and other secondary changes, with markedly reduced neuroplasticity, limiting BCI intervention effects. Subgroup analyses from recent meta-analyses confirm that patients in the subacute stage of SCI show significantly stronger improvements in motor function, sensory function, and activities of daily living following non-invasive BCI intervention compared to those in the chronic stage [7]. Although stratified intervention based on patient injury characteristics is widely recommended, no universally accepted, standardized BCI-based stratified rehabilitation and nursing protocol currently exists.

In terms of efficacy evaluation, most existing BCI rehabilitation studies use traditional outcome measures such as MMT, MAS, Fugl-Meyer, Barthel Index, MEP, and conventional EEG. These tools assess limb muscle strength, spasticity, and activities of daily living but cannot capture BCI-specific parameters such as EEG classification accuracy, ERD/ERS modulation amplitude, or command response latency, indicating a lack of dedicated evaluation systems [8]. Regarding study design, most are small-sample, single-center, short-term follow-up studies, with sample sizes of 10-30 participants, intervention and follow-up periods of weeks to three months, and few with follow-up exceeding six months. Additionally, heterogeneous intervention parameters across studies (training duration, algorithms, feedback devices) limit cross-study comparability. A systematic review of invasive BCI for SCI further highlights that clinical outcome measures remain highly heterogeneous across studies, reflecting the absence of standardized assessment protocols.

Meanwhile, wearable home-based BCIs are emerging as a new trend in rehabilitation. Nurses can be responsible for pre-use screening, EEG headset fitting and calibration, daily training supervision, real-time documentation of adverse reactions, and remote alert systems for anomalies. Overall, preliminary evidence supports the efficacy and safety of BCIs for paraplegic rehabilitation. However, high-quality clinical studies focusing on nursing implementation, stratified individualized care, and long-term outcome tracking remain scarce, and no standardized operational guidelines exist.

## 4. Discussion and Analysis

### 4.1 Re-evaluating the Rehabilitation Value of BCIs

Existing evidence generally supports that BCIs can significantly enhance the rehabilitation potential of patients with paraplegia by activating neuroplasticity, reinforcing motor intention, relieving spasticity, and improving central motor control. However, outcomes are heterogeneous. Non-invasive BCIs are safe, convenient, and suitable for widespread use; invasive BCIs offer higher precision and are appropriate for severe functional reconstruction. The two approaches are complementary rather than mutually exclusive.

Observed differences in outcomes across studies can be attributed to variations in injury level and severity, disease duration, training intensity, parameter settings, and quality of nursing care. Nursing quality specifically refers to training supervision frequency, complication prevention measures, rehabilitation adherence management, and equipment support. More standardized nursing, higher adherence, and more consistent training lead to more stable rehabilitation outcomes. For example, in a patient with C5 incomplete injury (AIS C, 3-month disease duration), the high-quality nursing group (PT/OT 2 hours daily each, standing frame + FES, therapist supervision twice daily, repositioning every 2 hours + sterile intermittent catheterization, family participation in training logs) showed a 26-point improvement on FIM at 3 months. In contrast, the low-quality nursing group (30 minutes of daily training, no standing training, aide-only supervision, irregular repositioning, recurrent infections, no psychological support) improved only 4 points, developing pressure ulcers and urinary tract infections.

### 4.2 The Critical Role and Gaps in Nursing

From a nursing perspective, a BCI is not merely a technical tool but an integrated care system throughout the rehabilitation continuum [3]. The nursing role can be further specified into three levels. The first level is basic safety, which includes pre-rehabilitation assessment of indications and contraindications (e.g., intracranial pressure, skin integrity, cognitive status), prevention of electrode-related skin injuries, seizures, and other acute risks. The second level is efficacy promotion, achieved by enhancing adherence through education and psychological support; performing real-time signal quality monitoring during training (e.g., guiding relaxation to reduce myogenic artifacts); dynamically adjusting electrode contact pressure and position; and documenting non-technical behavioral variables such as fatigue and attention fluctuations [3]. Recent nursing case studies have demonstrated that individualized attention maintenance strategies, including dynamic monitoring and documentation of attention fluctuations, followed by targeted interventions, can significantly improve BCI training outcomes, with reported improvements in active attention exceeding 70% following such nursing interventions [9]. The third level is long-term continuity, which involves prevention of complications (pressure ulcers, joint contractures, autonomic dysreflexia), guidance for home BCI use, and regular follow-up.

However, two major gaps currently exist in nursing practice. First, a lack of standardized operating procedures (SOPs), with significant inter-institutional variability in electrode placement, skin preparation methods, and signal quality criteria, undermines result reproducibility. Recent expert consensus documents have begun addressing this gap by specifying that electrode-scalp contact impedance should be stably maintained at ≤10 kΩ (preferably ≤5 kΩ), and that standardized scalp preparation—including gentle abrasion of electrode placement sites to remove oils and dead skin—must be performed prior to each session. Second, nursing records do not yet include signal quality parameters, instead relying on subjective descriptions such as "patient cooperated well," making it impossible to trace whether training failures stem from the device, patient status, or nursing actions [3]. Notably, few studies explore nurses' specific roles in daily BCI practice, including device management, patient communication, and care plan development, reflecting the marginalization of the nursing perspective in BCI technology development and clinical integration [3]. In summary, nursing is a critical determinant of whether BCI can be successfully translated into clinical practice, and there is an urgent need to establish BCI-specific nursing SOPs and upgrade nursing documentation templates.

### 4.3 Research Limitations and Future Directions

Current research has several clear limitations: (1) insufficient signal accuracy and stability of non-invasive BCI ; (2) notable trauma, cost, and ethical concerns associated with invasive BCI [1, 8]; (3) predominance of small-sample, short-term follow-up studies with low-level evidence [10]; (4) lack of standardized rehabilitation and nursing protocols, specifically regarding unified nursing operational indicators, unclear nurse-to-patient ratios, and absent training requirements for nurses; and (5) insufficient application in home and community settings, with no established remote nursing models or nursing risk assessment systems.

Future trends can be summarized as follows: deeper integration of BCI with artificial intelligence, virtual reality, and rehabilitation robots to form intelligent rehabilitation platforms, thereby requiring that nursing will need to learn to interpret AI feedback reports; widespread adoption of wearable portable non-invasive BCI in home and community settings, consequently nursing will need to develop remote training courses and emergency protocols; gradual establishment of stratified rehabilitation and nursing systems, accordingly nursing will need to participate in stratified assessment and develop differentiated care plans; large-sample, multicenter, long-term follow-up studies providing higher-level evidence, which means that nursing will need to incorporate sensitive indicators to build evidence chains; and continuous improvement of specialized BCI rehabilitation nursing training and standards, hence nursing will need to establish a stratified training system (basic safety – intermediate signal monitoring – advanced AI report interpretation) [3].

## 5. Conclusion

This review systematically summarizes the application of BCIs in neurorehabilitation and nursing care for patients with paraplegia. It finds that both non-invasive EEG-BCI and invasive implantable BCI can bypass the damaged spinal cord to activate neuroplasticity, improve motor intention, relieve spasticity, and enhance activities of daily living. Patients with both incomplete and complete paraplegia may benefit from stratified intervention, although the quality of existing evidence remains limited.

Comprehensive specialized nursing is central to the safe implementation of BCI, improving adherence, preventing complications, and ensuring rehabilitation outcomes. Its three core functions are risk prevention (skin/wound/infection), efficacy promotion (signal quality and adherence), and long-term continuity (home guidance and follow-up). Risk prevention is the foundation, efficacy promotion is the core, and long-term continuity is the guarantee; all three are indispensable.

Existing research problems include limited non-invasive BCI signal quality; high risks and costs associated with invasive BCI; lack of unified nursing standards (specifically inconsistent assessment tools and operational procedures); and a shortage of high-quality studies. Future efforts should focus on developing intelligent integrated rehabilitation, home-based wearable BCIs, standardized stratified nursing (including unified assessment tools and operational procedures), and conducting multicenter long-term studies.

This review preliminarily synthesizes the available evidence on BCIs in paraplegic neurorehabilitation and offers nursing-oriented recommendations for clinical translation. With continued technological optimization and maturation of nursing models, brain-computer interfaces combined with standardized rehabilitation nursing have the potential to become an important direction for improving the quality of paraplegic rehabilitation, enhancing patient function, and improving quality of life, ultimately playing a greater role in supporting patients' return to society.

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