Application Progress and Nursing Value of Brain-Computer Interface Technology in Upper Limb Motor Impairment Rehabilitation after Stroke

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Abstract: Stroke is a leading cause of death and disability among adults worldwide. Many people who have a stroke end up with problems moving their upper limbs, and this can make it much harder for them to do everyday activities and can greatly lower their overall quality of life. Standard rehabilitation often helps only a limited amount with upper limb problems in the later stage after stroke, because it mainly depends on passive treatments given by therapists, so patients are not very actively involved. In recent years, brain-computer interface (BCI) technology has made it possible to read a person's movement intentions in real time and turn them into external feedback. This creates an "intention-to-action" closed-loop system, which offers a new way to tackle this problem. Studies have demonstrated that when combined with functional electrical stimulation (fES) or visual feedback, upper limb motor function improves significantly under BCI intervention (SMD=0.62), making this approach particularly suitable for the subacute and chronic phases of stroke. The initial clinical application of implantable BCIs in patient care has preliminarily confirmed their safety and feasibility. However, the clinical implementation of BCIs for upper limb motor dysfunctionIn stroke patients, current management relies predominantly on monitoring signal quality during nursing care, load management, and psychological support. This review summarizes the technical principles and classifications of BCIs, the theory of neural plasticity, the current applications of BCIs in upper limb rehabilitation following stroke, and relevant research findings on their nursing value. From a nursing perspective, this review further discusses the unique advantages of BCIs in enhancing patient adherence to rehabilitation protocols, reducing adverse events, and strengthening patients' confidence in recovery. Ultimately, this work aims to establish a synergistic "technology–nursing" model for BCI-based rehabilitation, thereby promoting the standardized, precision-oriented, and equitable application of BCI technologies in clinical practice.

Keywords: Brain-Computer Interface; Stroke; Upper Limb Motor Dysfunction; Rehabilitation Nursing; Neural Plasticity

1. Research Background and Significance

Stroke is the main cause of death and disability among adults around the world. After a stroke, problems with moving the upper limbs are very common, and they are also one of the hardest problems to recover from. About 50% of stroke patients develop upper limb problems, which can make it hard for them to do everyday activities and can greatly reduce their ability to take part in social life. However, usual rehabilitation methods do not work well for patients with moderate-to-severe impairments [1].

Right now, the main way to help stroke patients recover motor function in the clinic is exercise therapy, and it is often used together with physical agents and occupational therapy. Exercise therapy is the foundation of limb rehabilitation. It uses passive, assisted, and resistance exercises to improve joint range of motion, muscle strength, balance, and walking function. Physical agents include functional electrical stimulation, transcranial magnetic stimulation, biofeedback, ultrasound, and magnetic therapy. The goal of occupational therapy is to help patients get back their activities of daily living (ADLS), such as dressing, eating, bathing, and using the toilet. Therapists do this by simulating real-life situations, training patients to use the affected limb, or teaching them compensatory techniques [2].

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Previous studies have shown that over half of stroke patients still exhibit upper limb motor dysfunction after 3-6 months of rehabilitation therapy. Consequently, identifying alternative safe and effective rehabilitation strategies to facilitate motor function recovery has become an urgent clinical priority. With the advancement of artificial intelligence, brain-computer interface (BCI) technology has emerged as a novel approach to addressing this challenge.

BCI is a therapeutic modality that directly acts on the brain. In recent years, BCI has developed rapidly and has been applied in the rehabilitation of patients who have suffered a stroke, ushering in neRecent trends in the motor rehabilitation of distal upper limb joints in stroke patients [3]. Because BCI acts directly on the brain to modulate neural plasticity and restore motor function, it offers clear advantages for improving patients' motor outcomes and has therefore attracted increasing attention. Clinical studies and treatment use have shown that BCI can clearly help stroke patients with severe movement problems improve their quality of life and regain motor function [4]. This highlights its potential for treatment and rehabilitation.

BCI can decode movement intentions and give feedback in real time. This creates an "intention–action" closed loop, which offers a new way to promote neural plasticity and help restore motor function. A 2025 review in Chinese Journal of Nursing ends by saying it has "implications for nursing practice," but it describes nursing roles only in general terms and gives limited detail about specific nursing interventions. However, the first nursing case study involving an implantable BCI revealed that progressive multimodal motor nursing-combined with quality control and mental health support-is a key factor for effectiveness. The existence of an "unexplored translational gap" between nursing care and BCI performance indicates that, even with identical devices and algorithms, different nursing approaches can lead to divergent rehabilitation outcomes [5].

This review article examines upper limb motor dysfunction in stroke patients, provides an overview of brain-computer interface (BCI) technology, discusses the current status of clinical applications of BCI in upper limb rehabilitation for stroke patients, highlights the advantages of such rehabilitation approaches and their corresponding nursing interventions, and identifies challenges associated with BCI implementation in this context. The aim of this study is to establish a nursing framework for the application of BCI in upper limb rehabilitation following stroke, propose key considerations and future directions, and thereby guide the translation of BCI technologies into clinical practice.

2 Overview of Upper Limb Motor Dysfunction in Stroke and Brain-Computer Interface Technology

2.1 Overview of Brain-Computer Interfaces

Brain-computer interface (BCI) technology is a device that can interact with the outside world by using signals that control electroencephalographic (EEG) activity. It works within a specific hardware and software framework and does not depend on the body's peripheral nerves or muscles. When a person engages in cognitive activities, specific electrical signals are produced, and the BCI device collects and processes them. The basic workflow mainly has four stages: signal acquisition, feature extraction, functional decoding, and device output. Depending on the source of BCI signals and the acquisition methodology, BCI systems can be categorized into implantable BCI systems employing invasive electrodes and non-implantable BCI systems utilizing non-invasive scalp electrodes. Implantable BCI systems are positioned close to the cerebral cortex, enabling stable EEG signal acquisition, however, they introduce additional risks to the patient, including the need to prevent immune rejection and wound infections. Surface EEG-based systems include three types: ① P300 potentials, originating from the pre-parietal region of the cerebral cortex and elicited by visual stimuli, ② sensorimotor rhythms, originating from the sensorimotor areas of the cerebral cortex, and ③ slow cortical potentials, primarily derived from the cerebral cortex [6].

2.2 Pathophysiological Mechanisms of Upper Limb Motor Dysfunction in Stroke

Post-stroke upper limb motor dysfunction is primarily caused by damage to the corticospinal tract (CST). The CST is a descending pathway

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that originates from the cerebral cortex and projects to the motor neurons of the spinal cord, injury to the CST reduces the cortex's ability to recruit these spinal motor neurons, leading to muscle weakness and impaired fine motor function. Studies have shown that, after a stroke, the loss of spinal motor neurons exerts a greater impact on extensor muscles than on flexor muscles, which explains why recovery of extensor function in the affected upper limb of hemiplegic patients is slower and more challenging than that of flexor function.

Endogenous neural remodeling following stroke includes synaptic remodeling, cortical reorganization, and compensatory activation in non-injured brain regions. However, overuse of the unaffected limb can induce aberrant synaptic plasticity, exacerbating "acquired uselessness" on the affected side. The objective of rehabilitation training is to steer this neural remodeling toward a direction conducive to functional recovery through task-oriented training and appropriate neuromodulation.

2.3 Principles and Classifications of Brain-Computer Interface Technology

A Brain-Computer Interface (BCI) is a device that captures and decodes neural activity from the brain, converting it into control signals for external devices, thereby enabling direct communication between the brain and external devices. Based on invasiveness, BCIs can be classified into invasive BCIs, non-invasive BCIs, and semi-invasive BCIs. Invasive BCIs involve craniotomy to implant electrodes directly into the cerebral cortex, their advantage is the acquisition of high-quality signals, but they carry surgical risks and the potential for immune rejection. Non-invasive BCIs utilize scalp electrodes to record electroencephalographic (EEG) signals, their advantage is safety and non-invasiveness, whereas their limitation is lower signal resolution. Semi-invasive BCIs represent an intermediate approach, in which electrodes are placed on the meninges.

Among non-invasive BCI systems,the three most commonly used for upper limb rehabilitation following a stroke are motor imagery (MI) BCI, steady-state visual evoked potential (SSVEP) BCI, and multimodal fusion BCI. These BCI systems are frequently integrated with external execution devices-such as exoskeletons, FES, or VR-to form closed-loop rehabilitation training systems.

2.4 Theoretical Mechanisms by Which BCI Promotes Neuroplasticity

According to the principles of Hebbian learning, connections between simultaneously activated neurons are strengthened. The BCI monitors the patient's motor intention in real time, once this intention emerges, the BCI provides immediate sensorimotor feedback, establishing a causal link between central motor commands and peripheral sensory feedback, thereby promoting synaptic remodeling within the corticospinal pathway. Multisensory BCI feedback enhances activation of higher-order cross-modal networks (e.g., the DMN, dorsal/ventral AN, and FPN) and relies on activity-dependent plasticity to facilitate interhemispheric functional integration, thereby accelerating motor function recovery.

3 Current Clinical Applications of Brain-Computer Interface Technology in Upper Limb Rehabilitation Following Stroke

3.1 Evidence-Based Evidence from Randomized Controlled Trials

In recent years, the efficacy of BCI in upper limb stroke rehabilitation has been supported by numerous high-quality randomized controlled trials (RCTs). Xia Xiaoqian et al. designed a prospective, single-center RCT involving patients with hemiplegia following strokeonset ranging from 2 weeks to 12 months after onset. Participants used an MI-SSVEP-based bimodal closed-loop BCI to control a robotic exoskeleton hand for grasping tasks. The results showed that, compared with the control group, the experimental group achieved significantly greater improvements in FMA-UE and mBI scores both after treatment and during follow-up (interaction effect for FMA-UE: $F=19.551$, $P<0.001$)[7].

For patients in the chronic phase of stroke, the combination of BCI and CIMT has also shown favorable outcomes. Studies have demonstrated that, compared with CIMT alone, CIMT combined with BCI produces better results in treating real-life functional outcomes (COPM, MAL), indicating that the rehabilitative effects of BCI can be transferred to real-life settings.

3.2 Systematic Reviews and Meta-Analyses

Multiple systematic reviews and meta-analyses have also confirmed the efficacy of BCI. A meta-analysis covering 21 randomized controlled trials (n=886) demonstrated that BCI

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training was effective in improving FMA-UE scores (MD=3.69,95% CI 2.41–4.96, P<0.00001), WMFT scores (MD=5.00,95% CI 2.14–7.86), and ARAT scores (MD=2.04,95% CI 0.25–3.82) in both subacute and chronic phase patients (subacute phase MD=4.24, chronic phase MD=2.63). Among these interventions, combined BCI + FES therapy produced the greatest improvement (FMA-UE: MD=4.37,95% CI 3.09–5.65) .

Another meta-analysis (involving 21 RCTs with 650 patients) also confirmed the efficacy of BCI in improving upper limb function (FMA-UE: MD=2.50, 95% CI 0.60–4.40) and ADL performance (MBI: MD=8.38, 95% CI 2.23–14.53) in patients with stroke during the chronic phase. Subgroup analyses demonstrated that BCI-FES yielded the greatest effect (FMA-UE: MD=5.00, 95% CI 1.86–8.13), with the optimal treatment regimen consisting of 30 minutes per session, 4–5 sessions per week, for 2 consecutive weeks (totaling 10–12 sessions), however, this therapeutic effect was not maintained during follow-up[8].

3.3 Diversified Development of BCI Rehabilitation Paradigms

Current BCI rehabilitation methods are moving away from single approaches and toward combined, multi-modal strategies. In the subacute and chronic stages, the BCI-FES method-where a person's movement intention is turned into electrical stimulation that directly activates paralyzed muscles-has shown strong results. The BCI-exoskeleton robot method uses mechanical power to help patients carry out standard movements, and it has been effective for patients with moderate-to-severe motor impairment [9]. The BCI-VR method uses immersive virtual environments to provide rich visual feedback, which makes training more engaging and motivates participants more. In addition, closed-loop BCI systems use real-time neurofeedback to help rebalance function between the two hemispheres and promote remodeling of the corticospinal tract (CST). These systems have become a new trend in neuromodulation interventions.

4. Advantages of Brain-Computer Interface Rehabilitation Technology and Its Nursing Application Value

4.1 Core Advantages of BCI Rehabilitation Technology

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4.2 Nursing Application Framework in BCI Rehabilitation

Today, BCI rehabilitation is no longer limited to just one method; it is moving toward combining several methods. In the subacute and chronic stages, the BCI-FES method has shown strong results: it turns a person's intention to move into electrical stimulation that directly activates paralyzed muscles. The BCI-exoskeleton robot method uses mechanical force to help patients perform typical movements, and it has been effective for patients with moderate-to-severe motor impairment [9]. The BCI-VR method uses immersive virtual environments to give rich visual feedback, which makes training more interesting and helps participants stay more motivated. In addition, BCI systems that form a closed loop use real-time neurofeedback to help rebalance function between the two sides of the brain and to promote remodeling of the corticospinal tract (CST). These systems have become a new trend in treatments that modulate the nervous system.Within this team, nurses are responsible for patient screening and assessment, monitoring and evaluation of rehabilitation training, psychological support, and other related tasks. (2) Dynamic assessment: Conducting proactive rehabilitation assessments led by specialized nurses, including evaluations of basic BCI knowledge and treatment-related knowledge, assessments of rehabilitation

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confidence and emotional state, and re-evaluation of nursing-related issues following initial treatment. (3) Standard operating procedures (SOP): Research has developed an SOP for motor imagery-based BCI to guide paralyzed patients in active rehabilitation, with preliminary validation demonstrating the SOP's scientific rationale, comprehensiveness, and specialization. This SOP can serve as a standardized reference for BCI rehabilitation nursing care.

5. Multidimensional Manifestations of Nursing Value Under BCI-Driven Conditions and the Three-Stage Evolution of Nursing Practice

5.1 Multidimensional Manifestations of Nursing Value Under BCI-Driven Care

From preoperative education to EEG monitoring, rehabilitation training, and motor imagery, the entire process incorporates psychological nursing interventions, including: dynamic attention monitoring, personalized maintenance, multi-stage assessment, collaborative decision-making and adaptation, monitoring of treatment response, synchronized dynamic interventions, behavioral guidance, and structured empowerment throughout the entire cycle. Nursing care is not merely about "adopting new technologies", it serves as the daily regulator, determining how this closed-loop system functions within real-world clinical settings.

The functions of BCI rehabilitation care are:① Keeping patients safe - making sure BCI therapy is safe through care around the procedure, monitoring during training, and risk assessment.② Making treatment work better - improving the quality of BCI signals and training results by helping patients stay focused, providing psychological support, and making personalized adjustments.③ Providing continuous care across settings - creating seamless, ongoing care from hospital to community to home, so patients do not miss out on rehabilitation after discharge.

5.2 Three-Level Evolution of Nursing Value Under BCI-Powered Care

5.2.1 Nursing assessment: from behavioral observation to interpretation of neural signals.

When it comes to assessment, BCI technology brings a major change for rehabilitation nurses. Traditionally, nurses assessed patients by observing visible behaviors: checking how well patients can move their limbs, testing muscle strength, and watching changes in facial expressions. But when using BCI, nurses now need to read and understand neural data, like EEG signals and ERD intensity. In short, assessment has moved from looking at obvious outward behaviors to detecting hidden brain activity [10].

Nurses need new assessment tools to support this deeper way of evaluation. Some clinical practices have tried an active dynamic assessment model for rehabilitation, led by specialist nurses. It uses a three-level step-by-step assessment framework, covering: basic cognitive ability and relevant knowledge, rehabilitation confidence and emotional status, and nursing points to note after the first round of BCI treatment.

Assessment tools: At present, common assessment tools used in BCI rehabilitation studies include the Fugl-Meyer Upper Extremity Score, the Revised Barthel Index and ERD intensity. Researchers also use scales such as the Hospital Anxiety and Depression Scale, the Stroke Patient Self-Efficacy Questionnaire, and the Zarit Caregiver Burden Scale.

5.2.2 Nursing decision-making: from executing medical orders to collaborative prescribing.

Brain-computer interface (BCI) rehabilitation is complicated, and this is changing what nurses do when making care decisions. In the past, nurses mostly just carried out nursing tasks following doctors' care plans. But BCI rehabilitation training is different: nurses need to change training settings right away based on how focused the patient is, how tired they are, and how good their brain signals are. That means nurses have to take an active part in working out and improving treatment plans.

This change can already be seen in real clinical work. For instance, some hospitals use a case management team. The team includes medical staff, technicians and engineers, and nurses join in to talk about and decide on treatment plans. Other places use a three-party model made up of doctors, engineers and nurses. This model includes repeated assessments, customized treatment, targeted nursing for each patient, ongoing observation, and flexible changes to care measures. Nurses know patients' overall situations best, so they act as an important

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bridge between clinical decisions and what patients actually need.

Nurses also play a bigger part in making decisions by overseeing the whole training process. During BCI training, whether the patient can stay focused has a direct impact on brain signal quality and how well the training works. Nurses need to use personalized ways to manage the patient's attention - for example, tracking and recording when their focus rises and falls, and giving suitable help accordingly. This kind of on-the-spot decision-making built on clinical experience is a professional skill nurses have, and computers cannot copy it.

5.2.3 Nursing humanities: from protection to the integration of technology and humanities.

BCI does not replace nursing care, rather, it gives nursing new significance and imposes new requirements. In the technology-intensive context of BCI rehabilitation, patients face not only functional impairment but also unfamiliarity with emerging technology, uncertainty about therapeutic outcomes, and reduced self-efficacy. Nursing care thus extends beyond bedside care to helping patients regain confidence in their ability to restore bodily control through technology and to re-establish hope for rehabilitation.

Clinical practice has shown that psychological preparation before BCI therapy is critically important. Nurses should assess patients' confidence in recovery and their emotional state, and identify psychological barriers that may undermine treatment engagement. During therapy, based on the patient's experience after the first session, nurses should re-evaluate nursing-related issues and implement targeted interventions, this experience-based, dynamic psychological intervention embodies truly personalized nursing care[11].

At a deeper level, the integration of technology and humanities raises new ethical challenges for nursing in BCI applications. In clinical settings, nurses must pay close attention to patients' autonomy, privacy, and informed consent. Invasive BCI systems come with ethical risks. These include unresolved issues about patient autonomy, privacy, and informed consent. Nurses are the healthcare professionals who have the most frequent contact with patients. Because of this, they act as the only guardians of patients' neural data privacy and of whether patients' informed consent is genuine and sufficient.

6. Conclusion

Brain-Computer Interface (BCI) gives stroke patients with upper limb problems a new rehabilitation approach that is active, precise, and measurable-namely, rebuilding the "intention–movement" circuit. Evidence shows that BCI, especially BCI-FES, can clearly improve upper limb motor function and daily living activities in stroke patients. Nursing care is an essential prerequisite for using BCI in rehabilitation in the clinic. However, the nursing application framework and standard operating procedures for BCI are still being developed. Also, the clinical use of BCI in rehabilitation faces several limitations: treatment results vary, there are technical challenges, there is a lack of standardization, and nursing support systems are not adequate. To address these limitations, this study systematically reviews how BCI is used in upper limb rehabilitation after stroke and explores building a nursing application framework. The goal is to promote the precise, standardized, and widespread adoption of BCI-based rehabilitation technology.Future BCI rehabilitation will evolve toward intelligence, personalization, and end-to-end integration. With AI, BCI systems can achieve adaptive decoding, provide personalized training recommendations, and incorporate multimodal neural fusion and brain-machine integration-key breakthroughs in BCI rehabilitation. Optimized decoding systems will establish an integrated diagnostic-treatment-assessment framework, facilitating the clinical application of multifunctional BCI solutions. The development of portable exoskeletal BCI systems will extend rehabilitation services from hospitals to community and home settings, offering stroke patients comprehensive, full-cycle rehabilitation support.

Future research should focus on the following four areas:①Run multicenter, large-sample, long-term randomized controlled trials (RCTs) to agree on a core set of outcome measures, find out which patients benefit most from BCI rehabilitation, and determine which BCI rehabilitation plans work best.②Do more research on the neural mechanisms of BCI rehabilitation, using functional neuroimaging and electrophysiological methods to clarify when and where BCI-induced neural remodeling occurs.③Develop standardized operating

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procedures (SOPs) for BCI rehabilitation nursing, carry out multicenter studies, and provide training and certification programs for specialized nurses.④ Conduct health economics research to provide evidence for including BCI rehabilitation technologies in medical insurance systems and for making related policies.

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