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Application of Brain-Computer Interface in Post-Stroke Disease Rehabilitations

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Abstract. Stroke is one of the leading causes of long-term disabling illness in the world, resulting in persistent functional impairment in 75% of survivors. Traditional rehabilitation methods are often limited by their inability to effectively activate long-term neuroplasticity. This study investigated the use of brain-computer interface (BCI) technology in post-stroke rehabilitation and systematically assessed its clinical efficacy for limb function recovery by analyzing neural signal decoding mechanisms and classification (invasive/non-invasive). The results of this paper showed that a motor imagery (MI)-based BCI training program enhanced neural coupling between the motor cortex and the affected limb, reflecting clinical significance in hand grasp, joint range of motion, and motor coordination. For comorbid upper and lower extremity dysfunction, the BCI intervention yielded across-the-board benefits: walking speed improved by 0.15 m/s, spasticity scores (wrists, fingers, and ankles) were significantly reduced, and Barthel Index (BI) scores improved by 5.0 points. These synchronized improvements confirm the synergistic effect of BCI on motor function, spasticity control and activities of daily living. The integrated BCI robotic system incorporates Error-Related Negativity (ERN) decoding, enabling real-time detection of motor intent errors (8.5:1 detection-to-false-alarm ratio) and precise millisecond adjustment of assistive forces. This technological advancement permits early initiation of active neuroplasticity training in acute phase patients with complete loss of voluntary movement, confirming superior efficacy compared to conventional therapy alone. By facilitating active neural remodeling, BCI technology overcomes the limitations of passive rehabilitation and offers transformative potential for chronic patients.

Keywords: Brain-computer interface, Stroke, Rehabilitation.

1. Introduction

Stroke, clinically termed cerebrovascular accident (CVA), results from cerebrovascular damage leading to focal neurological deficits including limb weakness, speech impairment, and nausea. This condition demonstrates five characteristic "highs": high incidence, recurrence rate, disability rate, mortality and socioeconomic burden. Strokes are primarily classified as ischemic (more prevalent) or hemorrhagic (10-20% of cases, involving vessel rupture with higher mortality). Common sequelae encompass motor dysfunction (e.g.hemiplegia), speech/swallowing disorders, sensory abnormalities, and cognitive-emotional impairments. Post-stroke neurological deficits frequently

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persist, with approximately 75% of survivors experiencing permanent disabilities that often severely compromise activities of daily living, including ambulation. Epidemiological data reveal a concerning 14.8% increase in stroke prevalence (2010-2019), currently affecting 12.42 million Chinese adults aged ≥40 years, with 40% developing severe disabilities. Rehabilitation typically initiates during the acute phase and may continue for extended periods [1]. Recent advances in stroke rehabilitation have yielded numerous innovative therapeutic approaches. Contemporary research indicates that the paradigm shift towards interdisciplinary integration mainly involves three advances, namely the improvement of neural regulation technology, the development of intelligent rehabilitation systems, and the optimization of critical rehabilitation period management. Notably, 5Hz high-frequency repetitive transcranial magnetic stimulation (rTMS) targeting the dorsolateral prefrontal cortex (DPC) has been shown to enhance functional connectivity with the primary motor cortex (PMC). Resting-state functional MRI (rs-fMRI) confirmed this intervention significantly improved Fugl-Meyer scores (Δ=5.0) and Wolf Motor Function Test performance, mediated through remodeling of DPC-motor area neural pathways [2]. Intelligent rehabilitation systems have undergone rapid development. The AI-driven VR upper limb rehabilitation system developed by Fujian University of Traditional Chinese Medicine incorporates Azure Kinect motion capture technology and surface electromyography (sEMG)-based muscle synergy analysis. A randomized controlled trial (RCT, n=50) demonstrated significantly greater improvement in Fugl-Meyer Assessment (FMA) upper extremity scores in the VR intervention group compared to conventional rehabilitation (5.0±1.2 vs. 4.2±0.78 points, $p<0.05$), along with a 41% enhancement in muscle synergy efficiency, achieving digital transformation of clinical assessment methodologies [3]. Rehabilitation timeline studies have identified the 3-month post-discharge period as the critical window for functional recovery. Longitudinal follow-up of 155 patients by an international research consortium revealed that rehabilitation initiation during this period optimizes quality of life improvements, particularly for severe cases or patients with limited social support requiring extended intervention of up to 6 months for outcome stabilization [4]. Furthermore, the brain-computer interface functional electrical stimulation (BCI-FES) system establishes a closed-loop brain-limb-brain feedback mechanism by decoding motor intentions to induce muscle contractions, thereby enhancing synaptic plasticity and neural oscillation synchronization. This approach shows particular efficacy for subacute-phase patients with flaccid paralysis [5]. Complementarily, core stability training (CST) has been shown to improve gait symmetry (reducing shoulder joint coefficient of variation by 18%) through activation of spinal central pattern generators (CPGs) and optimization of cerebellar-parietal sensory integration [6]. The current clinical challenges mainly involve three aspects: insufficient personalization of rehabilitation programs, scarcity of longitudinal outcome data, and unfair distribution of rehabilitation resources in primary healthcare institutions. While conventional rehabilitation methods demonstrate measurable improvements in physical function, they often foster passive training dependency, resulting in suboptimal recovery of activities of daily living (ADLs) and diminished long-term therapeutic efficacy. The emergence of brain-computer interface (BCI) technology has introduced transformative solutions for post-stroke rehabilitation. This paper systematically summarizes the basic principles and classification of brain-computer interface systems and their therapeutic roles and seminal contributions to various parts of the stroke-rehabilitated human body, advances that offer new therapeutic options for chronic stroke patients.

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2. The working principle and classification of brain-computer interface

The main core principle of the brain-computer interface is to capture real-time electrical signals of brain activity and connect them with external devices to convert them into external action information and external device commands. It consists of several stages of brain signal acquisition and processing, feature extraction, feature classification interface device control and feedback [7]. People have used the processing of brain information to obtain thinking information instead of using muscle activity for information transfer since ancient times. This is a colorful part of the history of human science and technology and also provides open ideas for the research of various neurological diseases. Brain-computer interfaces are currently classified into three categories based on invasiveness: invasive, partially invasive and non-invasive. The most widely used non-invasive EEG-based technologies and interfaces are currently used by the scientific community, as they do not require any brain surgery, and the signals can be measured by eliciting electrical activity in the brain using headgear or helmet-like electrodes outside the skull. Invasive BCI involves the direct implantation of electrodes into the cerebral cortex, providing high signal quality and precise control. Partially invasive BCI places electrodes in subdural or subcortical brain areas, providing a balance of higher signal quality than non-invasive methods and lower risk than invasive methods. Additionally, BCI is categorized as unidirectional and bidirectional, unidirectional in that only the brain emits signals to the device, and bidirectional in that the brain and the device can exchange information to enhance response to advanced applications [8].

3. Brain-computer interface for rehabilitation of various body parts in a late stage of stroke

3.1. Application of brain-computer interface to upper limb rehabilitation of stroke patients

Brain-computer interface (BCI) technology can directly decode brain signals, promote neural function remodeling and achieve autonomous motor control of patients to enhance the efficiency of rehabilitation, so many hospitals now use BCI as an auxiliary device for stroke rehabilitation. Approximately 50 percent of stroke patients have reduced mobility and dexterity of the upper limbs after recovery. Almost half of the patients have impaired hand paralysis and are unable to use their upper limbs normally, which seriously affects their daily activities and quality of life. Intensive training in the weeks to months after recovery is important for upper limb rehabilitation. And BCI can pair brain activity with existing sensory feedback, which can promote plasticity by strengthening neural connections, and can improve patients' upper limb function well [9]. In this study, 60 stroke patients with upper limb dysfunction were included and randomly assigned to the control group or experimental group in a 1:1 ratio. The control group only implemented a conventional rehabilitation treatment program; the experimental group received an additional three-week, five-times-a-week, 20-minute Motor Imagery Brain-Computer Interface (MI-BCI) training on top of conventional rehabilitation. The results of the study showed that the Fugl-Meyer Upper Extremity Motor Evaluation (FMA-UE) score of the experimental group was significantly improved by 8.0 points compared with the control group. Meanwhile, the response of the orientation network of the experimental group was enhanced, while the response time, total average response time, and total time of the executive control network showed a trend of shortening. These findings suggest that brain-computer interface technology may be more effective than conventional rehabilitation means in the rehabilitation of upper limb motor function in stroke patients [10]. In addition, brain-computer interface (BCI)-based motor imagery (MI) technology can optimize the outcome of rehabilitation, as the BCI system can decode electroencephalography (EEG) signals reflecting motor imagery in real-

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time and combine with sensory feedback to empower patients to autonomously manipulate computers, wheelchairs, robots and prosthetic devices. A correlation meta-analysis further confirmed that BCI training had a statistically significant benefit on the recovery of upper limb motor function in post-stroke patients compared to conventional treatment alone, with a zstandardized mean difference of 0.39 (95% confidence interval: 0.17 to 0.62; 95% prediction interval: 0.13 to 0.66). This result supports the positive role of the BCI system in promoting the recovery of upper limb motor function and brain function [11].

3.2. Brain-computer interface for hand-foot rehabilitation in stroke patients

Sebastian Sieghartsleitner and his team recruited 19 stroke subjects with upper and lower limb hemiparesis for a prospective study consisting of two rounds of BCI intervention sessions. Each round lasted three months and was administered two to three times per week for a total of 25 sessions. The results of the study revealed clinically significant improvements in a number of functional indicators: a mean increase of 4.2 points in the Fugl-Meyer Upper Extremity Motor Evaluation (FMA-UE) score and an increase of 5.0 points in the Barthel Index (BI), which reflects the ability to perform activities of daily living (ADLs). Spasticity associated with motor dysfunction was also alleviated, with a 1.0-point decrease in wrist and finger spasticity scores and a 0.5-point decrease in ankle spasticity scores. The walking function also improved, with an increase in step speed of 0.15 meters per second. This series of positive changes reflects an overall improvement in upper and lower extremity motor function, daily living ability, and occupation-related function. It is particularly noteworthy that the BCI accuracy of the patient systematically increased from 73% to 76% when comparing the data at the beginning and at the end of the treatment period, indicating that the patient's neuromodulation ability and system adaptability were effectively trained and strengthened in the course of the treatment. This result strongly confirms that under the premise of ensuring sufficient treatment time and practice opportunities, BCI rehabilitation therapy for stroke patients can effectively promote the recovery process of damaged body functions and significantly improve the ability to activities of daily living and social participation level [12]. In addition, modern rehabilitation technology integrates wearable sensor devices and high-precision motion capture systems, providing powerful tools for assessment and training. These techniques are capable of non-invasively and continuously collecting patients' gait spatial and temporal parameters (e.g., stride length, stride frequency, stride speed) and body dynamics data (e.g., joint angles, pressure distributions) to achieve objective and quantitative analyses of gait patterns and dynamic balance abilities. This fine-grained assessment is not only used to accurately determine the degree of walking function and balance disorders but also effectively assists clinicians and therapists in designing and implementing individualized gait training and rehabilitation programs. More importantly, the continuous monitoring of functional trends can help predict the potential for recovery and outcome of stroke survivors in terms of functional independence (e.g., home and community mobility) and broader functional mobility (e.g., instrumental activities of daily living). This not only greatly facilitates therapists to efficiently develop and adjust goal-oriented rehabilitation pathways and significantly reduces the time required for clinical decision-making, but also deepens the understanding of the pathological mechanisms of post-stroke-specific gait and mobility dysfunction, thus providing a solid scientific basis and technical support for the development of highly personalized, evidence-based rehabilitation intervention strategies [13].

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3.3. Application of brain-computer interface in rehabilitation robotics

Stroke patients often face the dual challenge of significant muscle weakness and severe spasticity and pain during the acute phase, which makes conventional rehabilitation difficult for most patients. While conventional rehabilitation systems require patients to struggle to complete movements, an innovative solution is provided by integrated brain-computer interface (BCI) technology, which senses the patient's neural state in real-time and intelligently adjusts external assistance by parsing signals of neural activity related to motor intent. This intrinsic feedback-based adaptation allows patients to safely start the rehabilitation process early and effectively overcome acute training barriers. In response, Akshay Kumar's team has developed a novel BCI-robotic fusion system, which is centered on a closed-loop neurofeedback mechanism. The system continuously acquires electroencephalogram (EEG) signals as an input source and dynamically adjusts the level of robotic assistance. To validate the system's recognition ability, the team simulated a rehabilitation scenario in 12 healthy subjects: recording their EEG signals while performing a standardized task and focusing on the analysis of error-related negative waves (ERNs) induced by incomplete tasks. The results show that the probability of correctly detecting incorrect trials when classifying based on background EEG features amounts to more than 8.5 times the false alarm rate. The high-precision recognition capability allows the robot to balance autonomous patient movement with necessary assistance. The system is not only suitable for patients who retain partial limb control but is also uniquely valuable for patients in the acute phase with near loss of voluntary movement. Matching the patient's residual neural activity with precise assistance, can stimulate neuroplasticity while avoiding excessive fatigue, thus opening up valuable early rehabilitation pathways for patients in the acute phase [14].

4. Conclusion

Brain-computer interfaces (BCIs) have moved from imagination to clinical practice in post-stroke rehabilitation, which can activate dormant neural pathways through closed-loop feedback and promote the reorganization of connections between the brain motor cortex and spinal cord. Core findings suggest that brain-computer interface interventions can effectively improve upper limb motor function. Compared with conventional rehabilitation, the Fugl-Meyer Assessment (FMA-UE) score improved by 8.0 points, while the response efficiency of the orienting network was improved and the latency of the executive control network was shortened. In joint limb rehabilitation, BCI training increased the patients' FMA-UE score by 4.2 points, Barthel Index (BI) by 5.0 points, reduced the spasticity of wrist, finger and ankle joints, and accelerated the striding speed by 0.15 m/s. For the bottleneck of rehabilitation in the acute phase, the BCI-robotics system can achieve the dynamic and precise control of the auxiliary strength by decoding the Error-Related Negative Wave (ERN) signals (with an identification accuracy of 8.5 times the misreporting rate) in real-time, so as to enable the patients who have lost the ability of autonomous locomotion to start the early training. Compared with traditional rehabilitation methods, BCI has a greater effect on active rehabilitation than passive treatment, allowing patients to actively participate in rehabilitation training and improving compliance. However, non-invasive BCI is now affected by cranial signal attenuation, the decoding error rate is high, and will make the patient's EEG ability decline after the increase in rehabilitation time, the decoding rate attenuation. Secondly, the unit price of BCI high-end equipment exceeds one million, and only a few provinces will BCI rehabilitation into medical insurance, economic pressure, BCI operation at the same time needs neuroscience and engineering composite background talents, at present, the relevant talent is relatively small. In the future, it may

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be possible to combine BCI and AI for self-control of gait, and the development of lightweight devices for home use could begin. Currently, the uneven maturity of technology, lack of standardization and cost are still the bottlenecks that prevent BCIs from being used for universal treatment. It is hoped that multidisciplinary co-operation can break the bottleneck in the future so that BCI can become a universal therapeutic instrument.

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