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Brain-Computer Interfaces in Stroke Rehabilitation: Mechanism, Applications, and Future

Zhijun Zhong

27 King's College Circle, University of Toronto, Toronto, Canada
Zhijun.zhong@mail.utoronto.ca

Abstract. Stroke is still regarded as one of the leading causes of long-term disability. Patients who have survived a stroke often suffer from motor, language, and cognitive impairments that impact their quality of life. There are limitations to conventional treatment like physical therapy, occupational therapy, speech-language therapy (SLT), or neuropharmacological agents' supplements. Most of these strategies have requirements for sufficient residual ability. Recently, the brain-computer interface (BCI) has gradually become a promising tool for stroke rehabilitation. Since it enables direct communication between the brain and external devices, this closed-loop circuit facilitates neuroplasticity and functional recovery. This paper provides an overview of BCI mechanisms and development and their application in post-stroke motor, language, and cognitive rehabilitation. It begins with an introduction to the development of invasive and non-invasive BCIs and states the underlying mechanisms of how BCIs encourage neuroplasticity and facilitate function restoration. Evidence from recent clinical studies and meta-analyses has demonstrated that BCI-based interventions with various paradigms like motor imagery (MI), action observation (AO), P300 event-related potential, etc. BCI with external devices like robotic exoskeletons, functional electrical stimulation (FES), and virtual reality (VR) can ameliorate motor, language, and cognitive impairments. Future research should address challenges related to signal reliability, device usability, clinical validation, and ethical considerations. The integration of BCIs with neurostimulation techniques and artificial intelligence (AI) could be the future direction for developing more personalized, adaptive, and applicable therapies.

Keywords: Brain-computer interface, Stroke rehabilitation, neurofeedback therapy, electroencephalogram

1. Introduction

In the past 30 years, stroke has been the second most common cause of mortality from non-communicable diseases (NCDs) [1]. Common post-stroke symptoms include one-sided paralysis, spatial neglect, blindness, language and cognitive deficits. Traditional stroke rehabilitation target on motor recovery by incorporating physical training (PT) on proximal and distal movements, gait training, resistance exercise, and balance drills. Patients are encouraged to do exercises that enhance the speed and strengths of multijointed movement. Constraint-Induced Movement Therapy (CIMT)

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is a common method which helps in arm recovery by repeatedly using the affected arm while preventing the use of the unaffected arm. There's also occupational therapy (OT) for patients to help patients relearn daily life skills, like dressing, bathing, eating, and leisure activities. For patients who experience aphasia, dysarthria, and swallowing disability, speech-language pathologists develop plans for them to do articulation exercises, cognitive-communication tasks, and swallowing strategies. Therapists would introduce augmentative and alternative communication (AAC) strategies to patients with serious communication disability, including communication boards, speech-generative devices, or software. To enhance the affected cognitive abilities, such as memory, attention, and executive function difficulties. Therapists would provide mnemonic techniques, spaced-exercises, time management, multitasking, and visual aids. Additionally, several supplementary neuropharmacological agents like acetylcholine, dopaminergic, and norepinephrine drugs aid procedural, language, and cognitive recovery [2,3]. While traditional stroke rehabilitation methods are designed based on patients' residual movements, many patients with severe symptoms always fail to participate. Additionally, conventional interventions may not provide personalized functional improvement, especially in those with severe impairments [4].

Brain computer interface (BCI) is a technology that connects human brain with computer, which utilizes computational algorithms to interpret patterns if brain activity and control external devices. It was once used to understand motor systems for patients suffering from spinal cord injury or locked-in syndrome. As BCI has shown its emerging role for neurorehabilitation, it also offers promising new approaches for stroke rehabilitation, particularly in motor, language, and cognitive aspects. This paper provides a general overview of BCI's role in stroke rehabilitation, including its mechanism, application, and its future. It aims to improve understanding of BCIs and its contribution to stroke rehabilitation. By listing evidence of BCI's effectiveness in repairing motor, language, and cognitive deficits, it provides a comprehensive view of BCI's multiple possibilities as a clinical tool. It highlights the limitations of current studies and raises concerns about the ethical issues related to BCIs in a clinical context. BCI's rapid development allows individuals to hypothesize its future development.

2. Development of brain computer interfaces

Current studies focus on two types of BCI system: invasive and non-invasive. Non-invasive BCI is based on electroencephalography (EEG) recording. By placing EEG on the scalp, electric activity of brain could be recorded and interpreted into certain command. Therefore, patients could perform intended actions with peripheral devices even without muscle innervation. By contrast, invasive BCI record signals directly from the surface or inside of the cortex by electrode. For instance, the electrocorticogram (ECoG) is a recording which receives electrical activity information from a macro electrode from the surface of the cortex. Since it attaches directly to the brain, the signal acquired is always stronger, that are able to produce more accurate results. However, its invasiveness and risk of tissue damage are always factors that people consider about.

Invasive BCIs developed earlier than non-invasive BCIs. Early clinical-use BCIs recorded Slow Cortical Potentials (SCP), allowing researchers to communicate with patients who have Locked-in Syndrome (LIS) or Amyotrophic Lateral Sclerosis (ALS). When the traditional eye-tracking method becomes impossible, BCI could translate brain signals into text, which enables patients to communicate with their family, doctors, and caregivers [5]. In the 2000s, invasive BCI started to function in restoration of arm movement and tactile sensation for patients with paralysis. Later, development of BCIs enabled recovery of even finer movements, including wrist and fingers. At the same time, non-invasive BCIs with less harm gradually replace invasive BCIs in several areas to

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help more disabled people, such as assisting wheelchair movement, communication, and even cursor control on a computer.

Non-invasive BCIs allow researchers to expand BCI use in areas other than motor assistance, including language, cognitive, mental health, and emotional regulation. With the development of different BCI paradigms, non-invasive BCI gradually requires less training and becomes more portable [6]. Thus, non-invasive BCIs have taken the place of invasive BCIs for controlling assistive devices and helping with motor recovery, like in post-stroke rehabilitation.

3. Brain computer interface application in stroke

Both ischemic and hemorrhagic stroke lead to damage in brain arteries, further resulting in neuronal apoptosis. Loss of neurons not only causes functional deficits in motor, language, and cognitive reserve, but also hinders neuroplasticity due to inflammation and oxidative stress [7]. Inducing neuroplasticity is a vital segment for BCI treating the aftereffects of stroke. As the undamaged brain region could rewire and take over the lost functions, neuroplasticity also creates new synaptic connections, which speed up the brain's self-repairment. When a patient's intention is detected by the recording device, the sensory feedback from the robotic arm is activated at the same time. This contingent activity enhances Hebbian plasticity of neurons "Fire together, wire together." In other words, BCIs play a role in closing the response loop, which allows for re-engaging of affected brain regions. This neurofeedback training revise abnormal patterns after stroke by making patients control their brain activity using real-time feedback. During this training, conditioning rewards could correct mental tasks and encourage brain adaptation. Depending on their design, BCIs may use one or more methods to support stroke rehabilitation [8].

3.1. BCI for post stroke motor recovery

Motor recovery was what BCI mainly targeted in early development, specifically LIS and ALS. EEG-BCIs are typically used for post-stroke motor rehabilitation. EEG detect motor intentions such as imagined or attempted movements. These brain signals are amplified and digitized, further preprocessed to remove the noise. BCI then extract, decode relevant features, and translates them to control assistive devices like robotic exoskeletons, functional electrical stimulation systems (FES), or virtual environments. One of the key paradigms of EEG-BCI is motor imagery (MI). MI represents a mental simulation of physical movement, such as grasping or walking. While imagining these movements, corresponding neuronal circuits are activated and strengthened [9,10]. Compared to other paradigms, such as SSVEP, P300, and SCP, MI is independent from external stimulus. Thus, it is a preferable method for patients who are not capable of generating responses. Other than MI, action observation (AO) is also a suggested mental task to activate the EEG. AO refers to the process where individuals watch videos or live demonstrations of particular actions performed by others. According to the mirror neuron theory, simply observing these moves can activate the same neural circuits involved if the observer were performing the movement. AO requires less skill training than MI intervention [11]. FES is activated after an action intention is decoded to stimulate the muscle affected by paralysis, producing proprioceptive feedback. Similarly, virtual reality (VR) enables patients to see their imagined movements with limbs, which stimulate neurons in the prefrontal cortex (PFC) and strengthen neuroplasticity [12,13].

Fugl-Meyer Assessment (FMA-UE) score is a standardized and quantitative measure of upper limb motor function, sensory ability, and joint movement. Early studies on upper limb rehabilitation exploit non-invasive BCI that combines the MIT-Manus robotic system in hemiparetic stroke

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patients, each receiving 12 one-hour sessions over four weeks. Both groups showed improvements in upper limb function with increased FMA-EU scores, especially the MI-BCI group has demonstrated greater long-term effects than only robotic therapy [14]. Studies on BCI later integrated with FES. Meta-analysis on BCI-FES showed a significant short-term effect on upper limb therapy, especially when incorporating the AO+MI combination [15,16]. Multi-modal sensory feedback BCI (Multi-FDBK-BCI) suggested by Lu et al. (2025) proposes a new strategy targeting chronic stroke survivors [17]. Combination of exoskeleton for proprioceptive input, tactile hand stimulation, and VR-generated visual cues amplifies patient's feedback and motor outcomes.

Lower limb rehabilitation requires different biomedical and functional design, especially on safety, body weight support, and complex joint movement. From the study of McCrimmon et al. (2015), several patients who underwent BCI-FES dorsiflexion therapy have shown an increase in gait speed [18]. Importantly, there's no statistically significant deterioration in gait during therapy. Later MI-BCI-FES training also demonstrate improved ankle mobility, step length, gait symmetry, and postural stability, which also reflected on lower extremity motor function (FMA-LE) score [19,20].

3.2. BCI for post stroke language restoration

Aphasia is a common deficit caused by stroke in the left hemisphere. Existing intervention for aphasia is speech and language therapy (SLT). Among SLT, impairment-based approaches target on phonology, semantics, or syntax deficits and enhance language ability through structured exercises. While the functional communication approach emphasizes practical communication, it works by training caregivers and removing environmental barriers. Conventional SLT always requires some level of speech, motor, and comprehensive ability. Non-invasive brain stimulation, like transcranial direct current stimulation (tDCS) and repetitive transcranial magnetic stimulation (rTMS) are tools that modulates cortical excitability and promotes neuroplasticity. However, their effects are often modest and task specific [21]. Event-related potential (ERP) is a brain response detected by EEG which is linked to specific sensory, cognitive or motor events. Musso et al. (2022)'s study showed how patients perform a simple auditory word detection task. They are asked to listen attentively to sentences with a missing final word and then identify target words internally when hearing a word list. Their brain ERP signals are continuously recorded by EEG. Once signals were detected, machine learning algorithms decode these signals in real time. Once patients correctly identify target words, they receive positive feedback of encouraging sounds or visual cues. The whole process could finish even for patients unable to speak. Evidence suggests that the BCI training method increases language processing speed and improves connectivity within key areas such as Broca's and Wernicke's regions. Unlike SLT, BCI enhanced language comprehension and processing instead of motor control [22]. Recent study found that patients with chronic post-stroke aphasia who trained with a visual P300 BCI showed improvements in spontaneous speech production, reduced aphasia severity, and better quality of life. In this system, patients were presented with a matrix of letters, and they focused attention on a target letter. BCI detects and translates into letter selection. This approach enables communication and may stimulate neural circuits involved in language production, particularly in individuals with motor aphasia who cannot rely on speech or muscle movement [23]. However, evidence and studies in larger sample size are still necessary to further confirm this effect.

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3.3. BCI for improving cognitive and attention deficits

Many stroke survivors presented cognitive deficits, including decreased attention span, difficulties in executive functioning, short-term memory, agnosia and apraxia. BCI's early application was for improving attention span for children who have diagnosed with attention deficit hyperactivity disorder (ADHD). EEG recorded frontal, theta, and beta electrical waves. While theta activity is associated with inattention, beta activity is linked to concentration [24]. In the later attention adaptive training, the theta-to-beta ratio (TBR) was detected by EEG-BCI in a VR game. During the game, if attention was low or moderate, the avatar's speed would be reduced or stopped. Immediate audiovisual cues are used to keep participants' brains attentive and further promote neuroplasticity. The experimental group showed a statistical improvement in attention score than control group [25]. Similarly, patients with chronic post-stroke attention deficits participated in slow-cortical potential (SCP) neurofeedback sessions. These sessions train patients to modulate their brain signals towards a more activated state. During these task sessions on computer, patients could see or hear how well they were controlling their brain activity through the therapist's real-time feedback. Results suggested this training process corrected the aberrant brain patterns and improved neuroplasticity and functional reorganization in attention networks. As patients gain better control over their brain activity, they showed improvements in attention, decision-making speed, and daily cognitive functioning. Besides, patients were observed with more self-efficacy and motivation, which are supported by the sense of mastery achieved through successful neurofeedback training [26]. Cognitive and language ability have a bi-directional effect on each other. Studies suggested that short-term P300-BCI training, as stated in language recovery, also rapidly modulate brain connectivity within the cerebello–thalamocortical pathway of attention and executive control pathway. Nevertheless, studies on cognitive and attentional rehabilitation remain little sample size and show little significance in result [27,28].

4. Limitation and ethical considerations for BCI for stroke rehabilitation

BCIs rely on accurate detection and interpretation of neural signals, which can be affected by noise, artifacts, and individual variability in brain activity. Even small activities like eye or neck muscle activity and compensatory trunk movement interfere with EEG, which might affect the quality of Hebbian learning. In addition, stroke EEG is prone to drift at the start of training or task sessions. Recalibrations of these technologies might prolong the therapy duration [29]. On the device side, many exoskeletons or FES rigs are heavy or difficult to wear on the device side. Therefore, misalignment between human and robotic joints produces discomfort and inaccurate proprioceptive feedback that could decrease the neuroplastic advantage of closed-loop training [30]. Moreover, clinical limitations of BCI include a lack of large and well-controlled trials. To record cortical signals effectively, patients should have partially preserved sensory pathways. Thus, patients with severe proprioceptive loss or neglect may receive little benefit from the BCI system. A recognized rubric seems necessary when selecting participants. In fact, multiple factors should be considered in BCI studies, such as how gender differences affect neuronal responses. In addition, most studies were done in small samples, and robust evidence of long-term superiority of BCI treatment over conventional therapy is still absent [29,31].

Despite limitations, there are also several ethical considerations on BCIs. Since BCI record neural data that may reveal cognitive or emotional states beyond motor intention, it raises concerns about how private information is stored, used, and protected. As many stroke patients experience cognitive or communicative impairments, it is difficult to ensure patient's voluntary participation. Therefore,

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researchers must make sure their participants fully understand the risks, benefits, and long-term effects of BCI research. As patients rarely understand how BCI networks work, lack of transparency might result in unrealistic expectation. To make sure participants could stick with study, clear communication should be prioritized. Equity is another challenge. Research and patent are dominated by high-income countries, while regions with the greatest stroke burden contribute fewer studies. From 2013 to 2023, China and the United States lead in research output in EEG-BCI rehabilitation. China has shown exponential growth and over 350 articles by 2023. Other significant contributors include Germany, Italy, and Japan, while Latin America, Africa, and Southeast Asia were underrepresented due to limited funding, infrastructure, and fewer trained specialists. Technological divide in access to future neuro-rehabilitation services contributes to further disparities [31,32].

5. Conclusion and prospects

To sum up, BCI has emerged as a transformative tool in stroke rehabilitation, which offers new hope for patients with severe motor, language, and cognitive deficits. Integration of BCIs with technologies such as FES, robotics, and VR has expanded their application to limb rehabilitation, language restoration, and cognitive training. However, there are still technical barriers, such as signal noise, user variability, and device usability, which continue to limit the adoption of BCIs in clinical practice. Many current systems require complex setups that can be burdensome for both patients and clinicians. Additionally, most clinical studies to date have involved small sample sizes, and robust evidence for long-term superiority over conventional therapies is still lacking. As BCIs become increasingly integrated into healthcare systems, ethical problems such as data privacy, informed consent, and equitable access should also be addressed.

Future directions could include research on hybrid and user-friendly BCIs for utilization in home or community settings. Recent studies on hybrid BCIs combines neural signals from EEG with physiological data like EMG from muscles. These hybrid brain-muscle-machine interfaces (hBMI) have shown increased accuracy in signal acquiring, allowing for more precise control on robot devices [32]. Increasing input sources is important to provide more natural and intuitive interactions. Outside clinical settings, it is necessary to incorporate features that reduce training routines and enable remote monitoring. To make it more user-friendly, exploration on tablet-paired platforms for home-based dry-electrode systems should grab more attention. Additionally, integration of BCI with artificial intelligence (AI) might create new algorithms for stroke rehabilitation and also decreased side effects. AI's analyzing ability could optimize the signal and feedback parameters, further predict treatments outcomes and adjust rehabilitation strategies. Therefore, AI and BCI integration might offer more personalized therapy, such as cross-domain rehabilitation. Furthermore, the adaptation of invasive BCIs in stroke rehabilitation for patients with severe symptoms also requires more attention. How to reduce invasiveness of BCIs and make it more biocompatible is essential for expanding their clinical applicability.

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