Recent Advances on Brain-Computer Interface Applications and Challenges in Stroke Rehabilitation

Haoqi Wang
Collefe of Life Sciences and Engineering, South West Jiaotong University, Chengdu, China

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Abstract: Stroke is the severe diseases for patients and their families. For many patients, the post-stroke motor disability means a really tough way to go back to the normal lives and a heavy burden for the patients' families. To treat the motor disability, the main strategy for increasing the primary motor cortex's activity through both medication and physical training is active motor training. However, those patients with severe motor disability may face difficulties when doing rehabilitation training as it is more difficult to track the rehabilitation process and observe outward improvements. Nowadays, the problem could be solved step by step with the assist of Brain-Computer Interface (BCI). Through translating the brain activity into specific signals and commands that guide the external devices, BCI can enhance the process of Motor Imagery and assist patients with specific feedback. This review summarize recent advances in stroke treatment with BCI and more applications.

1 INTRODUCTION

Brain-Computer Interface (BCI) is a recently developed biotechnology that has gained attention in recent years. It serves as a communication pathway between the brain and electronic devices such as computers. BCI measures, decodes, and translates brain activity into electrical and magnetic signals, then outputs this transformed information to external machines to execute corresponding actions. Due to its ability to convert neural signals, BCI has the potential to aid in the treatment of neurological diseases. Unlike the traditional pathways for brain signal output (peripheral nerves and muscle tissues), for individuals with significant motor dysfunction, BCI can offer alternate communication channels, improving their ability to communicate with their environment. The signal acquisition unit, signal processing unit, control unit, and application unit are the four primary parts of BCI. Microelectrodes, optoprobes, and magnetoprobes are the three types of probes utilized in BCI. Based on their degree of invasiveness and signal processing synchronization, BCIs are further divided into intrusive, somewhat invasive, and noninvasive categories (Awuah et al. 2024). The invasive type is the most precise, as it directly interacts with intracortical electrodes. Consequently, invasive BCIs are currently a major focus in BCI research. However, the implantation process may cause brain tissue damage or incorrect information transmission. BCI has the remarkable potential to translate brain activity, enabling people to control external devices through their immediate thoughts. In the medical field, BCI offers significant advantages by bypassing the normal pathways of neural signal output and allowing patients with severe motor dysfunction to communicate directly with the real world (Wen et al. 2021). As a result, BCI is considered a valuable tool in assisting patients with daily communication and neurorehabilitation.

The diminution or total loss of function in one or more bodily parts is referred to as a motor disability. Many neurological diseases, such as stroke, spinal cord injury, brain injury, Parkinson's disease, and cerebral palsy, can cause motor disabilities. The most crucial strategy for treating motor impairments after neurological disorders is rehabilitation training. In physical and occupational therapy, active motor training is a popular technique for promoting motor recovery in patients by increasing primary motor cortex activity. However, active motor training may not be effective for patients with severe motor disabilities. For example, individuals with paralysis or paraplegia may not be able to benefit from

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rehabilitation training through physical and occupational therapy (Chen et al. 2023). The process of Motor Imagery alters brain neuronal connections to adapt to the physical movement information that patients rehearse in their minds. This process is known as neuroplasticity. In motor rehabilitation, BCI is essential for supporting neuroplasticity because it gives the central nervous system useful feedback. By monitoring changes in brain activity in response to a stimulus or during voluntary movement practice, it aids in directing plasticity (Chen et al. 2023). This, in turn, helps patients access their motor systems and facilitates rehabilitation across all stages of motor recovery. BCIs are currently developing in two main directions. The first is enhancing the abilities of healthy individuals by integrating AI within their brains or externally on their bodies, allowing them to perform tasks that would otherwise be impossible without BCI. The second is their application in the treatment of neurological diseases, enabling patients to regain the ability to express their thoughts like able-bodied individuals. This review primarily focuses on the application of BCI in motor rehabilitation for patients who have suffered from strokes.

2 THE SIGNIFICANCE AND CURRENT APPLICATIONS OF BRAIN-COMPUTER INTERFACE

Brain Computer interface is an emerging technique that facilitates the communication between Human Brain and Artificial Intelligence devices. The emergence of BCI has changed a large quantity of industries including entertainment, gaming, automation, education, medical field and so on (Maiseli et al. 2023). Connecting to AI through our brain means a real dramatic change in our lives. AI possesses implausibly powerful functions that never could be achieved by human beings. They contain all the knowledge that are input by people, they have the ability to study by themselves and improve their study abilities, they are also able to work as calculators to aid people shorten their time in meaningful and time-consuming things. Therefore, BCI, which is the bridge between our brain and AI, works as a built -in AI that aids our brain and enhance our abilities as a average person. The applications of Brain-Computer Interfaces can be seen in many fields. In clinical fields, BCI can treat with many neurodiseases and help those patients back to the society better. For example, post-stroke rehabilitation with BCI may help patients gain motor and sensor ability (Yang et al. 2021). However, recent advances in non-invasive and portable brain imaging techniques related to EEG, have also facilitated the development of novel applications outside the medical and scientific areas. BCI has had a try in video game fields. Many famous games have been introduced to people with BCI like “Pacman” and “World of warcraft”, people may obtain better game experience through BCI as they can enhance our specific perception (Ahn et al. 2014). Beside that, fields of biometrics Authentification and civil and military aviation fields can also be highly integrated with BCI. In Biometrics authentification field, based on the research of electroencephalography, BCI is constructed for authentification. Brain-computer interface (BCI) systems establish direct human-machine communication by circumventing traditional motor pathways. These systems rely on the extraction of distinctive neural patterns from electroencephalogram (EEG) signals instead of motor characteristics, which are subsequently classified into specific cognitive states. These states are mapped to predefined machine commands. To address inter-subject variability, the extracted neural features must exhibit cross-user generalizability. In contrast, EEG-based identity recognition systems operate under an opposing principle: their goal is to distinguish individuals even when performing identical tasks. Here, inter-individual differences in neural feature patterns become advantageous, serving as discriminative markers for personal identification (Chan et al. 2018). Nowadays, BCI do have great potential in many fields and improve our experiences in our daily lives, it has the strength to change our world in the near future.

3 RECENT ADVANCEMENTS AND APPLICATIONS OF BRAIN-COMPUTER INTERFACE IN STROKE REHABILITATION

Stroke is a quite severe neurodiseases for human beings, many patients loss their motor ability and sensory ability after stroke, which leads to unabling to connect with the society and live by the patients selves. As a result, stroke not only causes selfdisability in patients, but also imposes burdens to the patients' family. The patients family needs to pay attention to take care of the patients, it's a cost of time, money and energy. The recovery process also means a tough way as there is no fully valid way to help those patients recover through traditional rehabilitation methods. However, Brain-Computer Interface seems to have the ability to help patients to recover through connecting the motor or sensory signals with the realistic motion and feeling. In this way, patients of stroke may have the chances to recover and return to normal lives. BCI's applications after stroke focus on several aspects, such as motor rehabilitation and sensory rehabilitation according to the recovery aspects, or focus on the upper, lower limbs and the hand part according to the position that requires to be treated, non-invasive therapy and invasive therapy according to their position comparing to the brain. One of the applications of BCI in stroke rehabilitation is the combination of BCI and the exoskeletons. Individuals suffering from severe muscle paralysis or impaired motion function can realize movement through the Brain/Exoskeleton devices by transforming their thoughts in the brain into the command in the exoskeleton. The B/NE devices can trigger motor rehabilitation after repeated use over several weeks. Also, BCI could also be used to drive electric stimulator to activate peripheral muscles in the form of functional electric stimulation to help those patients gain the ability to achieve movement and recover their motor ability through constant movements controlled by the brain (Colucci et al. 2022). The BCI-FES therapy help with promoting functional recovery and purposeful plasticity by activating the body's natural input and output pathways. Therefore, the motor rehabilitation and neural reactivation are facilitated (Yang et al. 2021). BCI-VR is also an emerging technique in stroke rehabilitation, comparing to traditional rehabilitation method, BCI-VR method shows more attraction for the patients to try rehabilitation as normal method may require a lot of vigor and energy, which make it boring and fatigued for patients. With VR, patients have more motivations when doing exercises, this will shorten the rehabilitation cycle and provide more meaningful feedbacks (Wen et al. 2021). Through motor training, BCI-VR systems could track and support cortical reorganization (Bermúdez i Badia et al. 2013). The benefit also shows when VR is used as an auxiliary equipment, the treatment time and the therapeutic effect can all be improved a lot (Vourvopoulos et al. 2019). As a result, the BCI shows great potential in rehabilitation in post-stroke treatment and will be applied more widely in the future.

4 MOTOR REHABILITATION AFTER STROKE

Motor disability is a very important pattern after stroke, which means the partially or completely loss of motor function at specific parts in patients' bodies. Motor disability may cause it harder for patients to achieve movement casually according to their thoughts. Reduced muscular function, impaired motor coordination, or even paralysis can result from a motor impairment (Chen et al. 2023). In order to help individuals with motor disabilities return to their regular life, rehabilitation training is one of the most crucial treatments. The primary method for promoting motor rehabilitation in patients is active motor training. Occupational and physical therapy as well as pharmaceutical interventions are the primary training approaches (Khan et al. 2020). The basic idea behind these techniques is that they might increase primary motor cortex activation. However, those patients with severe motor disability like paralysis in limbs may face difficulties when doing rehabilitation training as It is more difficult to track the healing process and observe improvements on the outside.Facing these problems, BCI technique provides an alternative avenue for motor rehabilitation. With the ability to bypass the normal output pathway of neuro signals, BCI measures, translates and transform electromagnetic or brain activity into command that controls external devices. This process cross the normal pathway that deliver signals form brain to specific body part. Instead, BCI recognizes and translates the brain activity into specific command and instruct the external devices to operate.

In Motor rehabilitation, motor imagery is an important part that can rehearse movement in the patients' brains, which is meaningful to the neuroplasticity (Belda-Lois et al. 2011). There are two steps involved in improving neuroplasticity. The functional plasticity linked to the synaptic efficiency alterations occurs during the first phase on a time scale ranging from a few minutes to a few days. Changes in synapse strength are strongly linked to learning new abilities and creating memories (Nicoll 2017). Functional plasticity enhances learning consolidation in the latter stage through changes in brain structure. New synapses and axons may form, axons and dendrites branches will also change, these changes are long-term modifications by particular intervention (Rossini et al. 2012). BCI can stimulate neuroplasticity to improve patients' movement ability in four different mechanisms. The first is called the neurofeedback training, when the patients get visual or auditory representation that they are interested in, their brain activity will be more active, then BCI will provide meaningful feedback to central nerve in order to help neuroplasticity. The second mechanism is reinforecement-based operant conditioning, which synchronize the motor imagery and actual movement by external devices. During this mechanism, correct and successful imagery will get positive feedback and real movement in specific part while wrong trial will not get real movement, even negative feedback will be used (Remsik et al. 2018). The third mechanism is repetitive engagement. When the patients achieve movement repetitively, Repetitive activation of related stroke-affected neural circuits may improve the axon connection and its current creation, thereby curing motor impairment (Mrachacz-Kersting et al. 2021). The last mechanism is derived from the Hebbian learning principle. The synaptic strength between neurons is strengthened when they are occasionally activated. The lack of motor control after stroke cause the difference between motor intension and execution, the difference is caused by lacking in the input feedback of movement execution, which can decreases the inhibitory drive on the motor system. BCI works by providing sensory feedback after movement execution (Ang et al. 2014).

5 TECHNIQUES APPLYING IN MOTOR-REHABILITATION OF BRAIN-COMPUTER INTERFACE

The Brain-Computer Interface (BCI) functions works in motor rehabilitation mainly depend on four main components: signal reception, signal processing, generation of a specific response in a machine and providing feedback to the central nerve system to fully achieve treatment effect through the four mechanism. The signal reception means to collect brain activity into the BCI system. There are two ways: invasive and non-invasive. Invasive shows high precision but also high risk in clinical application. Cortical surface microelectrodes, cortical penetrating microelectrodes, and profoundly penetrating electrodes are invasive electrodes that record distinct aspects of the brain action potential, resulting in a more accurate outcome. The EEG and fNIRS are the primary components of the non-invasive techniques. Using many electrodes applied to the scalp, EEG captures electrical signals that show the activity of neuronal populations during a brief period of time. fNIRS tracks the hemodynamic activity of the brain by measuring variations in the intensity of near-infrared light that has passed through the scalp and brain (Jöbsis 1977). Both of them possess good non-invasive property and are portable, they can also make up each others' flaws. Therefore, combining them together is becoming a potential method. The second process contains specific techniques to filter received brain signals and explain. Filtering and explanation are done via sensorimotor rhythms, slow cortical potentials, event-related potentials, and visual evoked potentials. These filtered signals are converted into voltage/time frequencies using methods like Fourier, common spatial filter, and wavelet transform. These signals are then subjected to additional analysis using classification algorithms before being output as a specific command for the external devices (Burns et al. 2014, Cervera et al. 2018). Then about the generation of a specific response in a machine, the devices are programmed to receive command and execute functions like basic movement to help rehabilitation and improve life quality. The last part is providing feedback to the nerve system and the brain. Brain signals are converted by BCI algorithms into both devices that provide real-time feedback and control commands for external movement execution devices. The patient represents or tries to produce passive limb movement, which is carried out by an orthosis, robot, or exoskeleton arm in the BCI loop. Prior RCTs have most frequently employed this kinaesthetic form of input, sometimes in conjunction with visual feedback (Frolov et al. 2018). The functional electrical stimulation (FES) in the BCI loop is considered the most preferable in physiology. When executing FES, more motor and sensory axons are depolarized, more powerful signals from muscles spindles are delivered to the central nerve system, the pulses from the muscle spindles can activate motor neurons simultaneously with the descending cortical command when representing a movement, thus inducing Hebbian association (Fu et al. 2022). With these useful techniques, motor rehabilitation have more chances to be treated or cured.

6 CHALLENGES AND OPPORTUNITIES: THE FUTURE OF BRAIN-COMPUTER INTERFACE IN NEUROREHABILITATION

The post-stroke recovery phase has historically been separated into three categories: acute, functional or subacute, and chronic or plateau. BCI that combining with other specific techniques not only benefit subacute phase, but also benefits the chronic phase. Comparing to the traditional rehabilitation methods, the time scale of rehabilitation is small and may not that useful when facing severe patuents (Marín-Medina et al. 2024). The future of BCI devices for neurorehabilitation is “BCI+X” mode. Many BCI devices show more possibilities cooperating with other techniques. “BCI+VR” mode make it easier for patients to take treatment with more attraction as it is a fatigued and painful training, the rehabilitation cycle will be shorter and the feedback would be more meaningful. Also, interaction between human brain and external BCI would provide a better working direction towards motor rehabilitation field.

The challenges also exist in the future of application of BCI. Though BCI show its great potential and power in motor rehabilitation, the field of post-stroke cognitive and speech rehabilitation using BCI still requires more efforts as it is at the first step of research. However, this field have not got focus from the whole society. The speech and cognitive function exist positive interactions, the cognitive function also will affect the motor rehabilitation, the success in cognitive and speech rehabilitation will also have a positive effect on the motor rehabilitation. As a result, more attention should be paid to cognitive and speech rehabilitation. In the future, recognizing different aspects of rehabilitation of post-stroke as an entirety should be the definite goal to aid more patients away from the stroke and return to normal lives. Another challenge is the difference in individual’s ability to use Motor Imagery to control the non-invasive Brain-Computer Interface, some patients may still have low or unstable control quality, which leads to low motivation to participate rehabilitation. This situation requires more intelligent signal processing algorithm and more specific adaptation to different degrees of cerebral injury. Another practical issue is the patients' fatigue during therapy. One common symptom following a stroke is fatigue (Alghamdi et al. 2021). It requires focusing on the rehabilitation for such a long time that make it not that easy for patients to overcome. As a result, more rehabilitation forms like combining with AI should be presented to the patients to make them have more attention on rehabilitation. Though there are still many questions that exists in the future, it is no denying that BCI has the potential to fully cure neurodiseases like stroke.

7 CONCLUSION

This review discusses recent advances of BCI’s applications in the field of post-stroke rehabilitation, especially the motor rehabilitation and relative cutting-edge technique combined with BCI. Research shows, motor rehabilitation with BCI has a large quantity of advantages than traditional “active motor training” when treating motor disability after stroke. As an alternative avenue, BCI bypasses the normal output pathway through translating the brain activity into command and signals to guide external devices to give patients abilities to achieve movement passively. Then the BCI works to build connections in neurons again to help the motor rehabilitation. Neuroplasticity is the important parts in motor rehabilitation. BCI could stimulate neuroplasticity with four mechanisms with its specific abilities like feedback offering, external devices assistance and so on. Techniques combined with EEG, fNIRS and VR are widely used to improve the treatment effect. These breakthroughs not only deepen our understanding of motor rehabilitation mechanisms, but also provides new therapy for the personalized medicine.

Though many advancements have been achieved, BCI therapy for motor rehabilitation also faces a large quantities of problems. For invasive BCI, it means a precise detector of our brain activity but with high surgical risk and may not that suitable for many patients. For non-invasive BCI, though it means lower risk, however, it may detect imprecisely and affect the translation part and subsequent feedback part and forms wrong connections. Also, brain science is still a subject that requires more research into it. As a result, translating the brain activity may also a tough issue for BCI, simple motor rehabilitation may works, but more elaborate functions and movement that enable patients to go back to normal lives still requires more knowledge of brain science. The future research should focus on the development of safer and more economical BCI therapy for stroke patients. Exploring the combined therapy’s potential like “BCI+X” mode. Otherwise, the further study of the brain activity, further improvement of artificial intelligence and the advancement in detectors like EEG and fNIRS will also benefit the optimizing of the current therapy. In conclusion, the rapid development of the BCI therapy for the post-stroke motor rehabilitation brings new hopes for the patients. The BCI therapy is a complex therapy that contains a huge range of knowledge from different fields. With the further development of the technique and the research, BCI therapy will find a better way to cure patients with pain.

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