Exploring the Application of Brain-Computer Interface Technology in Stroke Rehabilitation

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Abstract. As a serious neurological disease, stroke can cause irreparable impact on patients' daily lives, and also cause serious damage to patients' language functions, motor functions and other neurological functions. As science and technology have advanced, so too has the possibility for using brain-computer interface technology in the field of rehabilitation. However, BCI technology still faces many challenges in clinical applications, such as low accuracy of signal acquisition, complex signal processing process, and poor portability of BCI devices. The use of BCI technology in stroke rehabilitation is supported theoretically and technically in this paper, along with suggestions for future research. It also talks about how BCI technology is currently being used in stroke rehabilitation and goes into great detail about the basic ideas, classifications, and research advances in the field of rehabilitation using BCI technology. Future research can further optimize signal processing algorithms, improve the accuracy and stability of BCI system signal acquisition, explore safer and more portable equipment designs, strengthen multidisciplinary cooperation, and promote the clinical transformation of BCI technology, which will bring new breakthroughs in the field of stroke rehabilitation.

Keywords: Brain-Computer Interface; Stroke; Rehabilitation.

1. Introduction

Illnesses of the neurological system, including Parkinson's disease, stroke, Alzheimer's disease, and others, pose a significant threat to human health and life. Neurological disorders can affect the patient's body and have a profound impact on the functioning of the patient's nervous system. The disease that results in focal or overall brain tissue injury and damages the cerebral blood vessels of the brain is the stroke of these three types of diseases: brain, which has a variety of causes. Stroke may seriously affect the patients of the nervous system, which may include the limb, the partial or even total paralysis and motor function impairment, seriously restricting the situation, which is very difficult to achieve, so the patient's own independent ability [1]. Stroke may cause speech problems in addition to dysfunction of the motor system, including decreased sense of speech and various body parts in the body, which might result in sensory impairment as well as speech impairment. Because of the way in which these dysfunctions communicate, stroke patients receive very difficult and complicated treatment and rehabilitation as well.

Treatment for Stroke has historically been based on conventional therapies, which include physical therapy with medicine as the core component of treatment, including physical therapy and medicine therapy. However, although there were many different kinds of treatments for which traditional therapies were generally based, there are typically disadvantages, and it was challenging to determine their therapeutic efficacy while treating the central nervous system.(CNS); the main focus of this is on the peripheral therapies; the most of these patients cannot return to the pre-stroke level of function because of the short time of recuperation; therefore, in the stroke patients, the motor , speech and so on are described by slow, incomplete recovery, most of which cannot return to their pre-stroke level of function [2].

Recent years have seen the development of new ideas about the treatment and rehabilitation of stroke by breakthroughs in the areas of technology and neuroscience. Brain-computer interface (BCI) technology holds great promise for stroke sufferers' recovery [2-3]. With the help of BCI, which can realize the direct communication of the brain, the brain can directly control the external equipment, so as to realize the automatic control of the body, which will realize the brain-computer interaction technology to realize the information transmission of the cerebral cortex [4]. In order to increase the therapeutic effect and give patients more interactive and interesting rehabilitation, the application of BCI to the treatment and rehabilitation process of stroke may not only help patients achieve the same therapeutic effect as the patient and, consequently, have a more stimulating, and interactive, rehabilitation experience that is more interesting to the patient than the other way of doing so.

The use of BCI technology in stroke patients' rehabilitation will be the main topic of this article. The fundamentals of BCI and its classification will be covered in this essay, along with the state of research on BCI technology in the field of rehabilitation and the more popular related technologies currently in use. And at the same time, discuss the limitations of BCIs in clinical practice research and the future outlook of BCI technology.

2. Basic Introduction to BCI

BCI is an interdisciplinary technology that combines neurology, signal detection, signal processing, and pattern recognition. Jacques Vidal proposed the concept of BCI for the first time in 1973. According to Wikipedia, BCI is "a communication system that does not depend on the normal output pathways of the nerves and muscles around the brain." BCI technology has advanced quickly in recent years, with applications ranging from initial medical rehabilitation to intelligent control, augmented reality, and other sectors [5].

It is understandable that the BCI system can replace regular peripheral nerve and muscle tissue to facilitate communication between humans and computers, as well as between individuals and their surroundings. The conversion algorithm is at the heart of BCI technology, converting the user's input electroencephalography (EEG) signal into the output control signal or command [6]. To create an appropriate signal processing and conversion algorithm that can transform the neural electrical signal into a command or operation signal that the computer can recognize in real time, fast, and accurately via the BCI system.

Signal acquisition, processing and decoding, and output are the three components that make up BCI.

Signal acquisition is the process of creating and detecting characteristic signals of brain electrical activity with specific properties, as well as describing those properties using parameters. EEG signal actually refers to the characteristic EEG signal, which means that the human brain can produce EEG signals with specified time or frequency characteristics under specific external stimuli or thinking tasks.

Two categories of BCI systems can be distinguished based on the signal acquisition of BCI technology: invasive BCI and non-invasive BCI [7]. For all forms of BCI, the exchange of information between the brain and the computer (or any other device of the BCI system) needs to be converted into data that can be processed in real time. BCI must directly or indirectly detect electrical signals generated by the brain. Most non-invasive BCI detect electrical signals generated by the brain through EEG or indirectly through functional resonance imaging, functional infrared spectroscopy and other techniques [5]. Compared with non-invasive BCI technology, invasive BCI collects relevant geoelectrical signals such as cortical electroencephalography (ECoG) directly from the cerebral cortex. The signals collected by invasive BCI are clearer, and their amplitude is higher, allowing researchers to obtain more accurate data [8]. However, invasive BCI technology is more expensive, and its security needs to be improved. From the level of equipment and experiment cost, the current brain signal acquisition technology: magnetoencephalogram >FMSI > electroencephalogram > FNIS, EEG is still an effective tool for brain science research. EEG is the most popular and extensively researched technique for acquiring brain signals because of its benefits in terms of safety, time resolution, mobility, and composition [9].

Signal processing is the transformation and analysis of an original signal. The obtained raw brain signal frequently contains noise and interference; thus, it must be pre-processed, such as filtering and independent component analysis, to improve signal quality. The pre-processed signals are then extracted to yield time-domain, frequency-domain, and time-frequency features, with the most relevant characteristics chosen to reduce computing complexity and enhance classification accuracy.

The signal decoding creates precise instructions based on the characteristic signals received after signal processing, allowing the output device to operate properly. For example, by collecting and analyzing language-related brain impulses from the patient's cerebral cortex, the letter or word reflecting the patient's desire is immediately produced, allowing the patient and the outside world to communicate directly. Signal processing and decoding are critical components of the BCI system because they act as an intermediary between signal input and signal output. The BCI system's performance and user experience can be considerably enhanced by continuously optimizing signal processing and decoding algorithms, in conjunction with individualized models and multimodal fusion technologies.

3. Current Research Status and Widely Used Technologies

The current study of BCI has brought about a lot of amazing innovations, which have great potential to support motor rehabilitation in stroke patients. Research has shown that brain plasticity can be successfully increased, and motor function can be improved by BCI systems, especially those that combine EEG signals.

Tang et al. (2021) evaluated the effect of BCI-controlled functional electrical stimulation (FES) on the recovery of upper limb dysfunction in stroke patients [10]. The experiment's 34 stroke patients were split into two groups: one receiving conventional FES treatment and the other receiving BCI-controlled FES. The patients' upper limb motor function and activities of daily existence were assessed using the FMA-UE (Fugl-Meyer Upper Limb Motor Function Assessment Scale) and MBI (Modified Barthel Index). The results showed that the elbow reaction time of both groups of patients was effectively improved, and when compared to the control group, the experimental group's FMA-UE and MBI scores showed a substantial improvement. This study shows that BCI-controlled FES has a more obvious rehabilitation effect on upper limb dysfunction in stroke patients and a better recovery effect.

Peng et al. (2022) evaluated the efficacy and safety of BCI in treating upper limb dysfunction after stroke in recent years [11]. The study referred to 16 previous randomized controlled trials (RCTs). The results showed that BCI combined therapy had a statistically significant improvement in upper limb function and could improve the self-care ability of stroke patients. Among them, FMA was utilized in 15 trials to assess the impact of BCI as an intervention for stroke-related upper limb impairment. The final results showed that BCI treatment had a significant effect on the improvement of upper limb function after stroke, and there was no significant heterogeneity. After a stroke, upper limb dysfunction can be improved and daily life quality increased with BCI treatment or BCI in combination with other therapies. The recovery effect is best when the intervention time is 4 weeks.e quality of daily life. The recovery effect was best with an intervention duration of 4 weeks.

Guo et al. (2022) proposed a BCI-controlled soft robotic glove based on steady-state visual evoked potential (SSVEP) [4]. The glove consists of flexible joint actuators and rigid bone components, which can help stroke patients achieve hand function rehabilitation. During the experiment, the researchers randomly assigned 30 stroke patients to a robot treatment group, a control group that received treatment using traditional techniques, and a BCI-robot treatment group. Dual-stimulation SSVEP at 12 Hz and 15 Hz was employed by the BCI system in the experiment, and EEG data were collected using an Emotiv EPOC device with a sampling rate of 128 Hz. In the final clinical evaluation, the robot group received a lower score than the BCI-robot therapy group. and the control group in the Fugl-Meyer Upper Limb Motor Assessment (FMA-UL) and the Wolf Motor Function Test (WMFT). The experimental results showed that technology has a significant effect on the rehabilitation of hand function after stroke, demonstrating the ability of BCI technology to promote motor recovery and neural plasticity.

Ji et al. (2022) suggested a FES-based exoskeleton trajectory adaptive walking aid technique [12]. This technique can assist stroke patients in regaining their natural gait by automatically adjusting the electrical stimulation's output current intensity based on the joint angle trajectory error while walking. The exoskeleton hardware platform has adjustable-length hip, knee, and ankle joint devices to meet the different needs of different patients. At the same time, the exoskeleton hardware platform also integrates a small four-channel FES device for electrical stimulation assistance to patients. The electrical system has a graphical user interface (GUI) for device calibration and control, and it consists of a foot module, a hip module, a knee joint module, and a backpack module. The final experimental findings demonstrated that when the experimental group was walking with the assistance of electrical stimulation, the mean correlation coefficient between natural gait and knee angle was 0.78±0.1164, which was 0.13 higher than that of the control group without electrical stimulation. The range of motion of the knee joint in the experimental group increased by an average of 9.18°, the maximum knee angle increased by an average of 4.69°, and the minimum knee angle decreased by an average of 2.80°. The results show that electrical stimulation-assisted walking can effectively promote the recovery of the natural gait of stroke patients.

Liao et al. (2023) studied the effectiveness of motor imagery BCI (MI-BCI) combined with physical therapy on upper limb performance and brain activity in stroke patients [13]. 40 patients with ischemic stroke and upper limb motor impairment were split equally between a MI group and a control group for the investigation. The MI group received MI-BCI rehabilitation treatment, while the control group received conventional rehabilitation treatment. The final experimental results showed that the Fugl-Meyer Motor Assessment (FMA), Movement Assessment Scale (MAS), and non-contrast CT (NCCT) scores of the MI group were significantly higher than those of the control group receiving conventional rehabilitation treatment. This study shows that the combination of the MI-BCI system and FES can significantly improve the upper limb performance and brain activity of stroke patients andencourage stroke patients' recovery of upper limb motor function.

Current research on brain-computer interfaces has resulted in numerous innovations with significant potential for motor rehabilitation in stroke patients, which can effectively improve upper or lower limb dysfunction and boost motor function and daily quality of life recovery.

4. Limitations and Future Prospects of BCI

At present, research on invasive and non-invasive BCIT in rehabilitation assistance and training has made breakthrough progress, demonstrating great potential and addressing the shortcomings of traditional medical treatment methods. Still in the experimental application stage, existing BCIT rehabilitation systems are far from being used in a practical or commercial setting. There are several obstacles in clinical translation, including the development of fully implantable and wireless transmission devices, the power consumption and data storage of signal acquisition chips, as well as the lifespan and stability of signals, among many other issues and challenges. There is a lack of universal standards for BCI rehabilitation. For non-invasive brain-computer interface technologies (such as EEG-based BCI), they usually face the problem of low signal-to-noise ratio and are easily affected by electromyographic activity and environmental noise. Moreover, the bandwidth and information transmission rate of non-invasive brain-computer interface technologies are limited, which restricts the amount of information they can transmit. This limits the complexity of tasks they can effectively control and the accuracy and reliability of signal decoding. Although invasive BCI can provide higher-resolution signals, they carry the risks of surgical implantation, such as infection and tissue damage [8], which limit their wide application in clinical practice.

The future development of brain-computer interfaces still needs to focus on improving signal processing and decoding algorithms to enhance the accuracy and robustness of BCI systems and reduce the need for extensive calibration. At the same time, efforts should be made to promote the development and research of hardware such as chips and wearable devices to improve the practicality and comfort of BCI systems in clinical use [14].

Brain-computer interfaces are predicted to offer groundbreaking diagnostic and therapeutic solutions with increased interdisciplinary collaboration and technical developments, greatly enhancing patients' quality of life.However, the development of brain-computer interface technology must be approachedwith prudence and accountability, making certain that the interests of the patient come first, enhancing public awareness and understanding of BCI technology, and promoting collaboration among researchers, clinicians, and patients to advance BCI research and application.

It is anticipated that BCI technology will make major strides by tackling these issues and moving the previously listed research avenues, giving patients with neurological conditions fresh hope and expanding neurotechnology as a whole.

5. Conclusion

This article discusses the application prospects of stroke rehabilitation in depth. Traditional rehabilitation methods have a certain role in helping patients recover, but there are still some difficult problems to solve, such as slow recovery of patients and unsatisfactory recovery effects.The quick advancement of BCI technology in recent years has given stroke rehabilitation new hope.This article introduces the basic principles and classification of BCI technology, including key links such as signal acquisition, processing, and decoding, and analyzes its research status and application progress in the field of stroke rehabilitation.

BCI technology provides a new, more interactive, and interesting rehabilitation method for stroke rehabilitation that can stimulate patients' enthusiasm for rehabilitation and improve rehabilitation effects. By optimizing the combination of BCI technology and traditional rehabilitation methods, more efficient and personalized solutions are provided for future rehabilitation treatment. Whether it is the accuracy of signal processing, the safety of equipment, or the standardization of clinical application, BCI technology still has limitations. For example, the signal-to-noise ratio of non-invasive BCI technology is relatively low, while non-invasive BCI faces problems such as surgical risks and signal stability. At present, there is a lack of unified standards for BCI rehabilitation standards, which limits its clinical promotion.

Future studies should concentrate on increasing the accuracy of signal processing and stability of the BCI system, developing safer and more portable hardware equipment, and establishing unified clinical application standards to promote the clinical transformation of BCI technology, thereby bringing new breakthroughs in the field of stroke recovery. Further exploration of the application potential of BCI technology in other neurological diseases will also provide patients with a new way to improve their quality of life.

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