Case Analysis on Three Methods of BCI Systems for Stroke Rehabilitation

Jinshuo Wang*
School of Information and Electronics, Beijing Institute of Technology, Beijing, China
*Corresponding author: 1120211609@bit.edu.cn

Abstract. Stroke is a disease that can cause disability to patients, and many people suffer from stroke. Brain-computer interface (BCI) technology development leads to BCI stroke rehabilitation system. After several years of development of theory and technology, BCI systems show great potential in stroke rehabilitation. There are three specific methods of BCI stroke rehabilitation systems. The methods involve Functional Electric Stimulation, Robotics Assisted Systems, and Virtual Reality. This paper will introduce three methods and analyze the research cases of each technique. The article will introduce the principle and investigate some research cases of each method. The paper will present the procedure, analyze the results and evaluate each experiment. By analyzing the cases, it can be learned that all three methods are feasible and effective, proving that the BCI system for stroke rehabilitation is a promising therapy. At last, limitations on BCI systems will be analyzed, such as small sample size and limitations on particular actions.

Keywords: BCI; Stroke rehabilitation; FES; RAS; VR.

1. Introduction

Stroke is a medical disorder that manifests as a damaged cortex or a broken motor connection between the brain and limbs after an abrupt interruption of blood flow to a portion of the brain. So, stroke can cause damage to the patient’s motor function, which causes disability to stroke patients. The third most common reason for impairment is stroke. [1] There have been more than 13 million stroke patients in China, and by 2030, there may be more than 30 million, which imposes a significant burden on patients and their families. Traditionally, physical therapy or occupational therapy were conventional therapies for stroke rehabilitation.

Electroencephalogram (EEG)-measurable brain impulses can be acquired by a computer-based device called BCI, which converts them into commands, too. [2] The development of BCI leads to a relatively new therapy, which shows better effectiveness than conventional therapy. When people are thinking or imaging, the EEG acquisition device can acquire brain signals with the help of BCI technology. One kind of received EEG signal is motor imagery (MI). When people imagine executing tasks, MI will generate. As the research shows, when in the task movement execution or the task movement imagination, MI possesses the same motor area activation.[3] So researchers can use MI to study the brain signals related to movement, whether the subject is a patient or a healthy person. Though disrupted motor connection between the brain and limbs, the researchers can also get accurate MI to learn what the patients want to do.

According to Hebbian theory, cells that fire together wire together, promoting the nervous system's plasticity is beneficial to stroke rehabilitation.[4] Plastic changes can lead to improvements in motor control. Muti-sensory feedback is vital to plastic changes. So, close-loop feedback is more critical for BCI system. There are three methods to provide muti-sensory feedback:

1. Functional Electric Stimulation (FES):
In the BCI-FES system, BCI system and FES device are coupled. The FES device will stimulate the affected area to make the affected limb move. It will give visual and tactile feedback.

2. Robotics Assisted Systems (RAS):
In the BCI-RAS system, a robot will help the patient execute the task that the patient wants to do. It will also provide visual and tactile feedback.

3. Virtual Reality (VR)
In the BCI-VR system, the patient is provided with a virtual environment. The patient images task execution which is related to the virtual environment. The model in the environment will act according to MI. The feedback will be holistic as there are many kinds of feedback, including visual feedback, auditory feedback. Generally, BCI-VR system is often combined with FES or RAS, as FES and RAS can provide more feedback types, strengthening the motor function. No matter which method, the procedure is similar. Figure 1 provides a visualization of the procedure.

![Fig. 1 The procedure of BCI stroke rehabilitation systems](image)

In the following parts, to demonstrate the effectiveness and feasibility of the three methods, the paper will introduce the principle and analyze some research cases of each method. When analyzing every case, the paper will describe the experiment procedure and result and evaluate the experiment. As to the evaluation of experiments, there are test scores, such as Action Research Arm Test (ARAT), 9-Hole Peg Test(9-TP), and Fugl-Meyer Assessment (FMA). Besides, the rehabilitation effect can be judged by patients' motor control after the treatment.

2. BCI-FES System

Stroke neural damage typically disrupts the activation of various body parts' muscles. Therefore, an efficient "Functional Electrical Stimulation" technology has been adopted to restore muscle activity. FES offers a non-invasive strategy to reconnect motor pathways by stimulating muscle in the affected limb. According to research, in several clinical settings, FES has been used to recover walking, standing, arm moving, and other post-stroke rehabilitation skills. To recover the injured limb better with the help of FES, many critical factors, including dosage and therapy onset time, must be considered.

According to Hebb's principle, coupling peripheral and cortical activities could reinforce and repair defective motor performance. It would be useful to combine FES systems with other systems in charge of receiving cerebral activities to improve FES device’s efficacy. In order to record the brain signals brought by the imagination of the planned movement, BCI devices are employed in this context. The following three cases will be used to analyze the effectiveness and feasibility of the BCI-FES system.
2.1. The first research case

In this experiment, the researchers designed a BCI-FES rehabilitation system, including an EEG acquisition device using the BCI technology and FES device. Four subjects participated in the experiment, including two healthy subjects and two stroke patients.

Before the treatment, all the subjects need to take an off-line training. In the off-line training, the subjects were required to implement the relax state and imagery task switched in turn. After receiving the EEG data, the researchers will set the decision value to determine whether the subject is relaxed or motor-imaging. In the rehabilitation treatment, the BCI device can infer the motor intention of the subject by decision value. After receiving the command, the FES device will stimulate the targeted area.

In this study, there are two kinds of results. The first one is the classification accuracy rate. The second one is the event-related desynchronization (ERD) phenomenon. The high classification accuracy means that the BCI-FES system has a vast potential to restore impaired motor function, as accurate classification of motor intention is fundamental for stroke rehabilitation. Additionally, regarding the categorization accuracy rate, healthy individuals and stroke patients do not significantly differ from one another. The spectrogram time-frequency distribution of motor-related cortex analyzes the EEG phenomenon. By comparing the spectrogram of the same patient before and after the treatment, it can be learned that a stroke patient's ERD phenomenon is significantly enhanced. It proves that the BCI-FES system can lead to a favorable impact on recovery in motor performance. This experiment demonstrates the great potential of the BCI-FES system in stroke rehabilitation.[5]

2.2. The second research case

In this research, to demonstrate that BCI-mediated neurofeedback mechanisms can promote neuroplasticity, there were two groups with various input signals and feedback: the control group (EEG-based BCI) and the experiment group (Hybrid BCI). In the control group, EEG signals were collected. Visual realistic hands showed on the screen. When the subject controlled his/her hands to move, the visually realistic hands will move following his/her idea. It seemed that the subject successfully controlled the movement of his/her hands. Thus, the visual illusion of hand movement was the feedback. In the experiment group, visual realistic hands and motor imagery were similar. The brain signal collected was EEG and electromyogram (EMG). After collecting the brain signal, the device will deal with the EMG and EEG signals separately and fuse the EMG and EEG data. Then the fusion signal will manage the FES Controller, and the stimulation from the FES device that helps the patients exercise their muscles properly will be given to them. Thus, the affected hand's actual movement served as feedback.

After the treatment, researchers got the value of arm section of the Medical Research Council Scale (MRC), European Stroke Scale (ESS), and arm Fugl-Meyer scale (FM) in the control group and the experiment group. Figure 2 provides a visualization of the result. It can be inferred that hybrid BCI system is better than pure EEG-based BCI system in terms of clinical results. Hence, BCI-FES system for stroke rehabilitation is promising.[6]
2.3. The third research case

This study introduces the RecoveriX stroke rehabilitation system that utilizes the BCI technology and FES device.

The design of RecoveriX system is similar to other BCI-FES systems. There were only two subjects who were stroke patients participating in the experiment. The procedure of the treatment is as follows. There were several trials in one session. In every trial, the movement task will appear on the screen. Then the patient imaged hand-moving. The BCI device will process the MI, and the FES device will provide proper stimulation. Hence, close-loop feedback is realized.

After the treatment, the motor function of each patient has been recovered. For the first patient, his limitation of hand movement wasn't very significant, so the researchers attempted the 9-Hole Peg Test (9-HPT). The outcomes demonstrate that the patient accomplished the task effectively, and the time to complete the task is shorter and shorter. For the second patient, as her hand movement impairment was too severe, the researchers did not attempt 9-HPT. However, evidence shows the patient regained limited hand control after the treatment.

The clinical results show that the BCI-FES system is an excellent therapy for stroke rehabilitation. Nevertheless, given the small number of experimental samples, it is difficult to determine whether the BCI-FES system is a reliable therapy.

Additionally, RecoveriX is a company developing a kind of BCI-FES system, RecoveriX system, for stroke rehabilitation. It demonstrates the technology's viability that a company is working to develop it. [7]

3. BCI-RAS System

Unlike the BCI-FES system, the BCI-RAS system utilizes robots to help move the patient's affected limb. There are many kinds of robotics modes, such as passive and active-assistive. In passive mode, the patient does not move at all; instead, a robot controls every aspect of the paretic limb's mobility. When working in assistive mode, the robot helps the patient move the wounded limb appropriately by guiding their motions. The robots measure the patient's motions and modify their activities based on various control parameters. The main goal of the BCI-RAS system is to recover damaged limb motions by providing sensorimotor feedback. The following three cases will be used to analyze the viability and efficiency of the BCI-RAS system.
3.1. The first research case

The research introduces a BCI-RAS system for stroke rehabilitation. According to Hebbian Rule, the study designed a framework to increase cortical plasticity. The rehabilitation system is to help patients move their arms.

The rehabilitation setup is as follows: Firstly, to decide among the patient's movement intents, such as resting and extending, the system has to collect and pre-process brain signals and continuously update the movement intention categorization online. Then is the haptic feedback, which will bring improved performance. At last, it comes to treatment strategy. The rehabilitation session was divided into parts. A part was a group of trials that were separated from one another by a brief pause. The patient tried to move the forearm or imaged forearm-moving in each trial.

After the treatment, this study discussed the power spectra of two electrodes. It compares the spatial and spectral distribution of classifier weights throughout the treatment in various modes in healthy participants. The results demonstrate synchronization between the patient's desire and the movement of the robot controlling the patient's injured limb. Due to Hebbian theory, this synchronization will likely improve cortical plasticity. By evaluating the experiment, the BCI-RAS system can lead to an improvement in functional recovery.[8]

3.2. The second research case

The project’s objective is to examine the viability as well as effectiveness of BCI-RAS systems for stroke rehabilitation. Seventy-four patients participated in the project. They are all stroke patients and have their hands affected. Before the treatment, patients’ movement was estimated using FMMA and ARAT. The targeted area of the study is hand-grasping and hand-pinching.

Randomly, they were split into the BCI group and the control group. Patients in the BCI group received training using a robotic arm that can help the individual open his or her injured hand and is controlled by a BCI. On the contrary, the subjects in the control group were trained with only a robotic arm, without linking to the patient’s brain signal.

After the treatment, patients’ movement was estimated using FMMA and ARAT. By comparing the FMMA and ARAT of the patients before and after treatment, it can be known that the FMMA and ARAT scores rose in each group. However, the scores of the BCI group increased more. The positive results showed that the hand performance of the subjects in both groups had been improved. At the same time, the BCI-RAS system is proved to help improve hand function recovery more effectively. The positive results demonstrate the BCI-RAS system feasible.

In this study, fatigue is the most common adverse event, which must be taken seriously.[9]

3.3. The third research case

This study investigates the ability of the BCI-RAS system for stroke rehabilitation. Furthermore, the effectiveness of motor improvements on the upper limb that suffered a stroke utilizing the BCI-RAS system is also evaluated compared to traditional rehabilitation therapy. There were 2 phases in the study: the first was testing the capacity to use an EEG-based BCI device, and the second was estimating the efficacy in motor improvement. In the first phase, EEG signals were collected. After processing the EEG signals, it can be found that most stroke patients can use EEG-based BCI devices well, and there isn't a correlation between the capacity to use an EEG-based BCI device and the FMA of the patient. In the second phase, they were divided into two groups randomly: the BCI group and the control group. The experiment content of each group is similar to the second case. After the treatment, the gains in FMA scores show whether the BCI-RAS system or conventional therapy can improve motor function.

The results of the 2 phases demonstrate that the BCI-RAS system for stroke rehabilitation is suitable for most patients, and the BCI-RAS system can restore motor function.[10]
4. BCI-VR System

Stroke patients can restore their impaired limbs better in a realistic and motivating environment. To provide a more realistic environment, VR technology was introduced to stroke rehabilitation. VR can provide auditory, visual, and even haptic feedback for patients. In the virtual environment created by VR technology, the patient's motivation gets boosted, which benefits stroke recovery. Additionally, a realistic environment can stimulate real-world activities, which is impossible in other rehabilitation therapies. To improve the effectiveness of rehabilitative therapy, the BCI-VR system is often combined with the BCI-FES system or BCI-RAS system, as the combination can create a more realistic environment.

Compared with the BCI-FES system and BCI-RAS system, BCI-VR system is a relatively new technology. The following two cases will be used to analyze the viability and efficiency of the BCI-VR system.

4.1. The first research case

The study designed a BCI-VR system for stroke rehabilitation. There are three parts in the system, and the process is as follows: collecting of EEG signals, triggering control commands, and control of the movement of the virtual model.

The design of VR is crucial for stroke rehabilitation. The better the VR system, the more the patient focuses on it. The design comprises three parts: virtual training environment, user interface, and feedback.

The study designed VR scenes, virtual models, and animations for the virtual training environment. There are six training scenes and nine actions in the VR system. The subject can select training scenes and actions in the user interface. After the treatment, the number of successes will show on the user interface so that the researchers can get the result immediately. The design of feedback is vital, too. If the subject feels more realistic, he/she will concentrate more on motor imagery, which is more beneficial to stroke rehabilitation. In this study, the BCI-VR system will provide auditory, visual, and haptic feedback. The movement of the virtual model that was displayed on the screen gave patients visible feedback. Auditory feedback is provided by the display on the screen. The FES device provides haptic feedback.

The subjects of this study were all healthy. The subjects were required to complete all the training actions. At the same time, they were required to complete the actions in two cases: the screen showed the visual feedback or the screen showed nothing, which can compare the correct rate of BCI-VR system for stroke rehabilitation and conventional therapy.

After the treatment, the result shows that the subjects performed better when provided visual feedback from the screen. Under visual feedback, most individuals improved their accuracy in motor imaging. Additionally, the more complex the action is, the higher the correct rate the subjects got.

The findings demonstrate that the BCI-VR system can aid stroke therapy. At the time, the more realistic the VR system, the better the rehabilitation effect.[11]

4.2. The second research case

This study proves that the BCI-VR system for stroke rehabilitation is more effective than conventional therapy combined with VR technology.

The BCI-VR system consists of an EEG device, a motion tracking device (MTD), and a VR game. MTD monitors the patient's motion and records the motion data. As mentioned earlier, EEG devices record and processed the signals. After receiving the MTD and EEG device data, the VR game will run according to the patient's thoughts and motor. In the VR game, the subject need to finish the task with the help of the patient’s mind and wrist motion.

There were 12 subjects in this study. They were divided into three groups (A, B, and C). The study’s control group is Group A, which used the conventional rehabilitation therapy. The subjects in Group B were treated with VR games and MTD devices. The subjects in Group C were treated
with VR games, EEG devices, and MTD devices. Before the treatment, the researchers evaluated every subject’s Fugl-Meyer Upper Extremity Assessment (FMA-UE), as it will be a crucial metric for assessing the efficacy of the rehabilitation.

After the treatment, the FMA-UE of the subjects in each group were tested again. Comparing FMA-UE scores before the treatment and after the treatment shows that the patients trained by the BCI-VR system got more rehabilitation effectiveness. It proves that the BCI-VR system for stroke rehabilitation is effective.[12]

5. Conclusion

The paper introduces 3 methods of BCI systems for stroke rehabilitation. The paper introduces the principle and analyzes some research cases on each method. The studies show that signal classification accuracy is high, and most patients can manipulate the BCI device well. These positive facts, the accuracy of signal classification and the capacity to perform the BCI device, are vital to completing the rehabilitation treatment. The clinical results prove that every stroke rehabilitation system can effectively strengthen the patient's motor function. Compared with conventional therapies for stroke rehabilitation, BCI systems can get more positive effectiveness on motor recovery. So, BCI systems for stroke rehabilitation combined with FES, RAS, or VR is a promising therapy for restoring impaired motor function.

Though there are not much studies on which method of BCI system can get the best effectiveness on motor recovery, we can learn that the BCI-VR system can lead to more concentration on task execution as the virtual environment is more realistic. It can be learned that the effectiveness of the BCI-VR system is better than that of the BCI-FES system by the first case introduced in the third part. At the same degree, subjects participating in the BCI-VR system feel more enjoyable and exciting. To some degree, the BCI-VR system is better than the other.

The paper shows that when in stroke rehabilitation, two different methods can be combined. BCI-VR system combined with FES or RAS can provide more kinds of feedback so that the patients can focus more on the tasks, which is vital to motor recovery.

However, there are also limitations to the three methods. Firstly, rehabilitation is limited to particular actions, but the goal is to restore the motor function completely. Secondly, the number of sample sizes is small. Even in some research, all the subjects are healthy people. It's challenging to consider the three methods of BCI stroke rehabilitation systems reliable. Thirdly, the effectiveness of stroke rehabilitation is limited. Especially for severe stroke conditions, the patient can only execute limited movement tasks after the treatment.

References


