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Brain-Computer Interfaces in Robotic Arm for Motor Rehabilitation after Stroke

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Abstract:

Stroke is a common disease that can cause injury to humankind's neuron systems all over the world. To help these patients with their motor rehabilitation, applying Brain-Computer interface (BCI) technology has recently become a popular approach. One innovative method of using BCI technology to help patients regain motor ability is to develop a BCIs-controlled external robotic arm system. This paper aims to summarize some of the research focusing on this field, analyze their outstanding points and drawbacks, and provide several ways to improve this system. First, the author gives a brief introduction of BCIs controlled external robotic arm. After that, the author analyzes several advantages and disadvantages of this system and then gives some potential solutions, the fNIRS-EEG BCI and three implanting methods. Finally, the author discusses these previous studies and provides some potential future directions in advancing the BCIs-controlled external robotic arm system. In this review, the author mainly focuses on some previous approaches based on research and studies. By stressing the drawbacks and difficulties of each technique, the author comes up with other methods related to these latest studies. After that, the author combines these points together and reaches some new potential directions. The research contained in this review covers the past five years, from 2018 to 2023.

Keywords: Stroke; Brain-Computer Interfaces; fNIRS-EEG, Robotic arm

1. Introduction

A typical characteristic of stroke is the acute focal injury to the Central Nervous System (CNS) caused by neurological deficits, which leads to serious symptoms including cerebral infarction, intracerebral cerebral infarction, intracerebral hemorrhage (ICH), and subarachnoid hemorrhage (SAH), claiming people's life [1]. More than half of the patients around age 65 and over suffer from long-lasting reduction of mobility after stroke [2]. Some previous studies have found that recovery after stroke can be gradually difficult and become stable eventually because of the loss of neuroplasticity in the brain of patients [3]. Thus, it is unfortunate for these patients to lose the capacity to use their arms, legs, and even their faces.

Brain-computer interface (BCI) technology provides a pathway for the brain to communicate with computers through electrical signals. It is one innovative method to help patients with motor rehabilitation after a stroke. In recent studies, researchers have developed several creative ways to help patients with their recovery, such as the BCI-controlled robotic arm. In the experiment, the patients who are equipped with BCI techniques show a strong possibility of re-manipulating the things around them as they have not experienced a stroke before [4]. This kind of solution, including the robotic arm and other ways like that, provides the medical field with a new possible way to cure stroke patients.

However, these previous studies have encountered several challenging difficulties. To be specific, while applying the BCI technology, one obstacle is the accuracy in tracking and collecting useful signals generated from the brain in the Non-invasive method. The delay and errors in tests between experimenters and equipment can result in the limitation of the usage scope of this technique [5], making it hard to be promoted in the future. Another difficulty in the utilization of BCIs technology is the disadvantages of Invasive method. For long-term studies, many of them are limited by the Invasive method because of the immune response and electrode movement [6]. In a word, the use of BCIs technology still await to be improved.

To tackle these issues, this review has searched the literatures and studies in the BCIs field from recent years. With the summary of several challenging problems from previous studies, this article aims to figure out some of them and provide some innovative contributions to this field according to some new technology created by other scientists in recent years. For instance, in one study, functional near-infrared spectroscopy (fNIRS) has been proven to possess a huge potential for its ability to monitor the motor and cognitive functioning of patients over time [7]. This provides the Non-Invasive method with a new way to track and collect the signals from the brain more precisely. Another study focused on the Invasive method, comparing three different methods to better implant the Electroencephalography (EEG) electrodes for long-term experiments with less influence on the experimenters. According to this study, these methods provided high-quality EEG mechanical stability and lower chewing artifacts with an easier way to implant or remove the electrodes from the brain [8]. This introduces new accesses for the Invasive BCI devices to gain more high-quality data from the brains of patients, thus creating an avenue for better applying the BCI technology to help motor rehabilitation.

In this review, Ünal Hayta et al. built a 6 Degrees of Freedom industrial robotic arm with a lower error rate [9]. Agatha Lenartowicz and Sandra K. Loo developed the fNIRS-EEG BCIs [10]. Jasper et al. used the fNIRS-EEG BCIs to treat the ADHD [11]. Philippe Pouliot et al. analyzed the fMRIS-EEG system and the fNIRS-EEG system [12] and successfully achieved a long-lasting tracking method based on the work done by Gallagher et al. and Nguyen et al. [13]. However, the nonlinear graph cannot be well understood now, which means further studies are needed in the future. Benovitski et al. discussed three kinds of implanting strategies [8], including the use of different types of electrodes in the shape of disk, ring, and peg, which provides the world with a better pathway to implant electrodes in the brain for a long period.

The literature search in this essay revealed the different methods of BCIs technology harnessed in motor rehabilitation. In the past five years, numerous new articles and new methods have been published in the BCI field. Yet, there are still many points for BCIs technology used in motor rehabilitation after stroke that are waiting to be advanced in contemporary study. Therefore, in this review, we search different categories of articles around several techniques of BCI technology presented in conference proceedings, journals, and patents, which are divided into two different categories: (1) External Robotic Arm and (2) fNIRS-EEG BCIs technique. We analyze the contributions from different studies, the technical restrictions, and the future directions in each of them. We hope that this review can create our benefits to the researchers in BCI field matter for the (1) improvements of the accuracy of Non-Invasive methods, or the (2) better utilization of Invasive electrodes in BCIs technology.

2. External Robotic Arm Controlled by BCIs

Stroke can lead to several serious symptoms, one of which is the loss of motor ability [14]. Patients may suffer from disorders of being unable to move their bodies, including their facial muscles, arms, legs, etc., because of the injury in their neuron system [1]. One approach to help patients regain their motor ability is to construct an external robotic arms system controlled by their brain [15].

2.1 External Robotic Arm System

External Robotic Arm Systems can be an extra part of human beings' bodies via some technical assistance. This robotic system usually includes two main sections: the machine and the user.

As for the section of machines, in order to reach the point that enables users to interact with the surroundings, machines in this system are usually designed in the shape of creatures' bodies, such as hands, arms, legs, and so on. In the Robotic Arm System, machines are designed in the shape of arms, like the machine in Figure 1, which can enable the user to interact with objects in the surroundings by appropriately manipulating the machine. By using this system, the user can grab objects without using their arms, and they can also use other tools such as the pen, the stick, and other things like that with these things held in the robotic arms.

Fig. 1 External 6-degree freedom industrial robot arm [9]

In terms of the section of users, the objective categories of users can be broad. No matter which kinds of creatures they are, if they can be trained to correctly manipulate the robotic arm system, then they are the potential users of this system. To be specific, human beings can utilize this system; however, in some previous experiments, researchers have proved that some animals, such as monkeys, could harness this system after training, too [16]. In that case, it not only provides scientists with a new approach but also evokes them with the variability of the selection in creatures' species that can be used in experiments.

The External Robotic Arm System has shown its feasibility in interacting with reality. For example, in a study, the user could control the robotic arm to grab a cup of coffee and put the cup back on the desk after drinking. In another study, even a monkey could attain bananas to eat by using the robotic arm instead of their hands. Thus, according to the achievements created by previous studies, it is reasonable for human beings to apply the External Robotic Arm System to help patients who lose their motor ability due to some diseases like stroke with their motor rehabilitation.

2.2 Typical Brain-Computer Interfaces System

When it comes to the control system that can be applied in the External Robotic Arm System, the BCIs technology is one of the practical connections between the machine and the user. BCIs provides the user a pathway to interact with the computer through the electrical signals generated from users' brain [17]. By precisely collecting the signals from the cortex and rapidly processing them, BCIs technology can have the ability to initially translate the neuron signals into electronic information, which machines can identify. Then, after receiving these electronic messages, the robotic system can output the movements that are created from the brains of users.

BCIs system contains several parts, including the Signal Acquisition, the Signal Pre-processing, the Feature Extraction, the Classification and the Application Interface and Control. The diagram referred to as Figure 2 illustrates a hybrid system that combines functional near-infrared spectroscopy (fNIRS) with electroencephalography (EEG) to capture brain activity [7]. Initially, these devices collect and amplify brain signals, which are then subjected to filtering and pre-processing to eliminate noise and enhance signal quality. The next step involves extracting specific features from these processed signals, such as signal peak, slope, mean, kurtosis, skewness, and power spectrum density. These extracted features are then input into a classifier, which categorizes the signals. In the final stage, these classified signals are sent to a computer or other devices to create control commands for external hardware like exoskeletons, prostheses, wheelchairs, and neuro-interfaces for attention control. The feedback loop in a BCI system can be realized in various forms: it can be abstract, like a moving bar on a screen; embodied, as in virtual reality (VR) depiction of controlled activities; or through somatosensory feedback using haptic interfaces, robotics, or neuromuscular electrical stimulation (NMES) systems [18].

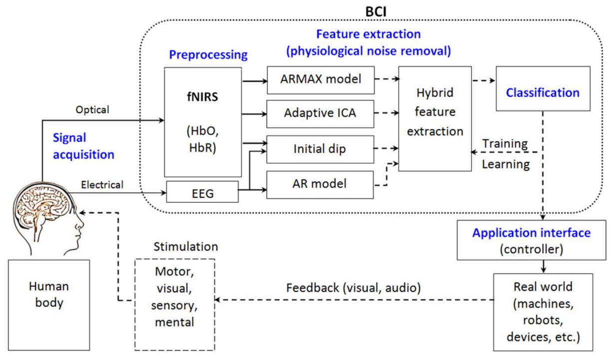

Fig. 2 Schematic of a hybrid fNIRS-EEG BCI [17]

The typical BCIs system above provides a possibility for controlling the Robotic Arm System by users' brain. However, while utilizing the BCIs system, speed, accuracy, ease of use and length of training period are some key points that need to be further considered [7]. Otherwise, it may reduce the quality of the movements output by the robotic arm, such as performing wrong gestures or movements and failing to output the correct signals.

2.3 Brain-Computer Interfaces in Controlling the External Robotic Arm

Benefiting from this powerful tool, the BCIs technology, building up a connection between the robotic arm and the user's brain has become the reality. Applying this technology allows scientists to form an intangible bond, the non-invasive BCIs, or a tangible bond, the invasive BCIs, in this creature-robotic system. Both of these provide human beings with new approaches to motor rehabilitation for patients.

Many previous studies have designed their own BCIs controlled robotic arm system and applied the system in their experiments for testing and data. For example, Sharlene et al. designed a bidirectional BCI to record neural activity from the motor cortex [5]. In their study, this bidirectional BCI contained two microelectrode arrays with 88 wired electrodes, which were implanted in the hand and arm zone of the motor cortex correspondingly in a 28-year-old male participant who had tetraplegia because of a C5 motor/C6 sensory ASIA B spinal cord injury. By using this bidirectional BCI to record neural activity from the cortex, they successfully evoked tactile sensations through intracortical microstimulation of the somatosensory cortex, supplementing vision with tactile percepts. Eventually, this system allows paraplegics to have better control of their prosthetic arms in clinical trials, showing that mimicking known principles of biocontrol could lead to important breakthroughs in BCI technology, with important implications for improving the quality of life of paraplegic patients.

Another unique BCIs controlled machine system designed by Ünal Hayta et al. successfully reached to an unexpected low error rate [9]. In their study, they applied an industrial robot arm with 6 Degrees of Freedom (DOF). Combining this 6 DOF robot arm with recording Electroencephalography (EEG) signals from 64 positions on the scalp, which is in accord with the International 10-10 System, they made further research in the twelve-time windows and the three-time windows for lowering the error rates. Finally, the most accurate results were obtained by setting the time window for developing spatial filters and the classifier at 3 seconds, with a variance time window of 1.5 seconds.

These studies have achieved several breakthroughs in BCIs controlled robotic arm systems, including lower error rates and better control for prosthetic arms. Through these approaches, paraplegic patients can enjoy a more stable and comfortable use of robotic arms through their brains.

3. fNIRS-EEG Brain-computer Interfaces

In previous studies, researchers have found great benefits from both functional near-infrared spectroscopy (fNIRS) and electroencephalography (EEG).

3.1 Electroencephalography

In BCIs technology, as a modality it, EEG is the most common method used in neural signals recording tasks [19]. With the portability of EEG, this recording approach allows scientists to gain more precise data from participants. For example, Agatha Lenartowicz and Sandra K. Loo have noticed the focal role EEG plays in neural functional assessment [10]. The usage of EEG in attention deficit hyperactivity disorder (ADHD) dates back to 75 years ago when Jasper et al. applied this technique and found the anomaly of EEG signals at frontal-central sensors [11]. These kinds of experiments and studies proved that mobility and accuracy in recording brain signals promote the use of EEGs to show a brilliant effect in BCIs.

3.2 BCIs Coupled with fNIRS-EEG Technique

Functional near-infrared spectroscopy (fNIRS) is an emerging non-invasive technique used in brain imaging, which has revealed huge potential in assessing the dynamic characteristics of the brain [20]. Secondly, fNIRS is immune to electromagnetic disturbances, allowing it to be used concurrently with EEG, magnetoencephalography, and functional magnetic resonance imaging (fMRI) technologies, allowing scientists to compose the fNIRS-EEG technique used in BCIs technology for improvements [20]. The fNIRS-EEG technique possesses better mobility and accuracy in detecting neural signals with some non-invasive devices [20]. For instance, Koo et al. created a specialized sensor frame where each segment contains three electrodes, one detector, and four sources, all positioned on one hemisphere of the scalp [10]. With the fNIRS-EEG BCI devices, researchers such as Philippe Pouliot et al. could track numerous neural signals, referring to Gallagher et al. and Nguyen et al. Applying this technique allows researchers to gain different data and models, including linear and nonlinear [12]. It also enables the scientists to gain higher-quality signals in participants' brains. However, the nonlinear data cannot be well understood now. Future studies may need to apply the non-perturbative approach to better figure out it [12].

4. Discussion

Brain-computer interfaces (BCIs) have been proven to possess a high potential in the medical field, especially for motor rehabilitation. However, due to several facets, including the speed, accuracy, ease of use and length of training period, while utilizing the BCIs, these points can be the restrictions that hinder the enhancement of BCIs controlled Robotic Arm. To tackle the issue of accuracy and speed in a non-invasive method, the fNIRS-EEG approach can be applied to breathtakingly remedy the drawback. According to some studies, using the hybrid fNIRS-EEG BCI system can be superior in improving the signals tracking tasks and signals processing tasks to the use of a single modality, which is partly because of the reduction in motion artifacts and the improvement in the reliability and robustness of signal interpretation [21]. This can help the patients to better control the robotic arm through a wearable device. Besides, in invasive method, the infection after operation can result in the high risks of death to patients and the difficulty of implanting electrodes in creatures' brain may leave obstacles in the promotion of invasive BCIs controlled system. Yet, there are 3 new implanting ways invented by Benovitski et al. [8], which are full of creativity, illustrating the possibility of implanting the EEG electrodes in the brain at a lower risk and can be removed easily. These enable the patients to further reduce the risks of being killed by infection and invasive electrodes, and they also allow the scientists to get high-quality EEG mechanical stability and lower chewing artifacts in the long period experiments.

However, it is clear that there are still several points that need to be further improved of BCIs controlled robotic arm system in motor rehabilitation. To commence with, although applying the fNIRS-EEG approach can provide patients with a more efficient data processing experience, the design of an external device in order to supply the off-laboratory/hospital environment can be challenging [7]. Specifically speaking, it requires strong wearability, high tolerance of motion artifacts, stable signal quality, elegant ergonomic design, and real-time long-term sampling capability embodied with fully integrated fNIRS-EEG BCIs hardware. The unknown region of combining fNIRS and EEG with issues in hardware design can prevent this technique from improving. Besides, the 3 implanting strategies also have some space for further enhancement. To be specific, in long-term experiments, a few numbers of electrode leads may erode the scalp where there are some loops in their placement. This can result in health problems for the implanted creatures.

Additionally, the design of the robotic arm system should be considered further. For instance, while applying the BCIs controlled robotic arm, patients who lack part of motor ability may have difficulties in carrying the robotic arm if they are out of the laboratory surroundings. Thus, harnessing a new type of external robotic arm that is comfortably wearable according to ergonomics or has a higher level of mobility may be a trend in the ulterior future.

For the sake of improving the BCIs controlled robotic arm system in motor rehabilitation, there is an urgent need for different aspects of the academic field. More experiments based on human engineering design shall be carried out in the future to design a better device for both the fNIRS-EEG BCI system and the external robotic arm. Apart from that, more researches in combining fNIRS and EEG are also needed to improve the accuracy of the fNIRS-EEG approach. As for the invasive BCI method, according to previous implanting ways, scientists need to find out a lot more new strategies to reduce the risks of injury or death. In that case, patients may better manipulate the BCIs system and thus interact with the world through the robotic arm, regaining their motor ability.

5. Conclusion

By reviewing the composition and functions of BCIs, their strong ability to provide the brain with a pathway to manipulate external machines and their high potential of being applied to help patients with their motor rehabilitation have now been revealed. In this review, the author gives a brief introduction to the definition of stroke and its symptoms, as well as the BCIs-controlled external robotic arm system. Then, the author searched and summarized several categories of approaches in assisting participants in controlling external robotic arms by BCIs, including the fNIRS-EEG BCIs for the non-invasive method and the 3 implanting strategies, where the electrodes are in the shape of disk, ring, and peg, for the invasive method. However, these approaches still have more room to be further advanced. Further studies in ergonomics, neurology, materialogy, and other related filed need to be carried out in order to construct a more advanced, mature, and practical BCIs controlled system for helping patients with motor rehabilitation. In conclusion, despite the fact that BCI controlled system can be powerful in different facets, it still needs a joint effort over the academic field to be further enhanced. Hopefully, this review will provide some researchers with several potential directions for improving this fabulous technique.

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