

Applications of EEG-Based Brain-Computer Interface Devices in Rehabilitation

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Abstract. BCI techniques narrow the gap between the human brain and external devices. Previous investigation using Brain-Machine Interfaces to control devices such as wheelchairs has shown that the technology could be effective in limb rehabilitation. There has been limited research on using BCI in performing a grasp and reach task using a prosthetic arm. The authors of this paper thus sought to determine how possible and effective the procedure can be performed considering the multiple degrees of freedom of the human arm. Moreover, stroke is among the leading causes of death globally. Stroke events, in most cases, leave the patient with severe brain damage that usually includes impaired motor functions. BCI-based techniques have shown the capacity to restore the motor functions of patients. However, there is a need for the BCI methods to be coupled with cognitive training approaches to improve other bodily functions of stroke patients. Also, since the first electroencephalography (EEG) and electromyography (EMG) were implemented in the 1920s, their clinical applications, theories, and testing techniques have improved tremendously. Generally, brain imaging techniques have evolved rapidly since the 1920s. This paper explores the applications of EEG-based Brain-Computer Interfaces in medical rehabilitation.

Keywords: EEG; Brain-Computer Interface; Human Brain and External Devices; Motor Functions; Medical Rehabilitation; Restore.

1. Introduction

Rehabilitative technologies are also called assistive technologies and are tools designed to help people living with disabilities perform normal activities at home, school, workplace, etc. [1] Disabled people could be individuals that are mentally incapacitated or cannot move or grasp[1] Assistive equipment are particularly popular in people with movement disability. However, there are several downsides to rehabilitative technology. First is the financial burden that patients experience in procuring the technology. Rehabilitation medicine is still developing; hence, equipment such as brain-computer interfaces has not yet reached the mass production stage [2]. Also, several rehabilitation means are not patient-specific [2]. It is necessary to adopt suitable rehabilitation means. Currently, rehabilitation methods based on the brain-computer interface have attracted researchers' attention.

Brain-computer interfaces are a progressive technology that offers a link between the brain and an external digital device, usually a computer [3]. The BCIs serve in two ways; they enhance and substitute the peripheral functioning capacity of humans and hence have a huge application in rehabilitative medicine [3]. Other applications are in neuroscience, robotics, and gaming. Due to the usefulness of the technology, efforts are being made to standardize it to make it easier to apply the same technology in various fields. BCIs are commonly used with electroencephalograms (EEG) in reconstructive medicine. An EEG is a technology that measures brain activity [4]. It involves inserting small metal discs called electrodes into a patient's skull to capture the brain's electrical activity. EEG is the main diagnostic tool for epilepsy but is also used to detect brain tumors, brain damage, and sleep disorders [4]. Several experiments have been conducted to determine the usefulness of the technology in alleviating the discomfort experienced by limbless individuals or those with malfunctioning arms and legs. The experiments involve using EEG to connect robotic limbs to the brain to control limb movement. The objective is to enable disabled people to perform normal limb functions like grasping, walking, running, etc.

This paper introduces the current status of rehabilitation research based on BCI. It peruses the work currently done with BCIs in assistive medicine. However, the scope of the literature only extends to patients with limb disorders and strokes.

2. The Human Arm Degrees of Freedom (DoF)

The human arm can move in seven independent ways when one factor in movements of the shoulder, elbow, wrist, and exclusion scapular motion when the wrist is positioned in space and the palm is oriented in a task that involves six DoF [5]. Prosthetic arms are, therefore, usually designed based on these possible arm movements. The seven degrees of freedom for a bionic arm include the shoulder joint with three degrees of freedom, the elbow joint and forearm with one DoF, and the wrist with two.

2.1 Noninvasive EEG-Based Control of a Robotic Arm for Reach and Grasp Task

Brain-computer interfaces aim to seamlessly sync the brain and artificial devices, which include robotic arms and legs[6]. BCI has been applied to a high degree of success in controlling both virtual and real-world objects. Success in the other fields has prompted technology enthusiasts and scientists to consider designing EEG-based robotic prosthetics[6]. Nevertheless, it hasn't proven easy to design noninvasive BCIs that effectively perform a human hand reach and grasp task. However, a reach and grasp task study was conducted on 13 human subjects. It effectively modulated their brain activity to perform reach and grasp, requiring multiple degrees of freedom with high accuracy. The ability of the subjects of this study to manipulate their brains to control the reach of a robotic arm and to maintain the ability for over several months strengthened the viability case for the human operation of prosthetic limbs using noninvasive BCI and EEG.

People suffering from extreme neuromuscular dysfunction or motor system injuries such as stroke and muscular dystrophy usually lose the ability to move and control their muscles[6]. According to [6], most of these people's brains usually retain the neural activity related to the motor function the same way as healthy people since the damage is usually peripheral; it does not affect the central nervous system. This group of people is a prime candidate for BCIs. Scientists can restore their peripheral motor functions using EEG and robotic limbs. EEG-based robotic limb technology aims to simulate the natural movement of the human arm by deciphering neural activity to high accuracy and transferring the information to a highly dexterous prosthetic limb[6].

However, technologists are facing a major hurdle in their quest to build a robust EEG-based interface for robotic limbs; an effective interface should be complex and advanced enough to achieve the multiple degrees of freedom necessary for an anthropomorphic prosthetic. The task gets harder with the developers opting to design noninvasive BCIs such as EEG-based ones[6]. Conventional BCIs are invasive and involve implanting electrode arrays inside the brain areas associated with movement, which track the activities of thousands of neurons. The disadvantage of the traditional approach is that the implanted electrode arrays cover unnecessarily large brain areas[6]. Moreover, the method poses the risk of post-surgery complications and infections. In addition, it is difficult to maintain stable chronic recordings with traditional BCIs, which makes them unsuitable for use with large subject populations[6]. In comparison, noninvasive EEGs spare subjects the need for unnecessary surgery and complications. Besides, little time is consumed in placing the electrodes on the scalp hence suitable for a large study sample[6].

Even though noninvasive BCIs like EEG-based robotics are a better alternative, control of a prosthetic limb using the technology has not been conclusively proven to be a proficient noninvasive system that can achieve multiple degrees of freedom control. Studies are ongoing to establish the efficacy of EEG control of robotic limbs in three dimensions.

2.2 Trajectory Path Planning of EEG-Controlled Robotic Arm Using Genetic Algorithm

In addition, another group of researchers set out to ascertain the efficacy of using a Genetic Algorithm (GA) to control a prosthetic arm. EEGs were placed on five healthy individuals, and their brain activity associated with motor movement was captured and grouped using the Support Vector Machine (SMV) Classifier. In addition, GA algorithms were developed using Matlab. In this study, EEG data was captured from the motor cortex of the subject's brain when the patient imagined moving an arm. The subjects were instructed to imagine moving either of their arms, and the brain signals were recorded separately for both the right and left arms. The arms' imagination features were then used to produce control signals using the SMV classifier. GA was used for path planning and reaching the object position. The GA technique has been used in several other BCI experiments. The approach has been applied to identify optimal trajectories for a robotic arm [7]. The study concluded that trajectory path planning using GA was at least 75% accurate for left-right arm movement. Moreover, the investigators found that GA is more efficient for trajectory planning with three-degree of freedom human arm. This study did not use GA with human arm kinematics or with higher degrees of freedom, leaving room for more research.

2.3 EEG-Based Interfaces for Rehabilitation of Stroke Patients

A cerebrovascular event is a medical term for a stroke. A stroke occurs when the brain is deprived of blood due to a clot or rupture of a blood vessel which leads to the cutting off of oxygen supply to the brain cells causing damage[7]. A cerebrovascular event may lead to loss of coordination in the limbs. Moreover, it is characterized by numbness or paralysis in the face, leg, or arm. Stroke patients can get help with their partial paralysis using brain-computer interface technology. They can benefit from EEG-based prosthetic limbs to replace the numbed arms and legs[7].

2.4 Brain-Machine Interface (BCI) Treatment for Motor Rehabilitation of Upper Body Muscles of Stroke Patients

Feasibility studies have been carried out to determine the proficiency of BCI in restoring the upper extremity muscle functionality of stroke patients. The upper extremities are the muscles that move the forearm, wrist, and hand, which are usually disabled in a cerebrovascular event.

Muscles of the Upper Extremity

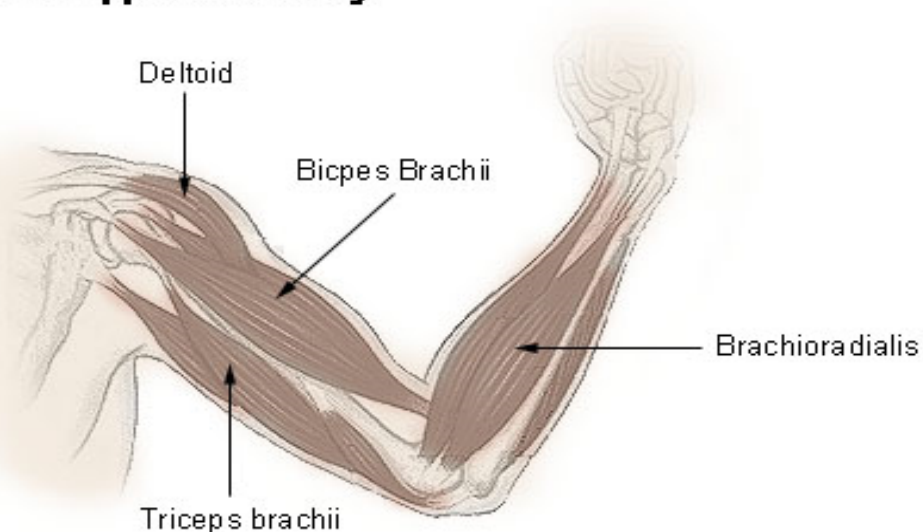


Figure 1. Muscles of Upper Extremity

National Cancer Institute. Muscles of Upper Extremity [Image]. https://training.seer.cancer.gov/images/anatomy/muscular/upper_extremity_muscles.jpg

Moreover, numerous publications have explored the possibility of using BCI systems as rehabilitation tools for restoring the muscular functions of subacute and stroke patients. Most studies have concluded that BCI therapy is an effective alternative to traditional stroke therapy methods; the former leads to better results[8]. BCI has enabled therapists to restore the neurological activity of stroke patients by inducing neural plasticity made possible by improving their motor coordination ability as patients perform tasks[8].

In one study, 51 patients with upper extremity malfunction were assessed using motor imagery BCI, and their functional brain activity was assessed before and after the therapy. The subjects were classified based on the period of their condition. Also, the patients were placed into four groups based on their stroke diagnosis. An LCD screen is placed in front of them. They were fitted with an EEG containing 16 active electrodes. The results of these studies revealed a significant increase in the motor functions of the prosthetic limbs the subjects were fitted with. Interestingly, the motor improvement was not related to the severity or stage of the stroke.

The investigators of this study concluded that the BCI technology effectively improves the functionality of upper extremities in patients with mild, moderate, or chronic stroke. They found that such an interface improves neuroplasticity in the central nervous system. Neuroplasticity is the ability of the brain to adapt to new experiences. In the case of stroke patients, it is how first their brains respond to induced motor functionality therapy[9]. Therefore, by using BCI therapy, this response is magnified.

Nevertheless, studies like the one discussed above face a major scope limitation; the therapies suggested therein are only limited to motor functions, neglecting non-motor impairments in cognition and emotion that are also caused by cerebrovascular events. Therefore, other investigations have sought to address this gap by exploring how BCI-based stroke therapies could be all-inclusive, targeted at bettering all outcomes, both motor and non-motor. These new studies reveal that motor and non-motor functions are highly correlated. The best stroke therapy outcomes can be achieved when rehabilitation techniques focus on both motor and related functions[8].

2.5 BCI for Post-Stroke Cognitive Training

Despite motor dysfunction being the most visible symptom of stroke, patients also suffer from cognitive impairments ranging from inattentiveness, memory deficit, slow information processing, and speech difficulty[8]. Speech deterioration, in particular, reveals a critical cognitive impairment since speech and language enable complex mental activities such as complex reasoning and the formation of abstractions and generalizations [10]. Prioritizing cognitive therapy for post-stroke patients is thus important since other therapies, such as motor rehabilitation, hinge on the ability of the patient to understand the instructions for carrying out the rehabilitation regimen. Furthermore, Motor Imaging (MI) and other computerized BCI therapies require the patient to be attentive to the tasks assigned for long periods. Thus patients unable to meet the set cognitive demands are excluded from rehabilitation. Therefore, in cases of severe cognitive damage, cognitive rehabilitation should precede motor and other forms of therapy[8].

Patients with moderate to severe Post Stroke Cognitive Impairment (PSCI) have improved critical cognitive function with conventional post-stroke cognitive training (PSCT) techniques. Nevertheless, PSCT methods are less explored compared to motor therapies [11]. Studies on PSCT therapies were inspired by the relative success of applying BCI-based neurofeedback training in treating neurodevelopment and neurodegenerative disorders. Furthermore, EEG has been used to a great extent of success in the cognitive training of adolescents suffering from inattentiveness. Researchers had hoped they could extrapolate the result to training stroke patients with cognitive damage[8].

Neurofeedback training for people with attention deficit problems usually involves stimulating the cortical regions of the patients' brains [12]. Researchers can observe increased attention spans when the technique is used for people with ADHD. Thus, from behavioral observations, BCI-based neurofeedback training has shown the capability to repair the cognitive dysfunction of patients by improving attention span, a critical cognitive function necessary to rehabilitate post-stroke patients.

In one neurofeedback cognitive training study, the Alpha wave brain activity of two patients was enhanced using an EEG, and the results revealed an improvement in the emotional cognition of the subjects as well as motor functions. Also, the speech pattern of one of the subjects improved, underscoring the need for a broad-spectrum post-stroke rehabilitation therapy instead of a focused one. Besides, inducing the brain's alpha wave activity has been demonstrated to be an effective approach to restoring both motor and cognitive functions of stroke patients as opposed to neuroplasticity training that mainly targets motor functions [12].

3. Discussion

The 1940s saw the development of an imaging technology called Event Potential. Moreover, the now famously Positron Emission Tomography (PET) was invented in the 1970s, followed by functional magnetic resonance imaging (fMRI) in the 1990s. All these imaging techniques are noninvasive and have been developed progressively to address bioethical issues.

EEG is widely preferred for medical rehabilitation since it is well suited for the measurement demands of the application [7]. The technique is safe and simple. Furthermore, EEG equipment is portable. Previously, EEG has been used primarily to analyze the brain activity accompanying a given disease or disorder, such as epileptic seizures and neurodegenerative diseases. In this case, epileptic patients were fitted with electrodes, and their brain activity was analyzed during an episode to determine the source of the attacks and predict future events. Also, physicians have used the EEG technique as a research protocol to determine how different brain areas are stimulated when subjects perform specific tasks[13]. Investigators would instruct subjects and then analyze the brain areas where electrical activity is intense. However, recent advancements in EEG techniques measure the fluctuations in the frequency band of brain waves[13]. When the captured frequency decreases after a subject perform a task, the phenomenon is known as event-related desynchronization (ERD).

In contrast, an increasing frequency band is known as event-related synchronization (ERS). Therefore, the recent EEG application is frequency analysis. Researchers hypothesize that ERD reflects an elevated cortical activity while ERS represents a decreased cortical function; a return to a low level [13]The cerebral cortex functions to control motor, visual and sensory activities, and hence the ERD and ERS information is useful in rehabilitating these functions [14].

3.1 EEG-EMG Coherence

The concept of EEG-EMG coherence has gained the interest of investigators since the discovery that EMG and EEG waves are correlated [13]. The relationship between the two was conceptualized after it was determined that myoelectric waves, the final output of the motor system, were rhythmic, just like brain waves. EEG measures the collective firing of neurons, while EEG detects the collective activity of the motor system. Since the EEG also captures the activity of spinal motor neurons, which control movement, an EEG-EMG combination is considered capable of determining how the cerebral cortex controls the spinal motor neurons[13]. The coherence is noninvasive; hence investigations are ongoing to determine how efficiently the technique can evaluate diseases that impair motor function and involuntary movement.

Furthermore, researchers are increasingly considering applying EEG-EMG coherence in tracing the development of neurodegenerative diseases[13]. In particular, the coherence frequency of 3-6 Hz, labeled a slow resting tremor, is a core biomarker of Parkinson's disease. Moreover, EEG-EMG coherence has also been detected in stroke patients.

3.2 The Brain-Machine Interface Applications

BMI applications in rehabilitation involve connecting brain activity with external devices such as prosthetic limbs using electrical circuits to supplement or mimic brain function[13]. Motor rehabilitation has perhaps benefitted the most from BMI applications. The rehabilitation involves output-type BMIs picking motor intention from brain activity and transferring the information to

external devices, which can then be used to perform a given task, such as operating a computer. The output BMI equipment can be invasive, as is the case where electrodes are implanted in the intracranial space, or noninvasive, as with the use of EEG and fMRI. In addition to the traditional use of BMI techniques to operate an external device, the method is gaining increased importance in medical rehabilitation, where it is used to restore damaged neural networks to improve motor and cognitive functions[13].

Furthermore, EEG and BMI have been useful in the field of neurofeedback. The field is concerned with controlling one's brain activity when the activity is presented as real-time information to the subject, usually using a computer monitor [15]. One can see the brain activity as it happens and tune it anyhow one wants, which will be displayed on the screen. Neurofeedback is a rehabilitative form of BMI in that it is used to improve the motor, cognitive, and psychological well-being of patients and healthy individuals.

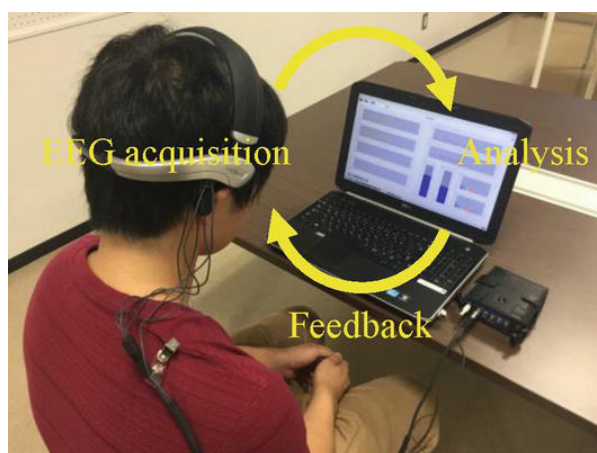


Figure 2. Neurofeedback Training

Brain boost. Neurofeedback Training [Image]. <https://brainboost.de/wp-content/uploads/2018/09/Neurofeedback-1.png>.

Various frequency bands of the brain waves are usually used in cognitive and motor training [13]. The frequency ranges can inform the specific psychological activity one intends to improve since the variation represents different brain functional capacities [13]. In addition, the neurofeedback technique is also being tested as a brain activity regulator. It has an advantage over other neuromodulation methods, such as transcranial magnetic (TMS) stimulation, which uses external stimulation to modulate brain functions [13]. Therefore, neurofeedback prevents the risk of burns and seizures associated with TMS. Moreover, output BCI has demonstrated positive results in helping people debilitated by age, illness, or aging live comfortable independent lives.

4. Conclusion

The electroencephalography technology promises to fundamentally assist disabled people in coping with their disability. Scientists are discovering huge applications of EEG-Based brain-machine interfaces that enable prosthetic limbs to function like natural limbs. Several reach-and-grasp experiments performed using human-controlled prosthetic limbs have been successful. Moreover, other techniques using the genetic algorithm to perform artificial arm movements have demonstrated that prosthetics can mimic the different movements of human limbs. In addition, brain-machine platforms have been applied in stroke patients with damaged upper body muscles, which have improved the movement of the muscles. Also, BCIs have proved effective in training patients with damaged cognitive function due to diseases to regain function; the technology has reversed cognitive damage in stroke patients. Besides, EEG-Based BMIs are being used by healthy patients to rewire their brain activity to improve their performance at work or in sports. Even though brain-computer

interfaces promise to revolutionize medical rehabilitation, there is a need to develop a strong bioethical code that will prevent the unethical application of the technology. Moreover, developers should focus more on developing noninvasive equipment to make more disabled persons feel comfortable opting for prosthetics.

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