Research Output Journal of Biological and Applied Science 3(1):35-39, 2024

ROJBAS Publications **ISSN: 1115-6120**

https://rojournals.org/roj-biological-and-applied-science/

Applications of Brain-Computer Interfaces (BCIS) in Neurorehabilitation

Val Hyginus Udoka Eze, Ugwu Chinyere N. and Ogenyi Fabian C.

Department of Publication and Extension Kampala International University Uganda

---

ABSTRACT

Brain-Computer Interfaces (BCIs) have emerged as a transformative technology in the field of neurorehabilitation, offering novel solutions to enhance the recovery of motor and cognitive functions following neurological injuries or degenerative diseases. This paper explores the various applications of BCIs in neurorehabilitation, focusing on their ability to facilitate activity-dependent plasticity, provide real-time feedback, and offer patient-specific, individualized therapy. We discuss the types of BCIs, including non-invasive methods such as EEG-based systems and invasive approaches utilizing intracortical electrodes, and their respective benefits and challenges. Additionally, the paper highlights current limitations in neurorehabilitation and how BCIs can address these gaps, ultimately improving the quality of life for patients with severe motor disabilities. Future directions and emerging technologies in BCI-driven neurorehabilitation are also examined, emphasizing the potential for more effective and integrated therapeutic solutions.

Keywords: Brain-Computer Interfaces (BCIs), Neurorehabilitation, Motor recovery, Cognitive rehabilitation, Activity-dependent plasticity.

INTRODUCTION

BCI platforms are an important tool for the integrative design and investigation of neurorehabilitation. The study of chronic, long-term BCI-mediated learning allows us to understand how rehabilitation after brain injury or during the effects of degenerative brain diseases can be enhanced using BCIs. Moreover, the use of BCIs can open new possibilities not only for communication (e.g., when people with severe motor disabilities or those in a locked-in state are able to express their wishes) but also for emotional and cognitive expression, expanding the range of rehabilitation programs offered by clinicians and opening new possibilities for entertainment for these populations [1, 2]. Dubbed the "brain" part of the body, BCI devices collect information on a user's intentions, emotions, and cognitive functions from his or her brain signals, which are generated through neuronal activity in the brain. Thus, BCIs have the potential to enable robots to read human thoughts since the former are currently only able to process external information via cameras and sensors. As is often argued, however, neural interfaces can be bidirectional. In this case, using another type of BCI that presents stimuli to the brain via its sensory channels, we could also enable robots to experience the environment like a human does. Indeed, a BCI can be treated as an interface that allows the brain to interact with the outside world, including with other brains. Combining BCI, robotics, and rehabilitation could simultaneously provide autonomous, cost-effective systems for assisting those with complex disabilities, generating promising possibilities for symbiotic systems in medical and other related rehabilitation fields [3].

NEUROREHABILITATION: CURRENT CHALLENGES AND LIMITATIONS

One main goal of neurorehabilitation is to improve motor and cognitive impairments from injuries of the central nervous system. These interventions are based on the principles of activity-dependent plasticity, which support functional recovery by promoting the regeneration, synaptic modulation, and reorganization of damaged neuronal circuits. By facilitating neuronal connectivity, activity-dependent plasticity mediates the acquisition of motor and cognitive skills. Intensive sustained repetition and timely feedback are essential for the successful promotion of plasticity as emphasized by the Hebbian postulate "Cells that fire together, wire together." Therefore, neurorehabilitation critically relies on high dosage and dedicated patient cooperation. Nevertheless, it is often the case that therapy cannot be provided in a high enough dose because of a limited number of therapists, budgetary constraints, travel time to specialized centers, insufficient motivation, patient dependency, limited cognitive capacity, and stroke survivors are often left with physical and cognitive disabilities. Many patients recover only partially from their deficits and experience a diminished quality of life. Shortcomings may be further exacerbated by over-extended healthcare funding or insufficient home care [4, 5]. BCIs have been developed to supplement and improve conventional neurorehabilitation. BCIs bypass damaged nerve pathways by transmitting information directly from the brain to improve or restore lost functions. These systems offer a promising and novel strategy to bridge the gap between intention and movement execution. Major advantages are that they require no (additional) movement to promote adaptive plasticity and provide 'intention-based' feedback, regardless of the amount of movement, motivation, or cognitive functioning. In recent years, a number of BCI-controlled robotics and interfaces have been introduced that allow patient-specific, individualized, and closed-loop (real-time) neurorehabilitation with high task-specificity and long intervention protocols. These systems proved useful and beneficial and were compatible with existing neurorehabilitation devices, paradigms, and therapeutic principles. They can augment active movement in an operating multi-sensory environment and are promising devices for patients who have suffered motor deficits, owing to both stroke or spinal cord injury. Moreover, complementary to these rehabilitative benefits, measuring human intentions using BCIs during usual activities may also trigger or influence synaptic reorganization that may lead to recovery—slightly similar to, for example, leading a "normal" life [6].

TYPES OF BRAIN-COMPUTER INTERFACES (BCIS) FOR NEUROREHABILITATION

Non-invasive BCI approaches include the use of electroencephalography (EEG), magnetoencephalography (MEG), and functional near-infrared spectroscopy (fNIRS) to record brain behavior. Despite promising results and increasing utilization of MEG and fNIRS, BCI mainly relies on scalp-EEG for several reasons including low cost, ease-of-use, and good temporal and sufficient spatial resolution for inference of movement-related brain dynamics [7]. Several forms of EEG-BCI variants exist, and their usefulness for neurorehabilitation varies. Based on the mode of information acquisition and the type of bio-signal learned or utilized by the BCI for BCI neurorehabilitation, EEG-based BCIs fall mainly into the three following sub-classes: Event-related desynchronization/synchronization (ERD/ERS)-based BCIs capitalize mainly on the EEG power suppression/excitation observed during mental imagery of intention-specific hand-arm motor tasks. Event-related potential (ERP)-based BCIs take advantage of the presence of target-differentiating components in the EEG, such as the P300 wave or N170 potential, to support function or communication in persons with spinal cord injury or severe motor impairment [8, 9]. Sensory/motor rhythms (SMR)-based BCIs are also called sensorimotor rhythm (SMR)-based BCIs, and they take advantage of the presence of frequency-specific EEG modulatory features linked to movement divulgence under varying limb motor tasks. All these EEG-BCI design variants have been generally evaluated for feedback-triggered motor-neurofeedback training approaches, which have validated potential in motor recovery [10]. An additional neurofeedback training approach involves the use of connectivity patterns in the brain. Indeed, the identification, mapping, and assessment of the therapeutic relevance of distinctive and purposeful brain connectivity changes occurring during neurorehabilitation comprising connectivity-guided, neurofeedback, and neuromodulatory BCI techniques are even more appreciated with models such as chronic stroke. Intraoperative BCI-based brain connectivity manipulation assist multi-focal motor-evoked paradigm for personalized multimodal assessment and guidance of surgical protocols [11].

INVASIVE BCIS

An invasive BCI extracts neural signals directly from the brain. The most widely used neural signals are based on action potentials containing the neuronal information, which are measured with microelectrodes implanted in the cortex or in deep brain structures. The main challenge with invasive BCIs is linking nerve structures with external output, corresponding to a control device. Once the connection between the anatomy of the implant and the corresponding external robotic or functional electric stimulation of muscles has been established, actions can be performed before the signals related to the action reach the muscles. Patients suffering from complete locked-in syndrome, Parkinson's disease, or spinal cord injury usually have the intact ability to produce the neural signals detected by the invasive BCIs, and therefore have been the population that has been targeted with this type of BCI. To date, low with good results can be offered by invasive BCIs to individuals with stroke during restorative or compensatory treatment, and the clinical applicability of this approach remains to be determined [11, 12]. Generally, when a neural prosthesis to generate functional restoration consists of a single information input, the recording and device application process are much easier than when it comes to prostheses requiring multiple inputs and outputs. Therefore, the most advanced experiments and demonstrations that have resulted in some chronically implanted brain-machine interfaces in monkeys and stroke patients have been applied to control the firing of small neural populations. Nonetheless, there is no reason to doubt that in a relatively short time period, prostheses will be developed to drive the required neural information from the necessary large number of neural signal recordings. This situation arises because it is normal for behavior to be provoked and for each actuating neuron to generate a certain modifiable signal. The capacity to rapidly and repeatedly navigate and differentiate different signals is truly modest for robot devices or stable setups that are easy to control. There is no doubt that the main concern here is the speed and strength of simulation [11].

NON-INVASIVE BCIS

Clinical application of BCI in EEG-based BCI-detected event approach:

a) Diseases and disorders - Non-invasive BCIs are demonstrated in their clinical relevance for communication, environmental control, and for the purpose of training and rehabilitation of patients with neuromuscular disorders and neurological injuries, like amyotrophic lateral sclerosis (ALS), multiple sclerosis, neuromuscular diseases, stroke, and also for patients in the minimally conscious state or even in the locked-in syndrome. These have been demonstrated and tested in clinical studies with subjects in these described clinical conditions or disorders, showing good clinical applicability and results in regard to its clinical indication or for the described neuroadaptive BCI-detected event or amplitude modulation mainly in the motor imagery available from the P300 BCI-detected event paradigm or amplitude modulation or other paradigms, in particular for iBCIs [13].

b) Enroll more specific subjects in the testing procedure to also confirm the iBCI technology and application integration with the prospective clinical benefits described, to really confirm or reject this hypothesis to particular clinical sub-groups and the significance of the benefits described for each kind of disease or disorder described, towards a more efficient translation of this iBCI technology, application, and evidence and demonstration process to real-life clinical practice [11, 14].

BENEFITS AND EFFICACY OF BCIS IN NEUROREHABILITATION

The field of neuroprosthetics continues to show much promise to enhance therapies for neurological disorders and for the overall quality of life of individuals with severe neuromuscular disabilities. The concept of inserting an intracortical electrode array in the motor cortex to extract movement intention was introduced by Kennedy in the mid-1990s. The idea was further advanced with the successful implantations in humans of a silicon-based slanted, multichannel microelectrode capable of providing years of stable single-unit recording from many channels. These devices became the first intracortical brain-computer interface (BCI) systems for humans with chronic tetraplegia. Since then, intracortical BCIs have demonstrated the clinical translation of providing individuals with various forms of severe paralysis due to neurological injuries the ability to control a computer cursor by simply thinking about moving the cursor with individual highly standardized units or spike trains [13]. There has been continued interest in the field of using BCIs in the relatively new concept of BCI-driven therapies. The focal point of BCI-driven therapies is the use of real-time feedback of neural parameters associated with a sensory-mediated functional training paradigm whereby the individuals directly control a contingent and informative sensory experience using processes such as touch or vision mediated by an assistive device. The fundamental assumptive value of the BCI-mediated therapy is predicated on the concept of activity-dependent plasticity and its relation to rehabilitation processes. Activity-dependent plasticity, driven by active movement attempts during task performance, can promote long-term changes in cortical motor representation. The general science has provided the feasibility and the beneficial neuroplastic effects of the neurotechnology using sensory-mediated signal processing that optimizes the facilitation of immediate targeted outcome rehearsal, resulting in improved neurological recovery [12, 15].

FUTURE DIRECTIONS AND EMERGING TECHNOLOGIES IN BCI FOR NEUROREHABILITATION

From a specific biomedical perspective focused on neurorehabilitation, it is important to highlight the impact of BCIs in several different applications such as those directly involved in assisting individuals with neurological injuries to communicate, engage in computing activities, operate neuroprosthetics apart from BCI control, or different brain/body augmentative devices. Here, it is important to highlight the communication expertise associated with BCIs. Many individuals with severe disability experience great frustration in their communication when they become dependent on others to interpret their speech. This problem can no longer happen as BCIs allow them to communicate by using brain signals. Many disabled persons also benefit from BCI paradigms to recover their motor skills. Disconnected neural systems caused by weakness, tetraplegia, or other motor disability might be partly reconnected by using BCIs [16]. Other Applications of BCIs in Neurorehabilitation Additionally, BCIs might further enable patients to play a more direct role in their rehabilitation process. Motivation can increase substantially because the BCI technology allows the patients to get better at using their own brains to interact with their surroundings. An attractive future with BCI support for rehabilitation would simultaneously satisfy all these aims: It is a comprehensive tailoring to the patient's capabilities and it can accelerate the rehabilitation process while minimizing the caregiver's effort. For example, virtual reality games which are used for task-specific rehabilitation can be tailored to the needs, circumstances, and abilities of the patient. Within the virtual environment, many "channels" support the patient's performance, i.e., the combination of brain-controlled hand motor tasks and activities that require hand-arm movement undertaken by the inert body. Moreover, the adaptable rehabilitation environment should recognize the motivated patient's state of fatigue, so that the rehabilitation action could be paused for an appropriate time [17].

CONCLUSION

Brain-Computer Interfaces represent a significant advancement in neurorehabilitation, providing innovative ways to enhance motor and cognitive recovery for individuals with neurological impairments. By bypassing damaged neural pathways and offering real-time, intention-based feedback, BCIs facilitate neuroplasticity and support the acquisition of new skills. The integration of BCIs with robotics and other assistive technologies holds great promise for creating autonomous and cost-effective rehabilitation systems. Although challenges remain, particularly with invasive BCIs, the continued development and refinement of these technologies are expected to yield substantial benefits. Future research should focus on optimizing BCI systems for broader clinical application, improving user experience, and exploring new therapeutic paradigms to further advance neurorehabilitation outcomes.

REFERENCES

1. Simon C, Bolton DA, Kennedy NC, Soekadar SR, Ruddy KL. Challenges and opportunities for the future of brain-computer interface in neurorehabilitation. Frontiers in neuroscience. 2021 Jul 2;15:699428. frontiersin.org
2. Tayebi H, Azadnajafabad S, Maroufi SF, Pour-Rashidi A, Khorasanizadeh M, Faramarzi S, Slavin KV. Applications of brain-computer interfaces in neurodegenerative diseases. Neurosurgical Review. 2023 May 31;46(1):131. [HTML]
3. Gu X, Cao Z, Jolfaei A, Xu P, Wu D, Jung TP, Lin CT. EEG-based brain-computer interfaces (BCIs): A survey of recent studies on signal sensing technologies and computational intelligence approaches and their applications. IEEE/ACM transactions on computational biology and bioinformatics. 2021 Jan 19;18(5):1645-66. [PDF]
4. Ecker A, Santander DE, Bolaños-Puchet S, Isbister JB, Reimann MW. Cortical cell assemblies and their underlying connectivity: an in silico study. bioRxiv. 2023 Feb 24:2023-02. biorxiv.org
5. Benghalem N. Master thesis: Neuromodulation of phenomenological plasticity rules. 2022. uliege.be
6. Awuah WA, Ahluwalia A, Darko K, Sanker V, Tan JK, Pearl TO, Ben-Jaafar A, Ranganathan S, Aderinto N, Mehta A, Shah MH. Bridging minds and machines: the recent advances of brain-computer interfaces in neurological and neurosurgical applications. World Neurosurgery. 2024 May 22. st-andrews.ac.uk
7. Orban M, Elsamanty M, Guo K, Zhang S et al. A review of brain activity and EEG-based brain–computer interfaces for rehabilitation application. Bioengineering. 2022. mdpi.com
8. Jamil N, Belkacem AN, Ouhbi S, Lakas A. Noninvasive electroencephalography equipment for assistive, adaptive, and rehabilitative brain–computer interfaces: a systematic literature review. Sensors. 2021. mdpi.com
9. Saibene A, Caglioni M, Corchs S, Gasparini F. EEG-based BCIs on motor imagery paradigm using wearable technologies: a systematic review. Sensors. 2023. mdpi.com
10. Li X, Wang L, Miao S, Yue Z, Tang Z, Su L, Zheng Y, Wu X, Wang S, Wang J, Dou Z. Sensorimotor rhythm-brain computer interface with audio-cue, motor observation and multisensory feedback for upper-limb stroke rehabilitation: a controlled study. Frontiers in Neuroscience. 2022 Mar 11;16:808830. frontiersin.org

11. Kvamme TL, Ros T, Overgaard M. Can neurofeedback provide evidence of direct brain-behavior causality?. Neuroimage. 2022. sciencedirect.com
12. Dehghani A, Soltanian-Zadeh H, Hossein-Zadeh GA. Probing fMRI brain connectivity and activity changes during emotion regulation by EEG neurofeedback. Frontiers in Human Neuroscience. 2023 Jan 6;16:988890. frontiersin.org
13. Krylova M, Skouras S, Razi A, Nicholson AA, Karner A, Steyrl D, Boukrina O, Rees G, Scharnowski F, Koush Y. Progressive modulation of resting-state brain activity during neurofeedback of positive-social emotion regulation networks. Scientific reports. 2021 Dec 3;11(1):23363. nature.com
14. Dehghani A, Soltanian-Zadeh H, Hossein-Zadeh GA. Global data-driven analysis of brain connectivity during emotion regulation by electroencephalography neurofeedback. Brain Connectivity. 2020 Aug 1;10(6):302-15. [HTML]
15. Lipp A, Cohen Kadosh K. Training the anxious brain: using fMRI- based neurofeedback to change brain activity in adolescence. Developmental Medicine & Child Neurology. 2020 Nov;62(11):1239-44. wiley.com
16. Dehghani A, Soltanian-Zadeh H, Hossein-Zadeh GA. Neural modulation enhancement using connectivity-based EEG neurofeedback with simultaneous fMRI for emotion regulation. Neuroimage. 2023. sciencedirect.com
17. Lisk S, Kadosh KC, Zich C, Haller SP, Lau JY. Training negative connectivity patterns between the dorsolateral prefrontal cortex and amygdala through fMRI-based neurofeedback to target adolescent socially-avoidant behaviour. Behaviour Research and Therapy. 2020 Dec 1;135:103760. ucl.ac.uk

CITATION: Val Hyginus Udoka Eze, Ugwu Chinyere N. and Ogenyi Fabian C. Applications of Brain-Computer Interfaces (BCIS) in Neurorehabilitation. Research Output Journal of Biological and Applied Science. 2024 3(1):35-39