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Development of Non-invasive Brain-computer Interfaces for Neurorehabilitation

Eliana Sorin*
Department of Neurology, Neurocritical Care and Neurorehabilitation, Paracelsus Medical University of Salzburg, Salzburg, Austria

Introduction

Brain-computer Interfaces (BCIs) have emerged as a transformative technology at the intersection of neuroscience, engineering and rehabilitation medicine, offering new avenues for restoring lost motor, sensory and cognitive functions. By enabling direct communication between the brain and external devices, BCIs bypass damaged neural pathways, providing a potential lifeline for individuals suffering from neurological conditions such as stroke, spinal cord injury, traumatic brain injury and neurodegenerative diseases. Among the various types of BCIs, non-invasive systems have gained increasing attention due to their safety, accessibility and ease of implementation, making them particularly suitable for clinical and at-home neurorehabilitation settings. Non-invasive BCIs typically rely on Electroencephalography (EEG), functional Near-Infrared Spectroscopy (fNIRS), or other surface-level neural recording methods to detect brain activity without the need for surgical intervention. These signals are processed in real time and translated into commands that can control computers, prosthetic limbs, exoskeletons, or virtual environments. When integrated with rehabilitative therapies, non-invasive BCIs have the potential to facilitate neuroplasticity the brain's ability to reorganize and form new connections by reinforcing motor intent and providing immediate feedback. This process can significantly enhance functional recovery and independence for patients with motor impairments [1].

Description

The field of neurorehabilitation has witnessed a significant transformation in recent years, driven by advances in technology that aim to improve recovery outcomes for individuals with neurological impairments. One of the most promising innovations in this domain is the development of Brain-Computer Interfaces (BCIs), particularly non-invasive systems, which allow direct communication between the brain and external devices without the need for surgical intervention. These non-invasive BCIs offer a safe, accessible and effective way to facilitate motor recovery, sensory perception and cognitive function in patients with neurological conditions such as stroke, spinal cord injury, traumatic brain injury and neurodegenerative diseases like Parkinson's disease and multiple sclerosis. Non-invasive BCIs work by detecting and interpreting brain signals generated by neuronal activity, which are then translated into commands to control external devices, such as prosthetic limbs, robotic exoskeletons, or Virtual Reality (VR) systems. There are several key types of non-invasive brain signal recording technologies used in BCIs, the most common being Electroencephalography (EEG), Functional Near-Infrared Spectroscopy (fNIRS) and Magnetoencephalography (MEG), with EEG being the most widely used due to its relatively low cost, portability and ability to provide real-time information about brain activity [2].

EEG measures the electrical activity of the brain through electrodes placed on the scalp. The signals recorded by these electrodes represent the synchronous firing of large groups of neurons and are often categorized into different frequency bands such as alpha, beta, delta and theta, each of which is associated with different states of brain activity (e.g., relaxation, attention, or movement). fNIRS, on the other hand, measures changes in blood oxygenation levels in the brain by using near-infrared light to penetrate the scalp. Neurorehabilitation aims to help individuals recover lost or impaired functions due to brain injury or neurological disorders. Traditional rehabilitation approaches often involve physical therapy, occupational therapy and cognitive training, but these treatments can be slow and may not always lead to significant recovery, particularly in patients with severe impairments. Non-invasive BCIs, however, provide a powerful tool to accelerate recovery by directly engaging the brain and promoting neuroplasticity the process by which the brain reorganizes itself and forms new neural connections in response to injury or damage [3].

One of the key principles behind neurorehabilitation with non-invasive BCIs is the concept of real-time feedback. By providing patients with immediate feedback on their brain activity or motor intent, BCIs can help them regain control over impaired movements or sensations. For example, in stroke patients, who may have lost the ability to control their hand or arm movements due to damage to the motor cortex, a BCI system can detect the patient's intention to move and provide real-time visual or auditory feedback. This feedback can be in the form of a virtual hand on a screen or an actual robotic arm that mimics the patient's movement attempts. This interaction helps to reinforce the neural pathways responsible for motor control, leading to enhanced neuroplasticity and improved motor function over time. Additionally, BCIs can be integrated with robotic exoskeletons or Functional Electrical Stimulation (FES) systems to assist patients in performing exercises that they may not be able to carry out independently. These systems not only provide physical assistance but also engage the brain's motor cortex by providing sensory feedback. Studies have shown that this kind of interaction between the brain, BCI and robotic devices can lead to improvements in both motor function and motor planning, particularly in individuals with severe mobility impairments, such as those with spinal cord injuries [4].

Wearability and comfort are also key considerations in the development of non-invasive BCIs. Since rehabilitation often requires repeated use over extended periods of time, BCI systems must be comfortable, unobtrusive and easy to wear. Advances in flexible and lightweight sensor technologies are helping to create more comfortable, user-friendly devices, such as dry EEG electrodes and headbands, which eliminate the need for messy conductive gels. These algorithms can analyze large volumes of real-time data from EEG or fNIRS, identifying patterns of neural activity associated with specific intentions or movements. By continuously refining the decoding process, these systems can improve their accuracy and responsiveness, resulting in more effective and efficient rehabilitation outcomes. Looking to the future, advancements in non-invasive BCI technology could transform the rehabilitation landscape, providing new tools for personalized, remote and real-time

***Address for Correspondence:** Eliana Sorin, Department of Neurology, Neurocritical Care and Neurorehabilitation, Paracelsus Medical University of Salzburg, Salzburg, Austria, E-mail: sorin.eliana@salzburg.med*

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neurorehabilitation. As BCI systems become more accurate, adaptive and user-friendly, they may enable patients to engage in continuous, at-home rehabilitation, thus reducing the need for frequent in-clinic visits. Moreover, the integration of BCI technology with other cutting-edge fields, such as virtual reality, augmented reality and robotics, holds the potential to create immersive and highly interactive rehabilitation environments that significantly enhance engagement, motivation and outcomes [5].

Conclusion

In conclusion, non-invasive brain-computer interfaces have the potential to revolutionize neurorehabilitation by enabling more effective, personalized and engaging therapies. As research continues to refine the technology and as machine learning and artificial intelligence further enhance signal processing and feedback mechanisms, BCIs will likely play an increasingly central role in helping patients recover lost functions, regain independence and improve their quality of life. With the promise of greater accessibility, comfort and precision, non-invasive BCIs are poised to become a cornerstone of future neurorehabilitation strategies.

Acknowledgment

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Conflict of Interest

None.

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