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A REVIEW OF ADVANCES IN NONINVASIVE BRAIN–MACHINE INTERFACES FOR ROBOTIC-ASSISTED REHABILITATION

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ABSTRACT

During the last decade, Brain machine interfaces (BMIs) have taken a giant leap forward, enabling unprecedented developments in brain-controlled robotic devices designed to restore autonomy in persons with severe disabilities. These new creations represent a radical jump in the development of assistive technologies that will allow patients to regain control over the environment and perform tasks that, until recently, were considered unthinkable. This review is an in-depth survey that explains the current state of and future directions for non-invasive BMI robotic systems by integrating knowledge extracted through detailed analysis of studies conducted in the last 10 years. It emphasizes the dynamic interaction between the user, the BMI system, and the robotic device, dissecting in great detail the progress attained and the challenges that this exciting but complex area continues to experience.

Despite these considerable gains, there remains a glaring gap in the research: the conspicuous lack of direct end-user evaluations, particularly those involving individuals with disabilities. Technological advances in signal processing and machine learning have sharpened BMI accuracy, but few devices have been well-trialed by the real end-users—those who would actually depend on the systems in daily life. Without feedback from disabled users, developers can only gain a partial view of the user experience, which will seriously constrain the refinement of BMI technology for real-world applications. This gap highlights the most imminent requirement for a user-centered research approach in which the voices and needs of intended users are put into the forefront.

A big challenge will be the integration of the BMI systems with robotic platforms. For BMIs to become more intuitive and responsive, interfaces need to be simplified so that there is a seamless translation from the brain signal to robotic action. That is where user-centered design comes in; it can improve usability and enhance comfort, thereby heightening the real-world impact of BMIs in clinical and everyday scenarios. Overcoming these challenges will be crucial for developing noninvasive brain-machine interfaces from experimental arrangements into practical, user-friendly devices that can significantly improve the quality of life for people with motor impairments.

Keywords: Robotic-Assisted Rehabilitation, Neurorehabilitation, User-Centered Design

INTRODUCTION

The convergence of neuroscience, robotics, and rehabilitation medicine has recently witnessed an increased interest with the advent of non-invasive brain-machine interfaces, or BMIs. These technologies interpret neural activity and open up entirely new opportunities for the management of robotic systems within the rehabilitation process framework. In contrary to conventional approaches requiring the implantation of invasive probes into the brain, nowadays non-invasive BMIs enable access to patients under the exclusion of such kind of treatment (Lisi, 2017). While non-invasive approaches, reliant on the interpretation of neural signals through the scalp, have considerably transformed robotic-assisted rehabilitation in recent times, this nascent technology still poses many important questions regarding its efficacy, scalability, and long-term clinical applicability. The review currently highlights recent developments that show both the great promise and challenges associated with these technologies.

Historically, BMIs were confined to the domain of basic research and often involved invasive techniques, such as recording neural activity with electrode arrays implanted directly into the brain. These early approaches showed the feasibility of brain control of external devices but were limited by important challenges, including high risks associated with surgery, limited patient accessibility, and ethical concerns surrounding invasive procedures. Indeed, technological advances have unmistakably steered the swing towards noninvasive methodologies, which work to read brain signals by placing external sensors on or near the scalp, thus avoiding surgical procedures and the risks attached to them. Non-invasive approaches using EEG, fNIRS, and MEG, though gaining in sensitivity and precision, have found expanding uses for applications in real-time control systems of robots (Tonin, 2021).

One of the most promising areas of application of noninvasive BMIs has been in the field of robotic-assisted rehabilitation, where the recovery of motor function is assisted through the use of robotic devices. The coupled brain-machine interfaces are then used in robotic systems ranging from exoskeletons to help patients walk to robotic arms that restore fine motor skills, allowing patients to control the devices with their neural activity. The potential of these devices to enhance motor recovery is immense (He et al. 2018). For example, individuals who have suffered a stroke may use such robotic devices to regain some level of mobility or dexterity in affected limbs, all while benefiting from the neuroplasticity that comes with the brain engaging with these external devices. The challenge remains in interpreting the signals emitted by the brain to effectively control the robotic systems under consideration, as this process is highly intricate.

Various hurdles need to be overcome before the noninvasive BMIs come into widespread use for clinical rehabilitation. The first important limitation is the challenge in decoding brain signals with enough accuracy. The electrical activity of the brain, which one is able to record using EEG, tends to be noisy and sometimes hard to decipher because neural patterns are intricate. Although EEG boasts high temporal resolution, capturing rapid changes in brain activity with good resolution, its spatial resolution is poor, complicating the identification of the precise source of neural signals (Semprini et al. 2018). Combining EEG with other neuroimaging methods, like fNIRS or functional magnetic resonance imaging (fMRI), would therefore help overcome these constraints. These techniques are directed towards increasing the spatial resolution of the acquired signals, which is expected to augment the systems' accuracy. Furthermore, one of the critical challenges facing noninvasive brain-machine interfaces for robotic rehabilitation is that of performing processing in real-time while seamlessly integrating sensory feedback.

Effective rehabilitation requires not only precise control of the robotic movements but also the ability to provide patients with sensory feedback, enabling them to feel what kinds of sensations would usually occur during movement. That feedback may be very important for motor learning and neuroplasticity. While most robotic rehabilitation systems can easily provide visual feedback, the integration of haptic or proprioceptive feedback still remains a thorny issue. Researchers are looking into how the integration of sensory feedback systems, like haptic gloves or wearable devices, with robotics controlled by BMI can be done in order to provide a holistic and immersive experience during rehabilitation (McConnell et al., 2017).
Despite these challenges, the field of noninvasive BMIs for robotic rehabilitation is advancing at a tremendous pace. Several studies have shown that noninvasive BMIs driving robotic systems can significantly improve the motor function of patients, and some evidence suggests that recovery may occur faster compared to conventional rehabilitation methods. For example, stroke patients have shown enhanced mobility of limbs and a decrease in spasticity when using such systems, while those with spinal cord injuries have revealed very promising signs of regaining control of limbs. Yet, with such great advancement, the clinical applicability of non-invasive BMIs remains severely limited. Signal variability, individual differences in brain activity, and the need for customized systems are some of the challenges that need to be overcome before these technologies can be fully integrated into everyday practice in rehabilitation (Retnaningsih et al. 2023).
The full promise of noninvasive brain-machine interfaces extends beyond allowing robotic-assisted rehabilitation but also includes their potential for providing a tailored and scalable method for neurorehabilitation (Keller, 2018). As our knowledge of the brain's adaptability and potential for reorganization evolves, so too will the sophistication of BMI technologies. With the ongoing development of machine learning, signal processing algorithms, and wearable technologies, one might imagine that translating noninvasive BMIs into mainstream rehabilitation practices could substantially improve motor recovery outcomes for patients around the world.

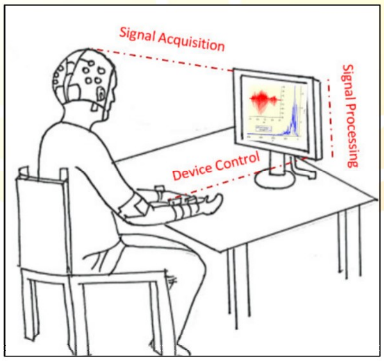

Figure 1. Schematics of Brain–Machine Interfaces for Robotic-Assisted Rehabilitation

METHODS

Rapid progress in neural signal acquisition, processing techniques, and robotic actuation have fostered the use of BMIs in robotic-assisted rehabilitation. This review synthesizes a wide array of methodologies that define the current state of the art.
Signal Acquisition Techniques: The electrical activity of the brain has been recorded in many noninvasive ways. Most importantly, these include electroencephalography, functional near-infrared spectroscopy, and magnetoencephalography.

Whereas EEG is usually preferred due to superior temporal resolution, it usually suffers from significant limitations in spatial resolution, so it is often augmented with methods such as fNIRS to provide an increase in accuracy. Lastly, magnetoencephalography has the advantage of offering the highest possible spatial resolution but substantial challenges remain in terms of cost and accessibility for much wider clinical use.

Signal Processing and Interpretation: Having acquired these neural signals, it becomes imperative to decode them. The complexity and usually disordered features of the neural patterns in the human brain have driven the necessity for signal processing. Machine learning algorithms, specifically those based on deep learning methodologies, have been used to process these unrefined signals with a view to mapping out significant patterns that could be converted into operational commands for robotic systems. It comprises complex preprocessing procedures including filtering, noise attenuation, and feature extraction in such a manner that the integrity of the signal is assured prior to processing by the decoding algorithms.

Robotic-Assisted Systems: These signals are then sent to robotic systems that can either augment or assist human movement after decoding the neural instructions. Some of the devices falling under this category are exoskeletons, which provide ambulation, and upper-limb robots focused on the restoration of fine motor function. The precision and responsiveness of these robotic systems are imperative in the designing of effective rehabilitation programs. Many robotic devices also contain real-time feedback systems, which are significant in producing the sensory input needed for patients to engage in motor learning and induce neural plasticity.

Incorporation of Sensory Feedback: The incorporation of sensory feedback presents a significant challenge within the domain of robotic rehabilitation. Although conventional systems typically depend on visual or proprioceptive cues, contemporary advancements are striving to incorporate more intricate modalities into the rehabilitation framework, including haptic feedback and virtual reality. This approach aids in closing the divide between cognitive processes and physical actions, thereby enhancing the efficacy and immersive quality of therapy and offering a comprehensive experience for patients.

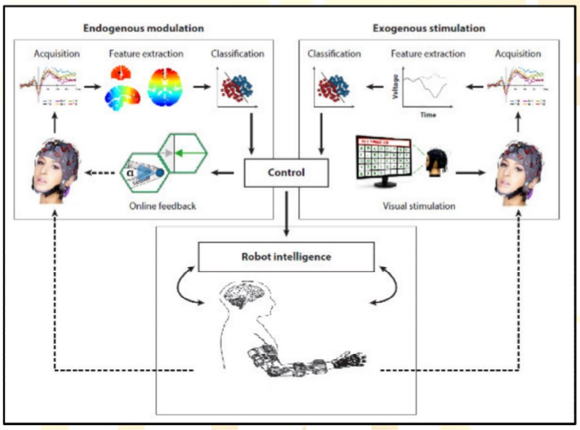

Figure 2. The BMI closed-loop framework for both endogenous (self-driven) and exogenous paradigms (Tonin, 2021).

In the endogenous paradigm, users actively modulate their brain activity through mental tasks (e.g., motor imagery) without relying on external inputs. In contrast, the exogenous paradigm involves neural responses that are induced by external stimuli, such as visual or auditory signals.

RESULTS

The results of recent studies in noninvasive BMI technologies for robotic-assisted rehabilitation are promising but varied.

EEG-Based Control: EEG-based BMIs have achieved remarkable progress in both precision and usability. Studies have demonstrated the feasibility of using EEG to control robotic devices, especially in stroke rehabilitation (Otto et al. 2012). For example, patients with partial limb paralysis have successfully used EEG to control robotic exoskeletons to perform functional tasks such as grasping objects or walking, which gives a glimpse into possible improvements in motor function after neurological injuries. However, the performance of EEG-based systems is often inconsistent, with factors such as signal noise and individual brainwave patterns affecting the consistency of the neural signal decoding.

fNIRS and Multi-Modal Approaches: Researchers have found that supplementing fNIRS with EEG significantly enhances the spatial resolution of brain activity measurements, hence enabling finer control over robotic movements. This combination has proved to be especially helpful in real-time decoding, where the accuracy of results is considered crucial. Moreover, multi-modal systems that integrate EEG, fNIRS, and sometimes MEG have been able to produce more robust and reliable results. This convergence of technologies has not only improved the interface's accuracy but also its usability for long-term rehabilitation purposes (Usakli, 2010).

Robotic System Effectiveness: The robotic systems themselves have also evolved dramatically. Studies have shown that patients with robotic exoskeletons controlled by BMIs demonstrate greater motor recovery than patients receiving conventional rehabilitation. Moreover, the addition of sensory feedback systems has been proven to enhance recovery rates, especially in fine motor tasks. However, the level of control that patients have over these systems is still somewhat limited by the resolution of noninvasive brain signals, and further refinements in signal decoding are necessary to enhance system responsiveness (Gevins, 1988).

Clinical Trials and Patient Outcomes: Results from clinical trials have established that robotic-assisted rehabilitation yields significant improvements in both motor function and the quality of life of the patients. For instance, survivors of a stroke have shown improved mobility in the limbs and reduced spasticity with the use of robotic-assisted devices, while BMI control allows them to feel more independent in their rehabilitative course. However, the results of these studies are inconsistent because some patients cannot control robotic systems effectively due to variability in brain activity and cognitive factors. These inconsistencies indicate more personalized rehabilitation approaches that might take into account individual neurological differences.

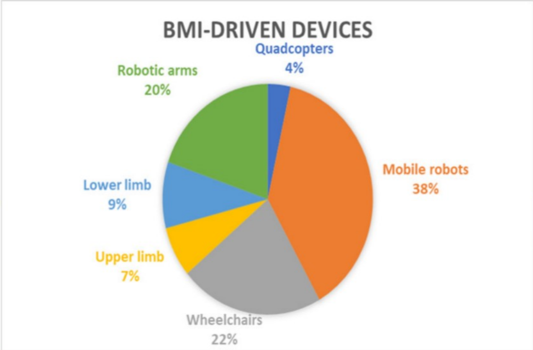

Figure 3. Proportions of BMI-controlled devices in the studies reviewed (Tonin, 2021).

This is due to the fact that many of the studies were specifically designed for motor rehabilitation, and as a result, predominantly employed self-paced BMI paradigms based on motor imagery.

CONCLUSION

In conclusion, noninvasive brain-machine interfaces represent a transformative frontier in the field of robotic-assisted rehabilitation, offering a powerful alternative to traditional therapies. Advances in neural signal acquisition, processing algorithms, and robotic actuation have reached a high level, pushing the boundaries of what is possible for individuals suffering from motor impairments. However, several challenges remain. It is obvious that the decoding of signals needs even more refinement to ensure good and reliable control of the robotic systems. Further areas of integration of sensory feedback and individualization of patient-specific robotic interventions also remain a challenge that calls for concentrated research. As non-invasive BMIs continue evolving, the potential of the technology for improving the quality of life and restoring functional independence in persons with neurological impairment becomes very clear.

However, there is still much work ahead. It will be the road to addressing the deficiencies of existing systems, developing more robust signal processing, and offering more user-friendly interfaces. Moreover, this will extend clinical trials with a greater variety of neurological conditions and more diverse patient populations to see the full range of their potential. The future of robotic-assisted rehabilitation using noninvasive BMIs is no doubt bright, but to realize the transformational possibilities, it will require further collaboration between neuroscientists, engineers, and clinicians.

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