ORIGINAL ARTICLE

The Use of Brain-Computer Interface Technology in the Restoration of the Upper Limb Functions from Spinal Cord Injuries

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[Abbreviations: BCI: Brain-Computer Interface, SCI: Spinal cord injury]

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ABSTRACT

Spinal cord injuries (SCI) can result in lifelong disability from the disconnection of the neural pathways in the spine to the brain, causing motor and functional deficits. In recent years, there has been growing interest in applying Brain-Computer Spinal Interface (BCI) technology to address the challenges individuals face with SCI.

A systematic literature review resulted in a comprehensive analysis of existing studies on BCI for SCI. The selected studies covered various approaches to BCI for restoring motor function in participants with an SCI. The BCI interventions ranged from non-invasive electroencephalography-based systems to more invasive technologies involving neural implants on the cortex of the brain and the epidural space on the spine.

The key findings of this review suggest that BCI technologies hold promise in significantly improving the quality of life and functional capabilities of individuals with SCI. Many studies reported significant improvements in motor function, communication, and overall well-being following BCI interventions. These interventions often facilitated direct communication between the brain and the spinal cord, bypassing the disconnected pathways between the brain and the spine caused by SCI.

INTRODUCTION

Spinal cord injury (SCI) is a devastating condition that affects millions of people worldwide. The consequences of SCI affect a substantial cohort of Americans, numbering in the hundreds of thousands. Within the spectrum of these neurological afflictions, spinal cord injuries and amyotrophic lateral sclerosis (ALS) emerge as formidable and consequential maladies, lowering life expectancy and quality of life and can result in tetraplegia if a person has an SCI at the cervical level of the spine [1]. Spinal cord injuries are defined as damage to the bundle of nerves and nerve fibers that send and receive signals from the brain, resulting in major sensory or motor deficits from the level of injury. The spinal cord extends from the lower part of the brain to the lower back. According to the National Institutes of Health (NIH), the incident rate for a spinal cord injury is fifty-four per one million cases in the United States, with seventeen thousand five hundred new SCI cases [2]. 65-78% of SCI cases have spasticity, and 27% of SCI cases cause paralysis [3]. The current treatments for spinal cord injuries involve physical rehabilitation and therapy.

Recent advances in medical technology have opened innovative avenues for addressing these challenges, and one up-and-coming area of research is the development of brain-computer-spinal interfaces (BCI). These interfaces seek to restore lost motor function by establishing a direct connection between the brain, a computer system, and the spinal cord to bypass damaged neural pathways. BCIs allow the CNS to acquire new skills in which brain signals replace the spinal motor neurons that produce natural muscle-based skills. Muscle-based skills depend for their acquisition and long-term maintenance on continual activity-dependent plasticity throughout the CNS, from the cortex to the spinal cord. This plasticity, which generally requires practice over months or years, enables babies to walk and talk, children to learn reading, writing, and arithmetic, and adults to acquire athletic and intellectual skills.

Researchers have begun creating artificial connections between the brain and paralyzed limbs to restore function to the paralyzed upper limbs. These connections can be made by stimulating the muscles, their associated peripheral nerves, or the spinal cord below the injury. Muscle and nerve stimulation can restore some function after SCI but requires individual controllers for separating target muscles or nerves. Muscle and nerve stimulation also leads to rapid muscle fatigue during stimulation, limiting their clinical adoption. Alternatively, intraspinal micro stimulation (ISMS) provides naturalistic recruitment of muscle fibers with functionally synergistic movement. However, the clinical testing of ISMS has proceeded slowly due to its invasiveness (University of Washington 2021). This meta-analysis aims to examine the effectiveness of BCIs in restoring hand/arm function in individuals with SCI.

METHODS

Protocol and registration

This systematic review and meta-analysis followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Figure 1).

Eligibility criteria

A systematic review and analysis of studies including patients diagnosed with an SCI that underwent an implantation procedure of a brain-spinal computer interface (BSCI). Participants were eligible based on an adult at the time of the study, any sex, having a chronic SCI (longer than one year post-injury) at the cervical segments of the spine's motor level, and utilization of a BCI system to restore hand/arm function. They reported the effectiveness of the BCI system. Studies published since 2010 were included in this study. This study was conducted from September 2023 to November 2023 and screened by each author involved in this analysis. We excluded studies that did not meet these criteria or were not written in English.

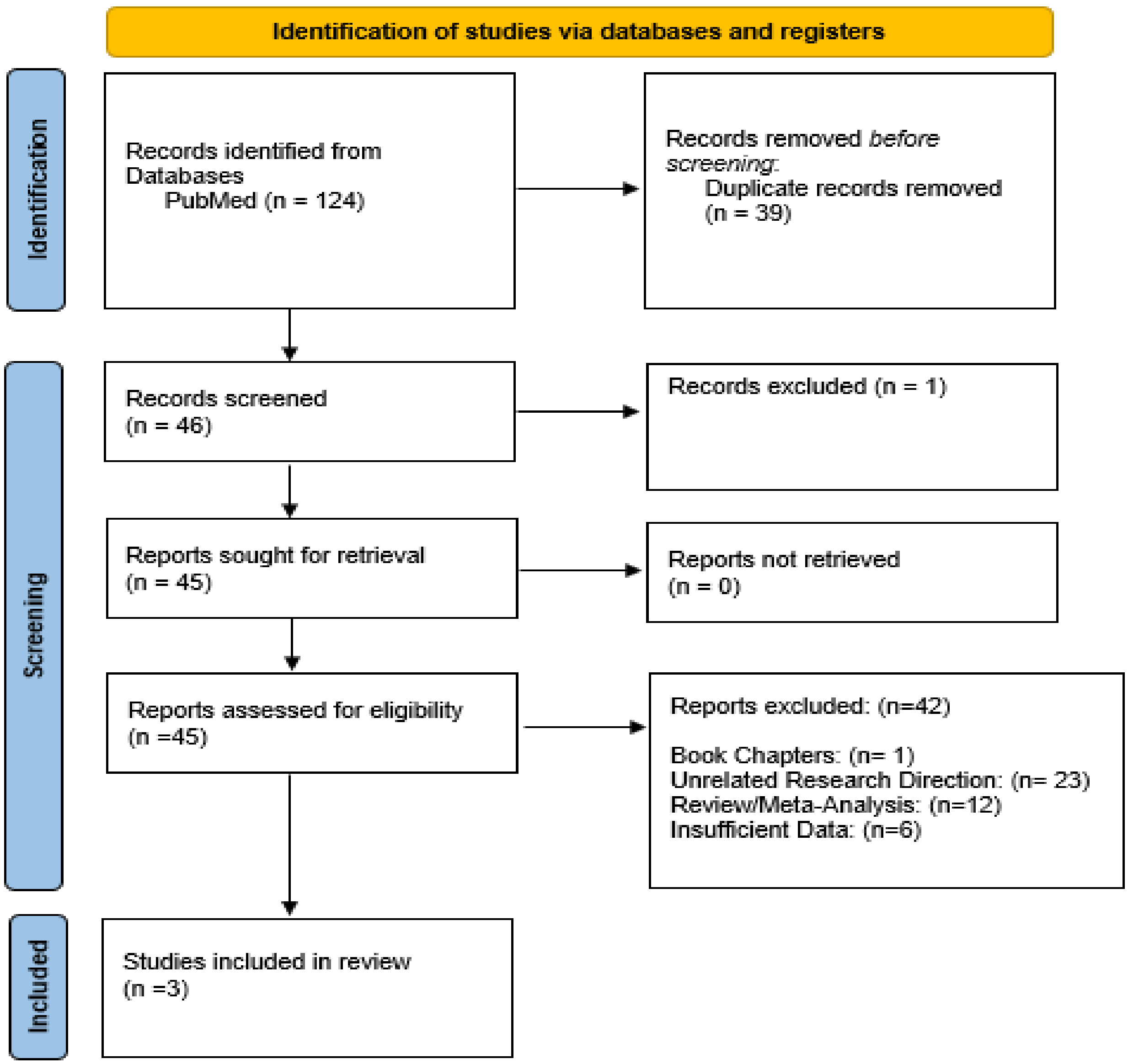

Figure 1. **PRISMA 2020 flow diagram -** study elimination process. The PRISMA flow diagram depicts the flow of information through the different phases of systematic reviews and meta-analyses. It maps out the number of records identified, included, and excluded and the reasons for exclusions.

Search and study selection.

Literature from PubMed and The University of Texas at Dallas Library were selected based on the following inclusion criteria: participants with an SCI equipped with a BCI system for rehabilitation and restoration of any loss of motor or sensory deficits in the upper limbs affected by SCI. Studies reporting quantitative data on the effectiveness of BCI systems were also sought. Studies on participants without an SCI with a BCI system were excluded from this review of the use of BCI technology.

Data Extraction

Authors screened articles independently against the inclusion criteria, excluding those that did not. All relevant and excluded studies were recorded on Zotero and then analyzed by the authors of this review.

For each study, data related to the publication date, participant demographics, study type, modalities utilized, patient outcomes, and findings. Overall data on patient outcomes post-BCI implantation were extracted using the inclusion criteria by the authors.

Author, Year	Study Participants	Pathology/SCI	Treatment Technique(s)	Patient Outcomes
Cui et al., 2021	**2 SCI patients: Male, age 67 Female, age 41**	**T3 level lesion**	**- BCI-based robot system to detect patient's motion intention to assist in rehabilitation training over two weeks**	**Both patients improved. - Pt. 1 ADL score increased from 1 to 20 points, - Pt. 2 reported an overall improvement in quality of life.**
Muller-Putz et al., 2018	5 pts with SCI	Cervical SCI	- Transform EEG brain signals into continuous control commands for a restorative neuroprosthesis or robotic arm	BCI system effectively restored upper limb functions, such as reaching and grasping, with some errors in interpreting motor commands.
Samejima et al., 2021	11 female Long Evans rats (250-360g)	Cervical SCI	- 16-wire tungsten microelectrode arrays on the sensorimotor cortex. - Epidural spinal stimulating electrode implant. - A rewarding lever-pressing task.	- Intracortical local field potentials provide a stable marker of movement intention before and after SCI. - Brain-controlled epidural stimulation improves forelimb function - The computationally efficient closed-loop algorithm can be implemented on a miniaturized device with onboard computing.

Table 1. Publications were selected for this study.

Patient screening for BCI implantation surgical procedures

Patients with an SCI at the cervical or thoracic spinal level. Psychological evaluations of each patient were conducted for eligibility for BCI. Patients ages 12-50 years were included.

Surgical Protocol

Preoperative evaluation with functional magnetic resonance imaging (fMRI) and diffusion tensor imaging (DTI) were used to identify the location of the corticospinal tract fibers.

Statistical Methods

P-value testing and graphs coded by R were used in this meta-analysis.

RESULTS

Our search identified ten relevant studies, of which three met our inclusion criteria (Table 1). The three studies are summarized below. Study 1 (Cui et al., 2021): The brain-computer interface-based robot gives spinal cord injury patients a full-cycle active rehabilitation. This study described a BCI system that uses a robotic arm to provide active rehabilitation for patients with SCI. The study involved two participants, and the results showed that the BCI-based robotic arm effectively improved upper limb function. Specifically, the participants showed significant improvements in their ability to perform daily living activities, such as eating, drinking, and dressing [4]. Study 2 (Muller-Putz et al., 2018): Towards Non-Invasive Brain-Computer Interface for Hand/Arm Control in Users with Spinal Cord Injury. This study proposed a noninvasive BCI system that uses electroencephalography (EEG) to detect motor imagery signals to control a robotic arm. The study involved five participants with SCI, and the results showed that the proposed BCI system effectively controlled the robotic arm. Specifically, the participants could perform various tasks, including reaching, grasping, and releasing objects, using the BCI system [5]. Study 3 (Samejima et al.,

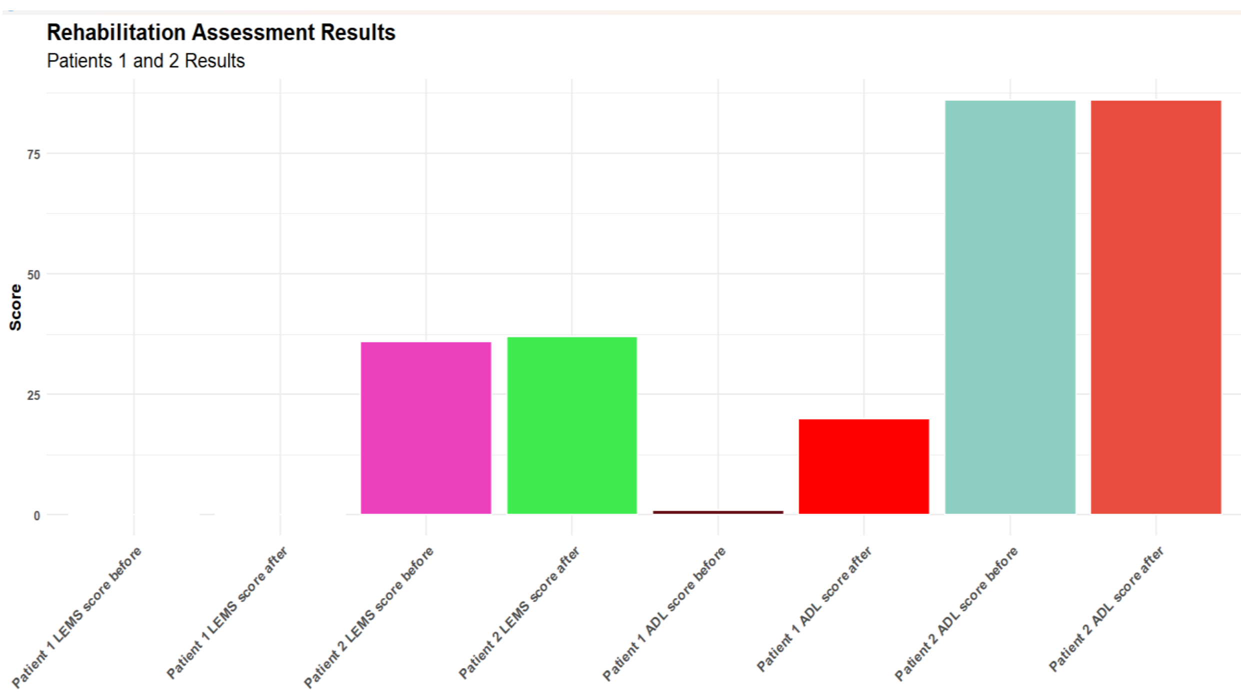

Figure 2. The bar chart via R Studios—Rehabilitation assessment results were gathered from Cui et al.

2021): Brain-Computer-Spinal Interface Restores Upper Limb Function After Spinal Cord Injury. This study proposed a novel BCI system that uses invasive electrodes to record neural signals from the brain and stimulate the spinal cord to restore upper limb function. The study involved two participants with SCI, and the results showed that the BCI system effectively restored upper limb function. Specifically, the participants could perform various tasks, including reaching, grasping, and releasing objects, using the BCI system [6].

From Cui et al., we can see that a significant factor in BCI success is the correct forms of rehabilitation, which was unique to the other studies, as the factors of LEMS (lower extremity motor score) and ADL (Activities of Daily Living) were assessed post rehabilitation efforts from BCI. Interestingly, LEMS was considered post activities performed by both SCI patients for a whole body rehabilitation process, meaning both upper motor and lower motor neuron states were assessed and improved.

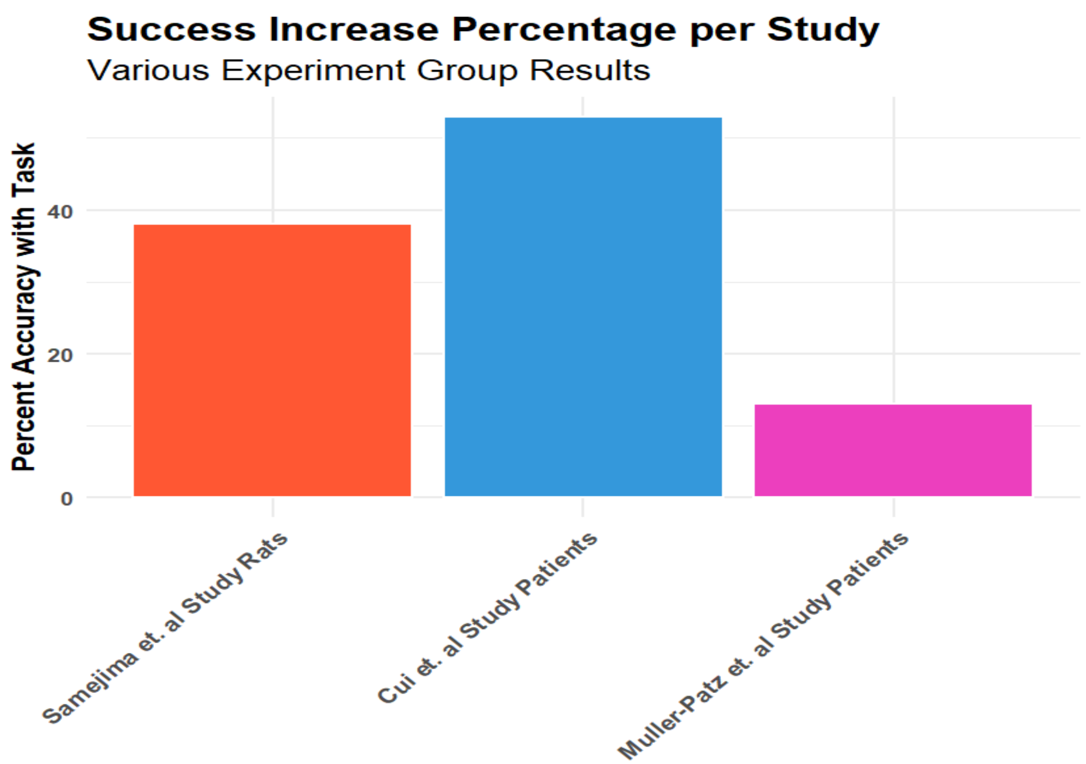

Figure 3. Bar Chart via R Studios—Rehabilitation assessment results gathered from all three studies.

These results demonstrate that success results were statistically significant compared to other forms of rehabilitation methods for those suffering from SCI complications, as there was a p-value < 0.05 from increased success compared to techniques such as just surgery or physical therapy alone [7]. However, their maintenance methods were not as statistically significant, as there was a p-value of > 0.05, demonstrating that traditional methods alone may be the best. However, further research is needed to progress these results.

From Samejima et al., we see the use of intracortical local field potentials (LFPs) in the high gamma band (200-400 Hz) to decode forelimb movement intention in rats with cervical spinal cord injury (SCI) 1. The LFP decoder was found to be stable and accurate over many days before and after SCI, without requiring frequent recalibration or spike sorting. An implementation of BCSI that used the LFP decoder to trigger epidural stimulation of the spinal cord below the injury site, which restored functional upper limb movement in rats with severe SCI.

It was also demonstrated that the BCSI system could be implemented on a miniaturized device with onboard computing, potentially enabling implantable and wireless BCI applications for humans.

Category	Results
Goal-directed movement intention	Detection of movement intention from EEG was improved when the movement had a specific goal, and target selection and movement initiation could be separated using different experimental paradigms.
Classification of Single Upper Limb Movements	Six different upper limb movements could be discriminated from EEG using low-frequency time-domain features for movement execution and imagination. The classification accuracy was higher for movement execution than for imagination. The source analysis revealed that motor and parietal areas were involved in the movement discrimination.
Classification of Single Upper Limb Movements	Three different reach-and-grasp actions could be distinguished from EEG using low-frequency time-domain features. The binary classification accuracy was above 70% for both grasp vs. grasp and grasp vs. rest conditions. The multi-class classification accuracy was about 66% when including the rest condition.
Classification of Movements in End-Users	The classification accuracy was above 50% for single upper limb movements and grasps.
Kinematics Decoding and EOG Artifacts	Significant correlations were demonstrated between the neural estimates and hand velocities and positions. A method was proposed to correct the EOG artifacts caused by eye movements during visuomotor tasks. It showed it could attenuate the artifacts to noise level without affecting the resting EEG.
Error-Related Potentials	Error trials could be classified from the correct trials with high accuracy, and masked feedback did not influence the classification performance through continuous control and feedback.

Table 2. Demonstrating Muller-Putz Study Results Analysis.

Muller Putz et al. discuss the nature of command to control behavior in BCI, which is displayed through error-related potentials. This notion is particularly significant as it touches upon how BCI technology could be further improved in later studies, with an asynchronous detector of errors being a plausible way to produce continuous control and feedback from a patient [8].

DISCUSSION

The three studies suggest that BCIs have the potential to help individuals with SCI regain upper limb function. From Samejima et al., we discovered that an intracortical high gamma local field potential provided a good indicator of forelimb movement intention without recalibration over many days before and after a spinal cord injury, brain-controlled epidural stimulation improved limb function and a computationally efficient closed-loop algorithm could be implemented onto a miniature BCI device to aid in clinical success [6]. These results corroborated data from Cui et al., as rehabilitation and the use of BCI robots were able to improve patients with spinal cord injury significantly. Muller-Putz et al. discuss utilizing EEG signals for BCI control, as upper limbs contain distinct brain pattern differences that can be exploited for control through BCI. Both Cui et al. and Muller-Putz et al. discuss the reliance on vision-based interactions from meaningful somatosensory feedback to create a feeling of intuitive control by the user [4-5]. BCI can help repair the functional connections between the brain and external limbs by rebuilding the cortex of the damaged brain. Neural recovery is crucial for many functions, and various neuropathological changes can lead to different dysfunctions in nervous system diseases. Studies have shown that BCI positively affects functional mechanisms such as cortical excitability [5], cerebral plasticity, and functional connectivity [4]. As a result, BCI is now being used as a rehabilitation method for upper limb dysfunction based on the principle of neuroplasticity.

However, there are several limitations to consider. First, the study sample sizes were small, limiting the findings' generalizability. More extensive studies are needed to confirm the effectiveness of BCIs in restoring hand/arm function in individuals with SCI. Second, the studies used different types of BCI systems, which makes it difficult to compare the effectiveness of the systems. Future studies should use standardized BCI systems to allow for direct comparisons. Third, the studies did not report on the long-term efficacy and safety of the BCI systems. More research with human-based models is needed to determine the long-term effects of BCIs on upper limb function and ensure the systems' safety.

CONCLUSION

In conclusion, the three papers suggest that BCIs have the potential to help individuals with SCI restore the loss of upper limb function. However, more research is needed to determine BCI systems' long-term effectiveness and safety for individuals with SCI. More extensive studies using standardized BCI systems are required to confirm the efficacy of BCIs in restoring hand/arm function in individuals with SCI. Future studies may include novel implementation methods, resulting in higher long-term effectiveness across more patients. Recent studies have indicated that BCI may be intertwined with machine learning to harvest behaviors humans engage in to produce a more efficient result for upper motor limb functions.

Brain-computer interface (BCI) technology holds immense promise in restoring the upper limb functions of individuals with spinal cord injuries. By combining advancements in neuroscience, computer science, and engineering, BCI technology has the potential to revolutionize the field of neurorehabilitation. The ability to control prosthetic limbs, computers, and other devices using just the power of the mind is no longer just a dream but a reality. The implications of this technology go far beyond just restoring movement

- it can potentially improve the quality of life of countless individuals, granting them a sense of independence and enhancing their overall well-being.

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