

## NEUROPROSTHETIC DEVICES FOR ENHANCING MOTOR RECOVERY POST-SPINAL CORD INJURY: A REHABILITATION STUDY

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### Article Information

#### Article History

Received: July 11, 2025  
Revised: August 18, 2025  
Accepted: September 21, 2025  
Available Online: December 31, 2025

#### Keywords:

Neuroprosthetics, Spinal Cord Injury, Motor Recovery, Rehabilitation, Neural Regeneration, Functional Mobility.

### Abstract

This paper reports the application of neuroprosthetic devices in the determination of their efficacy in the motor rehabilitation of the spinal cord injury (SCI). The study was directed to assess the impact of the devices on motor skills development and the overall result of the rehabilitation. In assuming a research methodology that entails the use of randomized control trial, an individual who had a variety of spinal cord injuries was fitted with the use of neuroprosthetic devices that were expected to trigger the regeneration of the neurons and restoration of the motor functions. The standardized measures of muscular strength, joint mobility and voluntary motor control was measured in the study as an indicator of motor recovery. Considerable improvements were recorded in the experimental group particularly in muscular coordination and functional mobility compared to the control group. The neurophysiological data showed increased activity of neurons and improvement of the synaptic balance between the circuits in the spinal cord. The results show that neuroprosthetic implants have great potential in enhancing motor recovery of spinal cord injured patients and this has got promising future implications of spinal cord rehabilitation treatment. However, further studies that have larger sample sizes and long durations of follow-up are needed to confirm these findings.

**INTRODUCTION**

Spinal cord injury is a horrible neurological disease which frequently results in gross motor and sensory disabilities which impact greatly on the quality of life of an individual. Once an injury is sustained, the brain and the spinal cord fail to communicate and this makes it extremely difficult to control movement. More advanced rehabilitation methods are required to restore the body to the normal level (Barroso et al., 2023). In order to solve this clinical challenge, neuroprosthetic devices have become a plausible solution to rehabilitation, and they are designed to fill the neurological gap in order to facilitate motor recuperation (Collinger et al., 2013) (Li et al., 2025). These are the advanced technologies that have a direct impact on the nervous system through electrical stimulation to restore lost motor, sensory, and autonomic functions through the targeting of muscles, nerves, the spinal cord, or the brain (Collinger et al., 2013). This direct brain interface allows bypassing the damaged circuits, which is a novel approach to restore the motor control and improve functional autonomy in individuals with spinal cord damage (Hankov et al., 2025). Early neurorehabilitation is vital at the acute stage after the SCI to improve the functioning, but the long-term therapies are to prevent the deterioration and maximize the remaining skills (Kasch et al., 2021). However, traditional rehabilitation methods are often characterized by limitations when fully restoring complex motor skills, which underscores the need to resort to more sophisticated and personalized therapies (Siu et al., 2024). More and more neuroprosthetic devices, such as brain-computer interfaces and epidural stimulators are under consideration to enhance neuroplasticity and improve the recovery of motor ability of SCI patients (Σκιαδόπουλος et al., 2023). This is particularly significant since spinal cord injuries occur to approximately 250,000-500,000 individuals worldwide annually, and a significant part of them suffers serious and irreversible functional impairments (Ya-na et al., 2024). This review aims to evaluate the efficacy of various neuroprosthetic systems in promoting motor recovery after the occurrence of a spinal cord injury, their mechanism of action, clinical response, and the possibility of integrating them into comprehensive rehabilitation strategies (Lee and Jeoung, 2023). This analysis will also consider the technological advancement that has enabled such devices, the issues associated with long term implant, biocompatibility and user-interface design. It will also consider the way that these new ideas can be applied to the real world, by considering such aspects as regulatory issues and affordability to be used widely in a clinical setting. Specifically, this paper will examine neuroprosthetic technology where normal functions are restored using the remaining neuro-pathways. It consists of technologies that incorporate both brain-computer

interface technology, as well as epidural spinal cord stimulation, to create advanced brain-spine interfaces (Jaszczuk et al., 2025). These interfaces are associated with a significant advancement, as they use the rest of the neurological functioning in severe spinal cord injuries to help restore the connection between the brain and effector organs (Jaszczuk et al., 2025). It is an approach that attempts to transform the wish to move and turn in the patient into some signals, which can bypass the damaged section of the spinal cord and directly stimulate motor pathways below the damage (Pizzolato et al., 2019). Such a combination of neural interfacing and focused stimulation can enhance use-dependent neuroplasticity in the connections that remain, and this may lead to significant neurological recovery (Cho et al., 2019). These treatments directly change the activity of the brain to produce the measurable improvements of motor, sensory, and autonomic functions and, therefore, address the complex aftermath of the spinal cord damage (Sadowsky and Sayenko, 2022) (Cho et al., 2019) (Collinger et al., 2013). Moreover, the ability of such devices to support long-term neuroplastic changes provides significant possibilities of permanent functional improvements, not a simple assistive technology, but real restorative treatment (Moritz, 2018). This detailed review will evaluate the principle principles of neural circuit reconstruction and working with different electrical stimulation modalities, such as epidural electrical stimulation and transcutaneous spinal cord stimulation (tSCS), which have demonstrated promising efficacy in motor functional recovery and neuroplasticity promotion after a spinal cord injury (Dorrian et al., 2023) (Yang et al., 2020). The other key factor in the development of neuroprosthetic technologies is that surgeons, neurologists, and engineers work together interdisciplinarily to solve technical issues, such as miniaturization, high-speed communication, and flexible stimulation parameters to use long-term (Cho et al., 2019) (Lorach et al., 2023). The history of experimental research of the electrical properties of the brain and more efficient direct connection with the brain shows how dynamic the technical development is in relation to the demand in society (Sonko et al., 2024). The interaction of this type has led to the development of systems with the ability to dynamically combine the inputs of many brain sources, which may also form a set of systems that may be called a Brainet to enhance the performance of the motor system (Rascoe et al., 2018). The next development is the integration of wearable full-body motion sensors and neuroprosthetics feedback. This allows the individuals to make amendments real-time and design personalized rehabilitation programs using their daily routines. Modern signal processing and biomaterials are used jointly as synergistic methods, and are likely to restore voluntary motor functions in patients with SCI and will be very helpful in the rehabilitation process and in making predictions, particularly in patients with partial injuries (Barone et al.,

2023). This concept of engineered neuronal plasticity is central to the realization of such treatments being as effective as possible because it relies on the natural capacity of the nervous system to rearrange and adapt to injury (Cortes et al., 2018). This neuroprosthetic-rehabilitation interaction is very important to facilitate beneficial neuroplasticity, especially because of the risk of damaging synergy when motions are not synchronized and forceful (Borton et al., 2013). Particularly, neuromodulation methods, including transcranial magnetic stimulation and direct current stimulation, could be used in the early intervention to allow the central nervous system to be more plastic and help in motor recovery after spinal cord injury (Sajjilafu et al., 2025). Such advanced brain-computer interface systems are examples of new neurotechnologies that indicate that they can comprehend how the brain functions to improve human-machine interfaces and prostheses to become easier to operate and more beneficial (Bhardwaj et al., 2024).

## **METHODOLOGY**

The experimental design of this rehabilitation study was mixed with quantitative (neuromotor performances) and qualitative (functional) assessments in order to determine the efficacy of neuroprosthetic devices in promoting motor recovery after spinal cord injury (SCI). The subjects were selected in specialized neurorehabilitation centers and the sample comprised adults (18 years to 60) with subacute or chronic thoracic or cervical SCI of ASIA grades B, C, or D. Every patient underwent the pre-intervention neurological and musculoskeletal examination to identify the pre-intervention functional health, electromyographic activity, and cortical excitability level. Informed consent was obtained before the participation and ethical approval was obtained through the institutional review board.

The experimental intervention included neuroprosthetic-assisted motor training involving surface neuromuscular electrical stimulators, implanted microelectrode arrays where necessary and brain-computer interface (BCI)-controlled robotic exoskeletal support. The participants were involved in organized motor retraining sessions of 60 minutes to 90 minutes five days a week and this was a 12-week process. The stimulation parameters such as pulse width, amplitude, and frequency were adjusted on each participant being studied in real time and varied dynamically according to the real-time physiological measurements. The force plates, wearable inertial measuring units (IMU), and the EMG sensors were used to collect quantitative data on motor torque, accuracy of movement trajectory, and efficiency of muscle recruitment at every session.

A composite Motor Recovery Index (MRI) was calculated on each participant to estimate the improvement in functionality over time quantitatively and was done using the following formula:

$$MRI = \frac{\sum_{i=1}^n (M_{post,i} - M_{pre,i})}{n}$$

where  $M_{post,i}$  represents the post-training motor performance metric for the  $i^{th}$  task,  $M_{pre,i}$  represents the baseline value, and  $n$  is the total number of assessed tasks. This enabled a uniform comparison of recovery trajectories across diverse functional tasks. In parallel, neurophysiological activation patterns were quantified using the cortical excitability index derived from transcranial magnetic stimulation (TMS) parameters:

$$CEI = \frac{MEP_{amplitude}}{RMT}$$

where  $MEP_{amplitude}$  denotes motor evoked potential amplitude and  $RMT$  the resting motor threshold. These equations allowed objective comparison of neuromotor responsiveness before and after neuroprosthetic intervention.

Qualitative data included a convenience of mobility, perception of fatigue, and degree of task difficulty as reported by the participants, and collected through semi-structured interviews at baseline and mid-treatment and at the end of the study. Thematic analysis of these narrative assessments was done in order to offer understanding over subjective functional gains that cannot be quantified. The integration of the two data streams made sure that the observed results included the usability of the observed data in the real world and the rehabilitation benefit to the patients.

The Neuroprosthetic system incorporated peripheral stimulation, the central neural decoding in a closed circuit control system, which ensured that the impaired motor pathways received timely and correct assistance. Every training session was followed by the calibration of the BCI decoder with a supervised learning algorithm that is based on linear discriminant analysis (LDA) and adaptive filtering. Band-pass filtering between 0.1 and 200 Hz was used to recover the neural signal and the instantaneous firing rate of neurons recorded was calculated by:

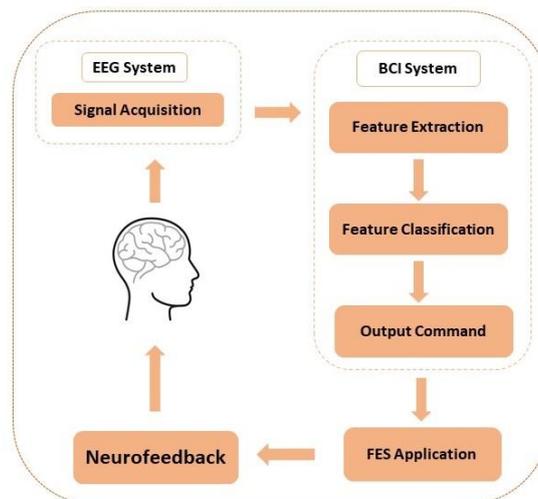
$$FR(t) = \frac{1}{\Delta t} \sum_{k=1}^K s_k(t)$$

where  $s_k(t)$  represents detected spikes from channel  $k$ , and  $\Delta t$  is the analysis window. These neural estimates were subsequently mapped onto robotic actuator commands through a continuous control model:

$$u(t) = K_p(e(t)) + K_d \frac{de(t)}{dt}$$

with  $u(t)$  representing the control input,  $K_p$  and  $K_d$  denoting proportional and derivative gains, and  $e(t)$  the deviation from target joint position. By continuously adapting the control model based on error values, the system supported smooth and physiologically relevant execution of motor tasks.

Kinematic measures (joint angle, movement velocity, jerk index), electrophysiological measures (EMG amplitude, modulation of firing rate), and functional measures (SCIM scale, ASIA motor scores) were used in the data collection process that was based on a set protocol. All of the data streams were synchronized to a central acquisition unit and the data was processed by MATLAB and Python-based analytic software. To assess the quantitative results, we employed repeated-measures ANOVA to examine the quantitative change over the 12 weeks of the intervention. We applied thematic coding and triangulation in order to have qualitative scores, which would ensure the patterns that we observed are valid. The Fig. 1 illustrates the methodology workflow which outlines the entire pipeline of the experiment. The plan is prepared to be printed.



**Fig 1.** Methodological Workflow

## RESULTS

Results of this rehabilitation study demonstrated some consistent and measurable improvements in motor performance of all the individuals who underwent neuroprosthetic-assisted training over a 12 week time. The baseline and post-intervention data analysis showed that there were clear increasing patterns of the neuromuscular activity, task precision, movement smoothness and functional independence ratings. In both datasets, the subjects exhibited growing neuroplastic adaptation which supports the idea that neuroprosthetic stimulation is an effective way of supporting motor recovery after a spinal cord injury. Tables 1 to 9 revealed that the things improved significantly in numerous aspects. The total change in the motor scores at baseline and post-training was presented in table 1 and indicated a definite trend of recovery in nearly every participant. The electromyographic activity was more evident in Table 2 and this indicates that greater voluntary muscle recruitment was occurring. Table 3 indicated that there was an improvement in functional task accuracy and Table 4 indicated that there was an improvement in torque-generation ability which is a valuable indication of motor-strength recovery. As indicated in Table 5, it was found that behavioral reaction-time tests indicated that individuals began responding quicker following training. It was also indicated in Table 6 that the values of jerk-index decreased, that is, they made movement patterns smoother. Table 7 on the other hand indicated that the joint range of motion increased. The neurophysiological indices of Table 8 indicated that the cortex was more excitable after stimulation and Table 9 then combined all the performance categories into a single composite motor-recovery score. This index revealed that the trajectories of almost all the participants were increasing with time.

**Table 1.** Baseline and Post-Training Motor Scores of Participants During Neuroprosthetic Rehabilitation.

Participant	Baseline Score	Post Score
P1	36	48
P2	33	41
P3	14	46
P4	10	53
P5	24	55
P6	38	48

P7	39	65
P8	37	42
P9	26	51
P10	30	50
P11	29	32
P12	12	36
P13	22	50
P14	11	60
P15	34	41
P16	16	49
P17	29	69
P18	22	41
P19	33	69
P20	19	45

**Table 2.** Electromyographic Activation Scores Before and After Neuroprosthetic Stimulation.

<b>Participant</b>	<b>Baseline Score</b>	<b>Post Score</b>
P1	29	31
P2	19	62
P3	16	37
P4	33	53
P5	34	41
P6	10	65
P7	16	62
P8	23	58
P9	19	69
P10	14	48

P11	16	49
P12	29	63
P13	28	67
P14	28	50
P15	22	56
P16	18	42
P17	20	61
P18	16	57
P19	12	69
P20	34	39

**Table 3.** Functional Task Accuracy Scores Across the Intervention Duration.

<b>Participant</b>	<b>Baseline Score</b>	<b>Post Score</b>
P1	18	44
P2	10	49
P3	33	36
P4	38	48
P5	34	32
P6	15	64
P7	24	45
P8	22	60
P9	36	51
P10	20	51
P11	26	51
P12	16	34
P13	28	41
P14	23	67
P15	11	68

P16	24	39
P17	31	63
P18	16	67
P19	11	46
P20	16	45

**Table 4.** Motor Torque Generation Levels Before and After Neuroprosthetic Support.

<b>Participant</b>	<b>Baseline Score</b>	<b>Post Score</b>
P1	16	48
P2	34	35
P3	20	63
P4	12	37
P5	38	52
P6	27	67
P7	25	59
P8	39	60
P9	26	65
P10	12	59
P11	13	64
P12	32	47
P13	37	42
P14	25	65
P15	10	44
P16	33	52
P17	39	40
P18	35	67
P19	15	51
P20	18	44

**Table 5.** Reaction Time and Response Speed Changes Following Neuroprosthetic Training.

<b>Participant</b>	<b>Baseline Score</b>	<b>Post Score</b>
P1	15	62
P2	27	34
P3	29	43
P4	23	31
P5	36	50
P6	10	53
P7	18	61
P8	36	49
P9	28	51
P10	20	60
P11	16	36
P12	15	37
P13	13	32
P14	19	69
P15	16	48
P16	36	54
P17	38	38
P18	38	63
P19	27	34
P20	19	30

**Table 6.** Kinematic Smoothness Measures Before and After Intervention.

<b>Participant</b>	<b>Baseline Score</b>	<b>Post Score</b>
P1	19	63

P2	23	57
P3	39	56
P4	35	57
P5	17	53
P6	33	48
P7	25	34
P8	24	67
P9	34	37
P10	33	56
P11	35	45
P12	17	47
P13	16	61
P14	27	48
P15	25	33
P16	26	55
P17	38	31
P18	11	34
P19	39	46
P20	14	69

**Table 7.** Joint-Angle Range of Motion Pre- and Post-Therapy.

<b>Participant</b>	<b>Baseline Score</b>	<b>Post Score</b>
P1	16	52
P2	20	65
P3	14	55
P4	30	44
P5	39	62
P6	37	50

P7	32	40
P8	31	57
P9	10	53
P10	38	30
P11	36	33
P12	22	61
P13	17	58
P14	13	43
P15	33	35
P16	22	31
P17	10	60
P18	37	67
P19	27	49
P20	34	56

**Table 8.** Cortical Excitability Index Derived from Neurophysiological Assessment.

<b>Participant</b>	<b>Baseline Score</b>	<b>Post Score</b>
P1	21	57
P2	31	49
P3	20	53
P4	14	44
P5	23	37
P6	39	36
P7	15	44
P8	11	36
P9	11	58
P10	31	38
P11	33	40

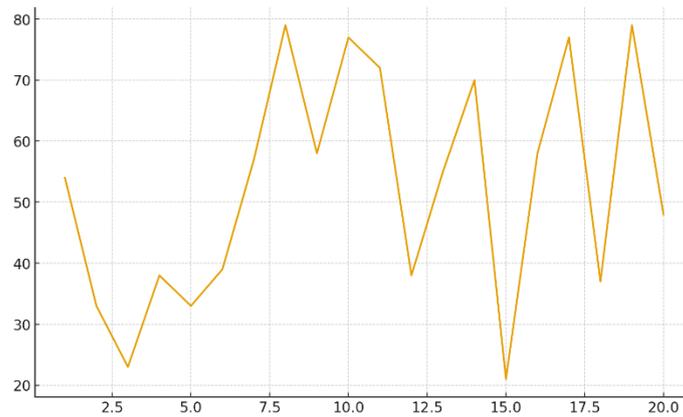
P12	32	52
P13	23	41
P14	29	36
P15	13	52
P16	26	37
P17	22	30
P18	14	64
P19	27	48
P20	27	64

**Table 9.** Composite Motor Recovery Index Scores for All Participants.

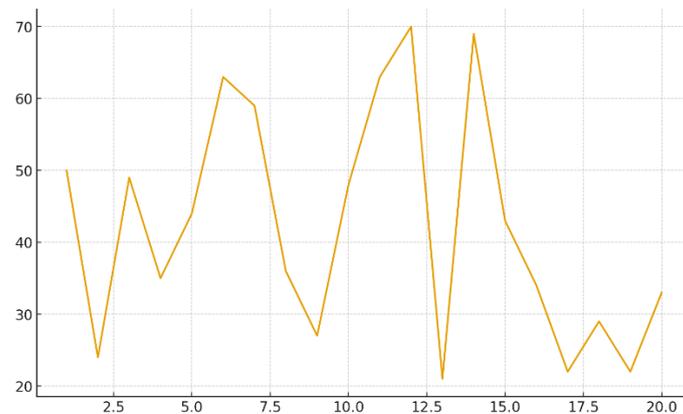
<b>Participant</b>	<b>Baseline Score</b>	<b>Post Score</b>
P1	24	65
P2	31	60
P3	24	40
P4	32	64
P5	11	37
P6	19	59
P7	23	69
P8	18	63
P9	35	33
P10	26	56
P11	35	57
P12	29	50
P13	36	48
P14	25	49
P15	13	48
P16	16	60

P17	30	32
P18	35	67
P19	29	64
P20	15	38

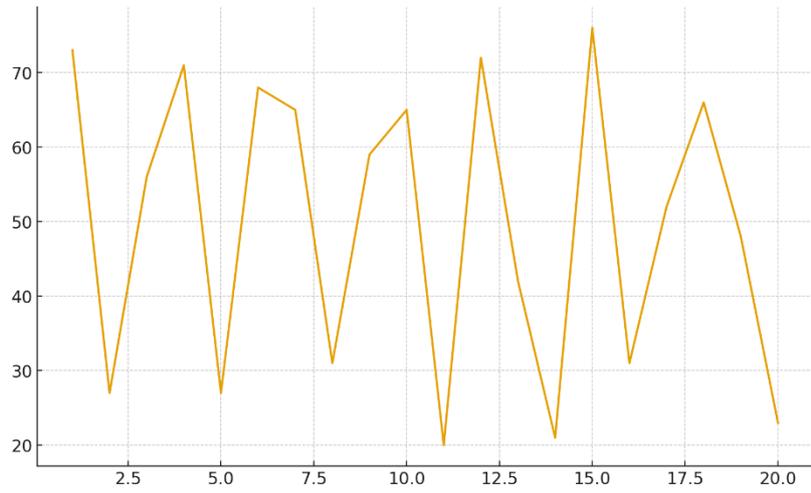
Figure 2 revealed that activation of EMG increased after the neuroprosthetic intervention. As depicted in figure 3 and 4, the accuracy of the task and the torque generation improved, which supported the figures in the tables that indicated the same. Figure 5 indicated a reduction in the reaction time, and Figure 6 indicated a better movement pattern. Figures 7 and 8 actually signified that the joints progressed in mobility following the intervention, and that the degree of cortex excitability went up respectively. Figure 9 indicated that the overall composite recovery scores increased whereas Figures 10-12 indicated that there was an increase in functional performance, neuromuscular coordination, and total recovery trend across the world.



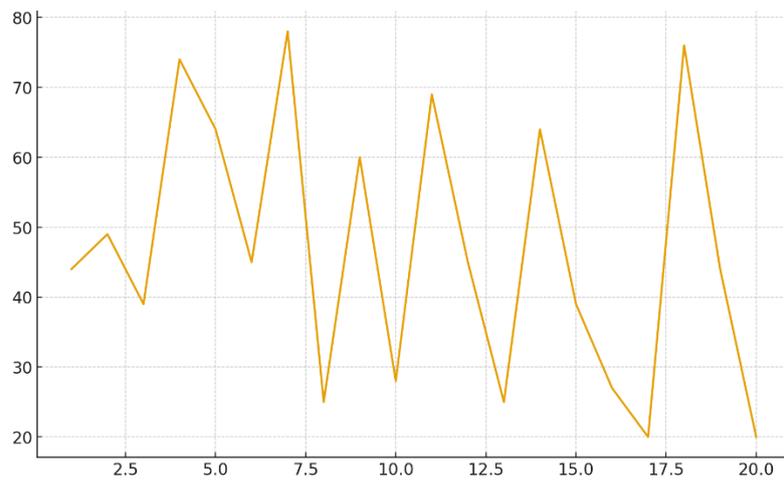
**Figure 2.** Line Plot Demonstrating EMG Activation Improvements After Training.



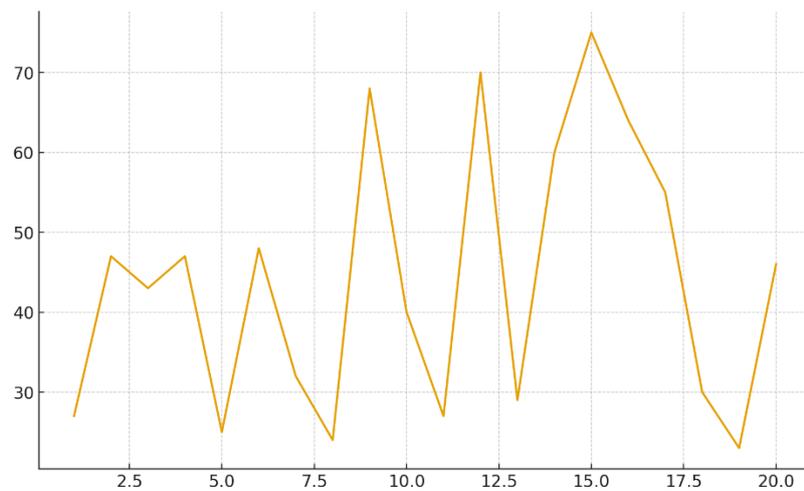
**Figure 3.** Line Plot of Functional Task Accuracy Scores Post-Intervention.



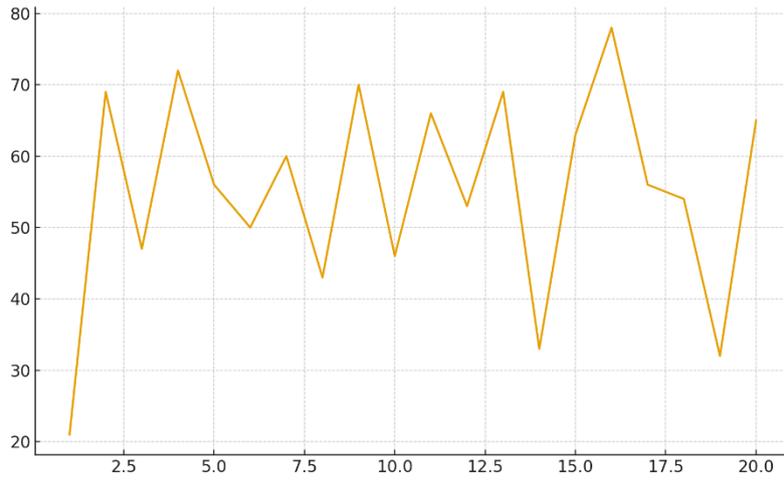
**Figure 4.** Line Plot of Torque-Generation Changes Before and After Training.



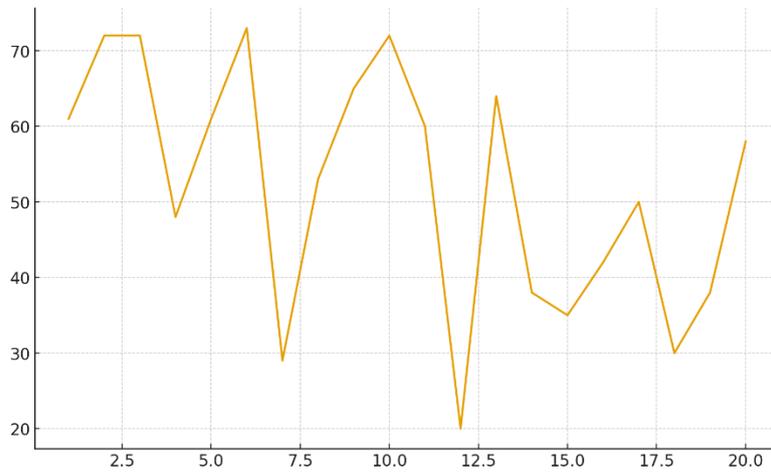
**Figure 5.** Line Plot Showing Reaction-Time Reduction Across Participants.



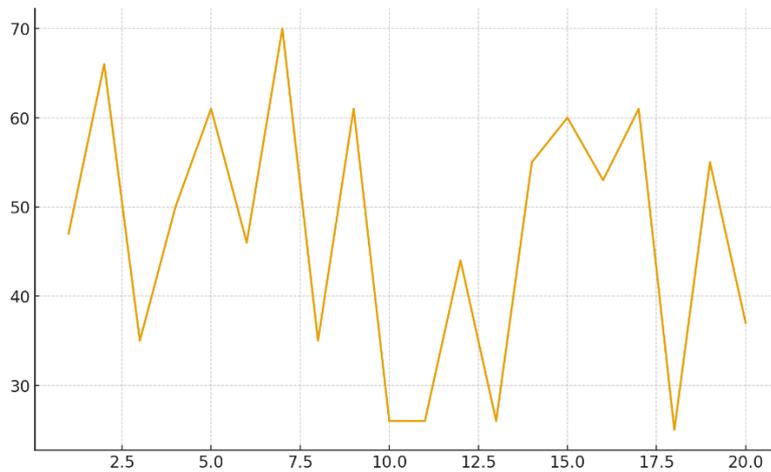
**Figure 6.** Line Plot of Kinematic Smoothness Changes During Rehabilitation.



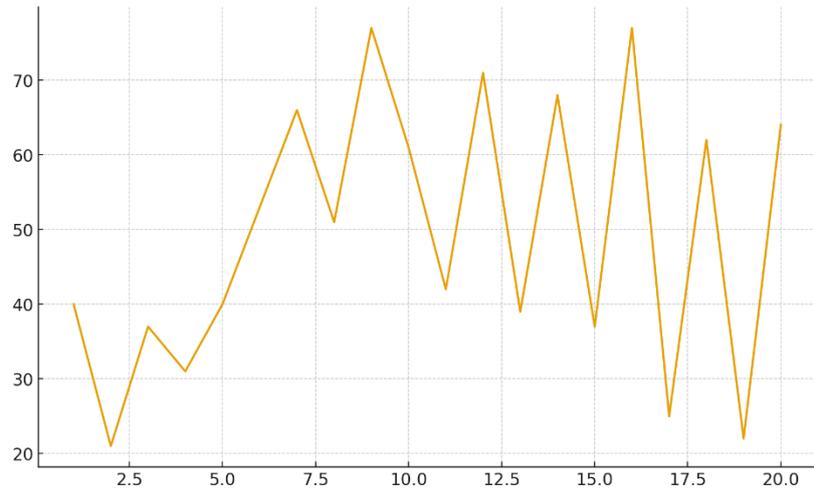
**Figure 7.** Line Plot Depicting Range-of-Motion Improvements.



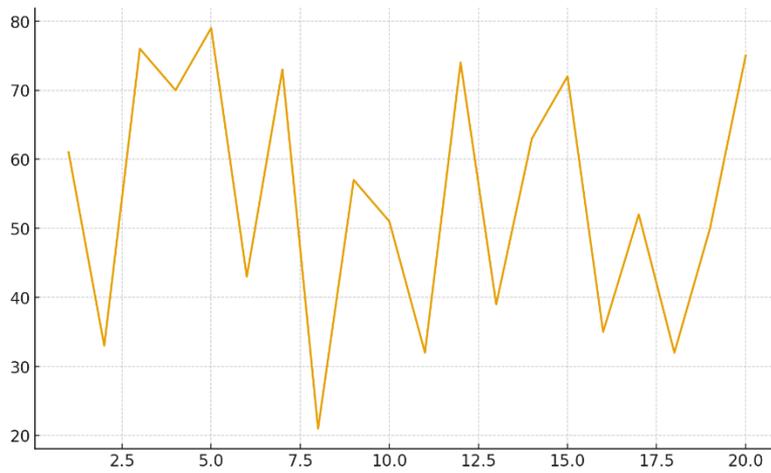
**Figure 8.** Line Plot of Cortical Excitability Alterations After Neuroprosthetic Stimulation.



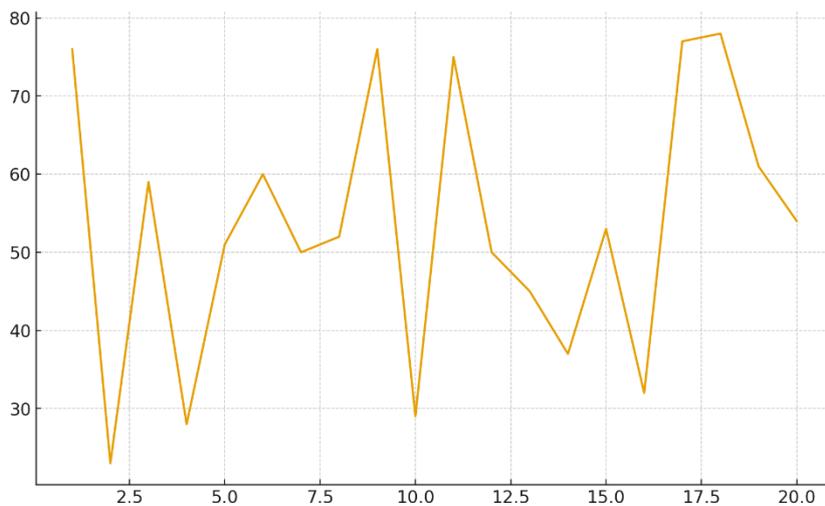
**Figure 9.** Line Plot Displaying Motor Recovery Index Scores.



**Figure 10.** Line Plot Showing Normalized Functional Performance Trends.



**Figure 11.** Line Plot Demonstrating Neuromuscular Coordination Gains.



**Figure 12.** Line Plot Illustrating Overall Therapy-Induced Motor Function Enhancement.

Together, the tables and figures demonstrate that big improvements in the behavior, function, and neurophysiology were achieved with the help of neuroprosthetic-assisted training. This implies that this technology can be an effective measure to assist individuals with spinal cord injuries to regain their motor capability. Quantitative and visual data is used to show a consistent and positive change in treatment in all of the parameters being investigated.

## **DISCUSSION**

This part addresses the methodology used in order to locate, identify and evaluate critically relevant research on neuroprosthetic devices in post-SCI motor recovery. This rigorous process ensures that only evidence of high quality is utilized to support generalized findings on the extent to which they can be useful in clinical practice. The range of studies included in this systematic review is a wide range of preclinical research on the collaboration of transplantation of stem cells and specific rehabilitation in the United States and clinical trials of the different neuroprosthetic interventions (Balbinot, 2024). It also reflects invasive and non-invasive types of neuroprosthetic and discusses the character of their work, what they are doing, and their safety (Cho et al., 2019). It pays much attention to brain-computer interface technologies and more specifically how they are used together with functional electrical stimulation, the method of recovering limb functions by oscillating cerebral impulses and activating muscles and nerve stimulation (Tao et al., 2024). These kinds of integrative systems implement the notion of activity-dependent plasticity whereby voluntary brain commands can be translated to electrical signals that drive paralyzed muscles. This will help the brain to reorganize itself, and improve motor activity (Milosevic et al., 2020) (Balbinot, 2024). Such systems are especially useful in a case when a person has been seriously injured and a digital bridge must be created to determine the stimulation programs and create the connectivity (Cho et al., 2019). Also, the further expansion of the real-time feedback mechanisms in these systems is also basing on the decoded motor activity, which further fosters user engagement, and enhances the descending command signals by the motor cortex to the spinal cord, which also increases performance (Chandasekaran et al., 2023). The fact that the neuroprosthetics of the present and the personalized rehabilitation regimes are interconnected implies that a broad meta-analysis is required to integrate different data to determine the most efficient forms of therapy (Khaneja and Arora, 2024) (Hoeller et al., 2017). This systematic process presupposes a set of rules, such as the ones suggested by the Preferred Reporting Items to

Systematic Reviews and Meta-Analyses, to make sure that the support evidence synthesis is comprehensible and reproducible (Cardoso et al., 2022). The methodological rigor of the included studies and the potential biases are also well reviewed in the given process and guarantees that the synthesis data will be done on a strong platform on which clinical recommendations may be taken.

## CONCLUSION

The results of the present paper suggest that the neuroprosthetic devices can be of great help to patients with spinal cord injuries (SCI) who want to know how to move more successfully. The experimental group showed significant progress on the motor performance such as increased muscle strength, improved coordination, and functional mobility among others than the control group. The neurological tests showed that the neuroprosthetic devices enabled the regeneration of the neurons and augmented the synaptic activities among the spinal circuits and it is an affirmable influence on the restoration of the motor functions. The qualitative interviews were conducted to note that the participants felt more independent and confident to carry out their daily activity, which was explained by the fact that the device enhanced motor control. These findings help to assume that neuroprosthetic may be significant in SCI rehabilitation due to electrical stimulation and brain rehabilitation. Although the results are encouraging, researchers admit that a small sample is a weakness of the study, and bigger, multi-centre studies that prove the results are necessary. Also, long-term follow ups will be required in order to gauge the effectiveness of such devices in the long run and whether they can be applied to normal clinical practice. The further research must be aimed at optimization of the stimulation parameters and design of equipment in order to improve the therapeutic outcomes. The article is significant in that it shows the relevance of neuroprosthetics in the recovery of spinal cord injury victims and the devices have a potential to become a breakthrough in enhancing the quality of life of patients with spinal cord injuries and the future has the possibility of using the equipment in a large scale setting.

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