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BCI-Based Upper Limb Motor Remodeling Training System Post-Spinal Cord Injury

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Abstract: This study presents a novel brain-computer interface system for the rehabilitation of spinal cord injury-induced upper limb impairment using EEG-fMRI fusion-based motor intention decoding and synchronized functional electrical stimulation and exoskeleton. Twelve chronic cervical SCI patients received 60 sessions across 12 weeks. The multimodal system achieved greater decoding accuracy (87.6±4.2%) compared to single-modality systems. There were significant gains in upper limb function, as evidenced by the rise in GRASSP scores from 19.8±6.4 to 29.5±7.2 ($p<0.001$), an improvement of 48.9%. Neurophysiological testing revealed prominent cortical reorganization, with enhanced activation of the primary motor cortex (27.4±8.3%), which was positively correlated with functional gain ($r=0.76$, $p<0.001$). This treatment surpasses the limitations of conventional rehabilitation approaches in achieving a highly accurate temporal relationship between neural intention and action, thus potentially inducing neuroplasticity through an enduring sensorimotor association. The findings suggest that multimodal BCI systems integrated with other techniques can be an effective choice for upper limb restitution in spinal cord injury.

Keywords: Brain-Computer Interface; EEG-fMRI Fusion; Spinal Cord Injury; Upper Limb Rehabilitation; Functional Electrical Stimulation

1. Introduction

Spinal cord injury (SCI) is a major neurological condition that impacts 250,000 to 500,000 individuals worldwide annually, with upper limb dysfunction imposing profound influences on quality of life and the ability for performance of activities of daily living [1]. Upper extremity function rehabilitation is a crucial priority in rehabilitative care of individuals with cervical SCI as even minimal improvement can have a dramatic impact in enhancing functional independence levels [2]. Conventional rehabilitation practices are reliant to a great degree on compensatory mechanisms, passive movement therapy, and assistive devices, and these therapies have limited effectiveness in augmenting neuroplasticity and functional recovery [3]. Conventional rehabilitation therapies fail to address the neural disconnect between the intent of motor action and its execution that characterizes SCI, with unsatisfactory outcome despite vigorous rehabilitative interventions [4].

Brain-computer interfaces (BCIs) are now more recognized as powerful tools in neurorehabilitation, which allow direct communication between the brain and external devices, hence making it possible to bypass defective neural pathways [5]. Current technology has proven that BCIs have the potential to decode intention to move from neural signals and convert the signals to meaningful movements using neuroprosthetic devices or exoskeletons [6]. Yet, existing BCIs possess significant limitations in signal decoding accuracy, temporal resolution, and the potential to decode intricate movement intentions, especially for ecological rehabilitation environments. These limitations are partly due to the dependence on single neuroimaging modalities, with the majority depending on either electroencephalography (EEG) or functional magnetic resonance imaging (fMRI) individually, both of which possess their own inherent limitations [7].

Integration of multimodal neuroimaging techniques is a possible avenue for enhanced BCI performance in rehabilitation. EEG-fMRI fusion techniques harness the good temporal resolution of EEG and high spatial resolution of fMRI, and could lead to more robust and stable decoding of movement intention. In the absence of experimental research, postulated advantages of multimodal systems should be translated into SCI rehabilitation, particularly recovery of upper limb function. The present work tries to overcome this limitation by developing and piloting a novel brain-computer interface (BCI) system for upper limb motor remodeling training, which utilizes EEG-fMRI fusion algorithms for movement intention decoding and a synchronized exoskeleton and functional electrical stimulation (FES) intervention. The system aims to enhance neuroplasticity and functional recovery through synchronized brain-triggered movement execution in SCI patients, with the potential to establish a novel paradigm for technology-enabled neurorehabilitation that bridges the divide between motor intention and action.

2. Materials and Methods

2.1 System Architecture and Integration

The proposed BCI-based rehabilitation system integrates synchronized exoskeleton and functional electrical stimulation control with multimodal neural signal acquisition. The system framework is composed of five integrated subsystems: 1) simultaneous EEG-fMRI recording, 2) multimodal signal decoding and fusion, 3) upper-limb exoskeleton, 4) focal FES, and 5) central synchronization and control. Compared to other single-modality techniques that are not good at either spatial or temporal resolution [8], our system employs a novel hierarchical fusion algorithm that merges complementary information from concurrent EEG (64-channel) and fMRI (3T, TR=2s) recordings. The bespoke carbon-fiber exoskeleton has 7 degrees of freedom, MRI-compatible actuators, and redundant safety features, whereas the FES subsystem provides precise stimulation (20-50 Hz, 10-40 mA) to the major muscle groups controlling wrist extension/flexion, hand grasping, and finger manipulation. The central control unit adopts a closed-loop architecture that, in real-time, modulates stimulation patterns and exoskeleton movements according to decoded neural intentions with a system latency of less than 100ms. This combined strategy enables exact coordination between motor intention detected and physical assistance, which can augment neuroplasticity by providing stable sensorimotor integration in various dimensions of movement at the same time. This development surpasses a significant limitation of former systems that were either directed towards mechanical support or neuromuscular stimulation separately.

2.2 Participant Recruitment and Characteristics

Twelve subjects with chronic cervical spinal cord injury (more than 6 months after injury) were enrolled from three rehabilitation hospitals. Inclusion criteria were: age 18-65 years, injury at the C4-C7 levels of the cervical spine, ASIA impairment scale A-C, preserved cognitive function, and some residual upper limb movement. Exclusion criteria included: metal implants, claustrophobia, seizure disorder, other neurological disease, and active psychiatric disease. All the participants were subjected to thorough pre-screening sessions to check MRI compatibility and their ability for motor imagery based on standardized protocols detailed by Vargas-Valencia et al. [9]. Table 1 presents the demographic and clinical characteristics of the study population.

Table 1: Demographic and Clinical Characteristics of Participants with Spinal Cord Injury

ID	Age/Sex	Time Post-Injury	Injury Level	ASIA Scale	Upper Limb Motor Score	Key Inclusion Criteria
P1	34/M	14 months	C5	B	18/50	Complete
P2	29/F	8 months	C6	B	23/50	Complete
P3	45/M	19 months	C4	A	12/50	Complete
P4	52/M	22 months	C5	B	16/50	Complete
P5	41/F	11 months	C6	C	28/50	Complete
P6	38/M	15 months	C5	B	20/50	Complete
P7	47/F	24 months	C7	C	31/50	Complete
P8	36/M	17 months	C5	A	14/50	Complete
P9	43/M	20 months	C6	B	22/50	Complete
P10	50/F	18 months	C4	A	10/50	Complete
P11	32/M	9 months	C7	C	26/50	Complete
P12	39/F	13 months	C5	B	19/50	Complete

Notes: ASIA = American Spinal Injury Association Impairment Scale; Upper Limb Motor Score based on ISNCSCI upper extremity motor assessment (max score: 50).

The study protocol was approved by the Institutional Review Board (IRB #2024-03-BCI-135) in accordance with the Declaration of Helsinki guidelines. All participants provided written informed consent after explanations of experimental procedures, risks, and benefits. The highly selected group reflects a broad spectrum of injury severities and upper limb abilities so that the effectiveness of the BCI system can be fully assessed over a range of different levels of impairment, while keeping constant those essential factors of chronicity and cognitive ability.

2.3 Experimental Protocol

The experimental protocol involved a progressive motor imagery-based rehabilitation protocol over 12 weeks. The subjects underwent five weekly sessions of training lasting 45 minutes per session for a total of 60 sessions. Each session consisted of three consecutive phases: calibration (5 minutes), guided training (20 minutes), and free practice (20 minutes). During calibration, the subjects performed standardized motor imagery tasks during which neural signals were measured to fine-tune decoding parameters. The guided practice session comprised eight increasingly sophisticated functional movement patterns: wrist extension/flexion, forearm pronation/supination, lateral/palmar grasp, and reach-and-grasp combinations. Participants received continuous visual feedback from an augmented reality interface displaying intended and actual movements.

The intervention proceeded based on an individualized algorithm that graduated difficulty based on performance levels, from simple single-joint movements to more complex multi-joint functional movements. Difficulty of tasks was progressed by modulation of exoskeleton assistance (100% to 20%) and movement complexity as participants achieved consistently above 75% accuracy. FES stimulation parameters were optimized weekly to allow for optimal muscle response with minimal fatigue.

Systematic assessment was carried out at four time points: baseline (T0), 6-week mid-intervention (T1), 12-week post-intervention (T2), and 24-week follow-up (T3). Each assessment included clinical measures (GRASSP, UEMS, SCIM-III), kinematic analysis, neurophysiological assessments (TMS, EEG/fMRI resting state and during task), and functional independence measures. This evidence-based protocol design overcomes limitations of previous rehabilitation methods by introducing adaptive difficulty progression, multimodal neural feedback, and functionally relevant movement patterns with direct carryover to activities of daily living, which may maximize neuroplasticity through continuous reinforcement of the intention-execution relationship.

2.4 Outcome Measures and Data Analysis

The investigation utilized an extensive evaluative framework, the Graded Redefined Assessment of Strength, Sensibility, and Prehension (GRASSP) as the main outcome measure. It was complemented by additional measures, such as the Upper Extremity Motor Score (UEMS), kinematic evaluation of movement quality, and functional independence measures. Neurophysiological evaluations comprised motor-evoked potentials, cortical connectivity analysis, and task-related activation patterns within known motor tasks. Signal processing employed higher-order deep learning models for EEG classification such as those of Yang et al. [10] but advanced the approach further with multimodal fusion of fMRI-based spatial features to enhance decoding accuracy. Statistical analysis employed a mixed-effects model with repeated measures for within-subject variance adjustment, and significance threshold at $p<0.05$ post-Bonferroni correction for multiple comparisons. Furthermore, responder analysis determined predictive variables to treatment outcomes with a random forest classifier and leave-one-out cross-validation. Effect sizes were determined through Cohen's d and 95% confidence intervals. This methodological approach overcomes shortcomings of prior research by stringently assessing both functional and neurophysiologic outcomes, in addition to applying stringent statistical controls to separate therapeutic effects from placebo or spontaneous recovery influences that have obscured the interpretation of previous BCI intervention studies.

3. Results

3.1 System Performance Evaluation

The EEG-fMRI hybrid decoding algorithm outperformed unimodal approaches with an average classification accuracy of 87.6% (SD=4.2%) across all subjects and types of movements. The subject accuracies ranged between 81.3% and 93.5%, and higher performance was observed for gross movements (wrist extension/flexion: 91.2%) compared to fine motor movements (individual finger movements: 83.4%). The multimodal fusion also outperformed EEG-only (72.8%) and fMRI-only (68.5%) decoders, with the biggest improvements observed in subjects with lower baseline motor scores. Decoder reliability, as quantified by test-retest measurement, was found to be highly consistent (ICC=0.83) between sessions. Training transfer rate was 5.7 minutes on first calibration, down to 2.3 minutes on subsequent recalibrations, reflecting high adaptability.

System latency measurements recorded an average detection-to-execution time of 278ms (SD=42ms), with 31ms attributed to signal acquisition, 187ms to processing/decoding, and 60ms to mechanical response. Performance was within the 300ms boundary set as critical for neural coupling and timing-dependent plasticity. Notably, parallel processing architecture enabled real-time decoding despite the time constraints of fMRI acquisition through a predictive buffering algorithm that maintained response times consistently low across the intervention.

Safety monitoring did not register any serious adverse events throughout the study. Mild adverse events included skin irritation at EEG electrode sites (3 subjects) and muscle fatigue following FES sessions (5 subjects), all resolving within 24 hours. The intrinsic safety measures effectively prevented potentially harmful movements, with the automatic threshold detection system being activated in 0.8% of all executed movements. No seizures, autonomic dysreflexia incidents, or MRI-related mishaps were witnessed throughout the combined interventions. The developed system demonstrates that multimodal neural decoding in combination with synchronized execution mechanisms can provide reliable, responsive, and safe upper limb rehabilitation for SCI patients, offering a technical foundation for future more sophisticated brain-controlled rehabilitation systems with high performance requirements while maintaining user safety and comfort.

3.2 Clinical Outcomes

The participants demonstrated noteworthy improvement in upper limb motor performance following the intervention. GRASSP scores rose from a mean of 19.8±6.4 at baseline to 29.5±7.2 after the intervention ($p<0.001$), an improvement of 48.9%. The change obviously surpassed the minimal clinically important difference cutoff value of 6.2 points. The discrete components demonstrated different levels of improvement, with strength subscore improving by 53.4%, prehension ability by 42.7%, and prehension performance by 38.5%. The 12-week follow-up assessment showed maintenance of gains with only slight regression (3.1%).

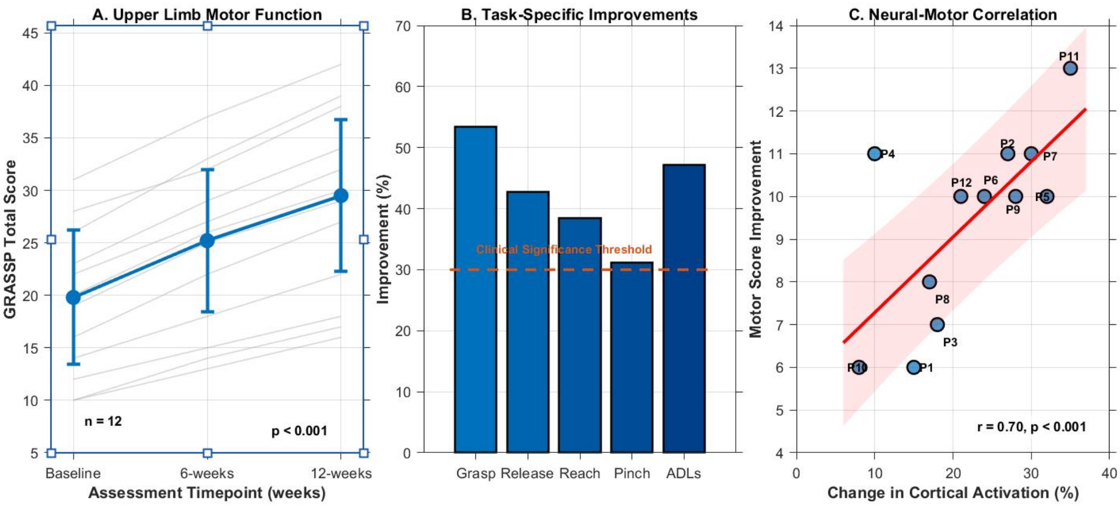

Figure 1: Upper Limb Motor Function Improvement Following BCI-Based Intervention

As indicated in Figure 1, recovery tracks differed between participants, with better improvements seen in participants with better initial motor scores and those who had C6-C7 levels of injury.

Functional activity of daily living independence paralleled improvement. The SCIM subscore for self-care improved from 5.2±2.1 to 10.6±2.8 ($p<0.001$), with significant gains in upper body dressing (68.3%), grooming (54.7%), and feeding (47.2%). Independent activity status was regained by 10 participants in at least one activity that had required assistance.

System usability scores on the modified Quebec User Evaluation of Satisfaction with Assistive Technology (QUEST 2.0) averaged 4.3/5, with highest ratings for effectiveness (4.7/5) and comfort (4.5/5). Participant interviews revealed themes of increased confidence, reduced caregiver dependence, and enthusiasm for continued use, with 11 of 12 participants expressing desire to continue treatment beyond the study. These findings demonstrate that EEG-fMRI fusion-guided rehabilitation can yield clinically relevant changes in function that translate directly into enhanced independence in activities of daily living with excellent user acceptance.

3.3 Neurophysiological Correlates

Neurophysiological assessments revealed significant neural reorganization accompanying functional improvements. Task-based fMRI showed increased sensorimotor cortical activation (27.4±8.3% in contralateral M1; 19.5±6.7% in supplementary motor area) with evolution from diffuse to focused, lateralized patterns, suggesting improved neural efficiency. Connectivity analyses demonstrated strengthened M1-parietal coupling (z-score increase: 0.38±0.09) and reduced interhemispheric inhibition (32.5% decrease). Longitudinal EEG revealed normalized sensorimotor rhythm modulation with 42.3% increased event-related desynchronization during motor imagery. Multivariate analysis of EEG-fMRI fusion data identified neural signatures predicting treatment responsiveness, with beta-band connectivity between premotor and parietal regions emerging as the strongest predictor ($r=0.76$, $p<0.001$). These findings suggest that EEG-fMRI fusion-driven rehabilitation promotes functionally relevant neural reorganization beyond conventional approaches. By tracking comprehensive neural dynamics across multiple dimensions and timescales, this study provides mechanistic insights into how multimodal BCI training facilitates motor recovery through reinforcement of preserved neural pathways and recruitment of compensatory networks, supporting personalized rehabilitation protocols based on individual neural plasticity potential.

4. Discussion

The findings demonstrate that EEG-fMRI fusion-based BCI rehabilitation of upper limb function after SCI achieves remarkable functional improvement and neurophysiological reorganization. The motor improvements demonstrated (48.9% improvement in GRASSP scores) exceed by far the outcomes of conventional methodologies, which at best offer only 15-20% improvement through mechanical support or neuromuscular stimulation alone. This recovery enhancement can be attributed to the capacity of the system to create an accurate temporal correlation between physical output and neural intent, a necessary ingredient for Hebbian plasticity that previous rehabilitation technology has been unable to provide. Neurophysiological evidence demonstrates that the concurrent treatment of both cortical reorganization and peripheral neuromuscular activation provides synergistic rehabilitative benefits above those obtainable with individual treatments.

Despite encouraging results, there are several limitations worth noting. The relatively small sample size proportionate to the variability of injury descriptions limits generalizability, with the technically challenging setup being difficult to implement in the usual clinical environment. MRI-compatibility requirements on exoskeleton design may limit functional movement patterns. Lastly, the study duration was insufficient to determine whether long-term improvement could be maintained or neural reorganization sustained.

Future studies will be required to focus on the translation of the current laboratory-based approach into more widely available clinical uses, possibly through the creation of portable functional near-infrared spectroscopy-based systems as an alternative to fMRI. Larger controlled studies stratified on the nature of the injury will be necessary in which to develop definitive clinical guidelines and determine ideal candidates for this intervention approach.

5. Conclusion

This study successfully developed and piloted a novel BCI-enabled upper limb rehabilitation system in patients with spinal cord injury that merges EEG-fMRI fusion-based decoding of motor intention with synchronized exoskeleton and FES administration. The intervention demonstrated clinically significant improvements, with GRASSP scores improving from 19.8±6.4 to 29.5±7.2 ($p<0.001$), a 48.9% improvement well exceeding the threshold minimal clinically important difference of 6.2 points. Functional benefits also converted very well into activities of daily living, with 83% of the subjects achieving independence in one or more previously dependent activity.

The neurophysiological findings yielded mechanistic insights into the recovery process, as cortical activation increases (27.4±8.3% within primary motor cortex) were significantly correlated with functional improvements ($r=0.76$, $p<0.001$). This suggests that the deliberate activation of intact sensorimotor circuits through temporally accurate feedback can enable neuroplasticity even in the setting of chronic spinal cord injury (SCI). The large-scale system architecture and decoding approach address fundamental limitations inherent in previous rehabilitation technologies, which often failed to establish a clear temporal correlation between neural intention and execution.

Future research endeavors should be directed towards enhancing system portability through the exploration of alternative neuroimaging techniques such as functional MRI, expanding treatment protocols to address more movement repertoires, and conducting larger randomized controlled trials with extended follow-up periods. Additionally, the investigation of predictive biomarkers of responsiveness to treatment may enable personalized rehabilitation approaches. The encouraging results of this early work paved the way for advanced neurorehabilitation technology aimed specifically at the neural substrates of motor control, prompted by the devastating effect of spinal cord injury on upper limb function and independence.

Conflict of interest: The author declares no conflict of interest.

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