Real-time Motor Execution Decoding using EEG for Closed-Loop Neuromodulation in Spinal Cord Injury Rehabilitation

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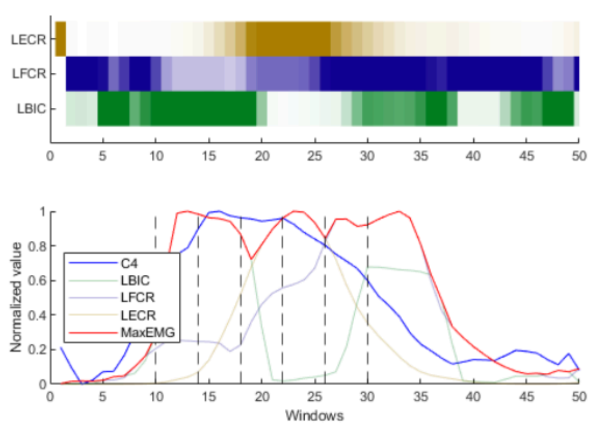
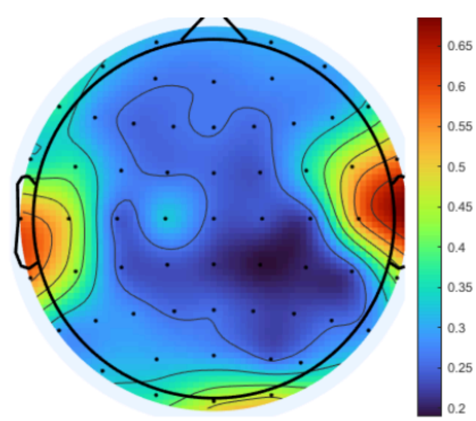
Effective motor rehabilitation after spinal cord injury (SCI) requires neuromodulation systems that are precise, adaptive, and fast enough to promote plasticity. However, existing stimulation approaches often rely on open-loop systems, suffer from high decoding delays, and frequently target unstable or non-specific neural features, limitations that reduce motor-related M1 activity, hinder learning, and compromise real-world translation. To address these challenges, we developed a real-time, low-latency (0.5 s) EEG-based Motor Execution (ME) decoding model designed for integration into a closed-loop Brain–Computer Interface (BCI) delivering personalized Epidural Spinal Stimulation (ESS). High-density Electroencephalography (EEG) (64 channels, 2.5 kHz) and Electromyography (EMG) (16 channels, 2kHz) were collected from SCI participants (n=2) during 100 reaching–grasping trials. EEG Signals were preprocessed using downsampling, referencing, filtering, and Artifact Subspace Reconstruction (ASR). Power Spectral Density (PSD) was applied to compute alpha (8-12 Hz) and beta (13-30 Hz) band power using 1 s windows with 0.5 s steps and normalized via a rolling median-based rate of change. EEG–EMG consistency analysis identified movement-relevant features over motor areas (e.g., C3/C4), yielding a robust and biologically meaningful channel selection. A logistic regression model coupled with a Bayesian Hidden Markov Model (HMM) achieved Area Under the Curve (AUC) improvements from 0.6 to 0.85 across repetitions, reflecting learning-related neural dynamics. In a separate day with targeted stimulation, AUC increased 0.7 to 0.9, while off-target stimulation degraded performance (0.6), validating model sensitivity to appropriate neuromodulation. A real-time implementation using computationally efficient filters, PSD estimation, and single exponential smoothing maintained performance with minimal latency. This low-latency, non-invasive ME decoding BCI demonstrates a promising pathway toward adaptive, personalized neuromodulation that may enhance upper-limb motor recovery, supporting future integrative strategies for SCI regeneration and repair.





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