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Decoding of Lower-Limb Movement Intent from Scalp Electroencephalography (EEG) in Children

A.S. Alamir[1,2]*, J.L. Contreras-Vidal[2]

[1]*Department of Electrical and Computer Engineering, Jazan University, KSA;* [2]*Noninvasive Brain-Machine Interface Systems Laboratory, NSF Industry-University Cooperative Research Center for Building Reliable Advances and Innovations in Neurotechnology (IUCRC BRAIN) Center, University of Houston, Texas, USA*

*P.O. Box: 899, Abu Arish, Saudi Arabia; E-mail: asalamir@uh.edu

Introduction: Brain-computer interfaces (BCIs) can be used to decode movement intent from brain signals and, thus, provide a direct communication link with external virtual or physical machines such as computers, exoskeletons or prosthetic limbs. Those signals can also be utilized to promote neuroplasticity in the central nervous system to recover motor functions. Although rehabilitation-based BCIs have been broadly applied to the adult population and showed promising results, these adult-optimized BCIs might not work well for the pediatric population. In a systematic review of children BCIs, Orlandi et al. found that only 12 publications published between 2008 and 2021 reported BCI performance. Out of those studies, only one non-invasive study addressed mobility, indicating the need for more studies in this field.

Material, Methods and Results: Two experiments were conducted. The first experiment (Cued Dataset, N=5, Age: 7.6 ± 2.3 years; single session tasks: visually-cued sit-stand transitions and walk-stop locomotion with at least 20 of each) involved visual cues to indicate the start of movement, which can be suitable for synchronous BCIs. The second experiment (Self-initiated Case Study, N=1, Age: 12 years, a total of 12 sessions collected in a course of seven weeks, Task: volitional sit-stand transitions and walk-stop locomotions with at least 20 of each) was self-triggered in terms of timing of movement and its category (Sit/Stand/Walk), which is appropriate for asynchronous BCIs. Acquisition of Electroencephalography (EEG) and electromyography (EMG) data was synchronized. To characterize EEG, the time-locked signals were processed for offline analysis. To close the loop and implement a real-time BCI, two types of state-dependent classification models were built for decoding movement intent from EEG and predicting the next transition. Two pipelines for pre-processing EEG data before utilizing them as an input to neural networks for classification were tested: one with the adaptive noise cancelling H-infinity filter, and the other with an ICA-based spatial filter designed to decompose EEG into independent sources. The convolutional neural networks implemented for training, validation, and real-time testing are composed of normalization, 1-D temporal convolution, rectifying linear unit, self-attention, fully connected, and SoftMax layers. Sensitivity analysis was performed with the input to the neural networks altered in terms of duration, frequency, and channels. For the offline analysis, movement related cortical potentials are observed clearly, especially in the channels closer to the central areas. Event-related spectral perturbation analysis indicates that all movement classes show a large decrease in power in the δ band. Moreover, an increase in power in the lower δ band starts to appear about one second before the movement onset. ICA and EEG dipole source localization investigation revealed the involvement of Brodmann Areas 6 and 8, areas known for their roles in motor planning, learning, and control. The sensitivity test results highlight the significance of the δ-band and window duration of 2 seconds for decoding. To investigate the capability of decoders to detect movement intent from single trials coming from completely an unseen session, models were trained on data from sessions 1 through 11 of the Case Study and tested on session 12. Overall, the mean F1-Score of the Seated Model was 0.80 (chance level≃ 0.5) whereas it was 0.54 for the Standing Model (chance level≃0.3).

Conclusion: This study demonstrates the feasibility of using EEG signals to predict movement intent in children for synchronous and asynchronous BCIs. EEG preceding movement onset was characterized in time, frequency, and IC domains. A prototype BCI based on the outcomes of this research was developed and evaluated. The findings of this research could substantially assist in developing pediatric BCIs that are capable of controlling walking exoskeletons and, consequently, improving their users' motor control. This work also promotes access of BCI systems to pediatric populations.

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