Enhancing Movement Directions Decoding in EEG-BCI through Force Feedback

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***Abstract*—In advancing brain-computer interface (BCI), force feedback has demonstrated potential in enhancing neurophysiological interactions during motor tasks. This study investigated the impact of force feedback on brain activity and the accuracy of decoding movement direction. We developed an electroencephalogram (EEG)-based BCI paradigm with four levels of force feedback (i.e., 0 N, 8 N, 16 N, 24 N) applied during right-hand movements to left and right directions. Six participants were involved to ensure robust results. Three deep learning models—DeepConvNet, ShallowConvNet, and EEGNet—were used to decode movement directions. Findings from event-related desynchronization/event-related synchronization (ERD/ERS) and movement-related cortical potentials (MRCPs) indicated that increased force feedback significantly enhanced the brain's response to motor stimuli. The decoding results revealed that force feedback notably improved decoding accuracy of DeepConvNet and EEGNet, particularly under medium and high-intensity conditions. Specifically, three models demonstrated accuracy improvements of 11%, 4%, and 12% under high-intensity force feedback, respectively. These results suggest that specific force feedback enhances motor area responsiveness, improving movement intention decoding in BCI. Our study confirms the positive impact of force feedback on BCI performance, highlighting the potential of force feedback-based BCI systems.**

***Index Terms*—Brain-computer interface (BCI); electroencephalogram (EEG); force feedback; movement direction decoding**

I. Introduction

Electroencephalography (EEG) is a non-invasive electrophysiological monitoring method that records spontaneous electrical brain activity over a specific duration through electrodes positioned on the scalp [1]. Nowadays, EEG technology has become a pivotal tool in neuroscience, widely used in various domains such as diagnosing brain disorders like epilepsy, cognitive neuroscience, biometrics, and brain-computer interfaces (BCI) [2,3]. The non-invasive nature and excellent temporal resolution of EEG make it an ideal choice for monitoring brain activity during motor tasks. Extensive research indicates that EEG can reflect the kinematic and dynamic characteristics of limb movement [4]. Decoding hand movement directions from EEG signals is a particularly active area of BCI research [5-8]. For instance, Wang et al. achieved a classification accuracy of 70.29% for six types of movements, including individual and coordinated hand movements, using linear discriminant analysis and support vector machine [7]. Similarly, Zhang et al. proposed a deep learning model combining convolutional neural networks and bidirectional long short-term memory networks, which attained an average classification accuracy of 73.39% for three coordinated directions of hand movements [8].

Traditionally, visual and auditory feedback have been widely used in EEG research to enhance participant interactivity and engagement. Visual feedback often involves the use of visual cues like animations and videos to help participants focus and complete the tasks. Alimardani et al. had shown that visual feedback design can positively enhance the performance of participants in motor imagery tasks [9]. Auditory feedback, on the other hand, employs audio cues to direct participants to complete tasks, which is particularly beneficial for studies targeting visually impaired individuals. Nijboer et al. had demonstrated that auditory feedback-based BCIs can be as effective as visual BCIs [10]. Recently, force feedback has been introduced into EEG studies, providing a novel method to stimulate brain activity [11,12]. This shows promising potential in BCI, with evidence suggesting that force feedback can enhance upper limb rehabilitation in BCI applications [13].

Although extensive research has been conducted on visual and auditory feedback in EEG studies, the exploration of force feedback remains relatively limited. Current research predominantly focuses on cognitive responses to non-contact stimuli, with insufficient attention to how contact feedback

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