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A Portable, Low-Cost BCI for Stroke Rehabilitation

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***Introduction*:** Millions of stroke survivors are affected by disability associated with movement impairment. According to preliminary studies [1,2], experimental therapies that couple brain-computer interfaces (BCIs) with movement (e.g., via functional electrical stimulation [FES]) facilitate motor recovery. However, current BCI systems are inappropriate for use outside the lab. These systems typically employ bulky and expensive (~$25,000) commercial amplifiers and desktop computers (Fig. 1A). For BCIs to be a feasible rehabilitative option for those with motor dysfunction, they must be portable and affordable while retaining the performance.

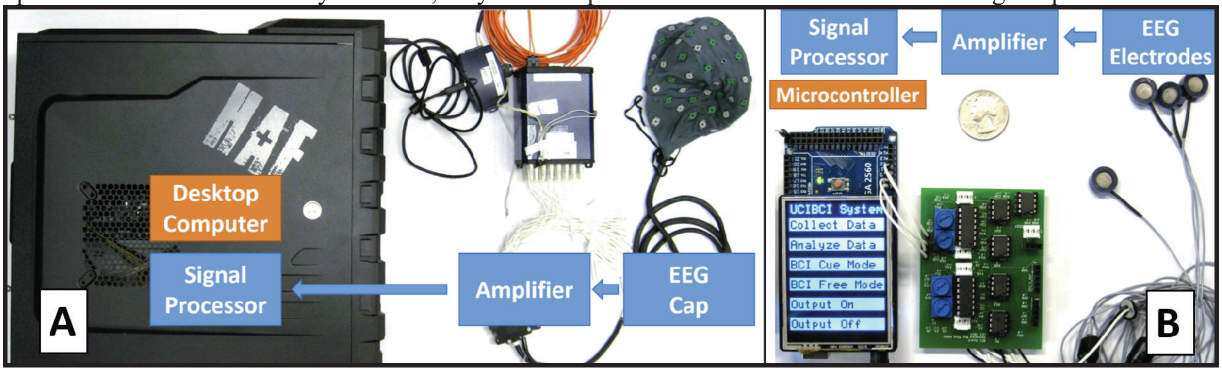

Figure 1. *A: A traditional BCI system (~$30,000). B: The developed, miniaturized BCI system (~$300). In both systems, brain signals are captured by the EEG cap/electrodes, amplified, and then sent to a processor for decoding.*

***Methods and Results*:** The proposed system consists of 5 EEG electrodes, a custom 4-channel EEG amplifier array, a commercial microcontroller (Arduino, Ivrea, Italy), and a touchscreen (Fig. 1B), with overall cost of ~$300. Each EEG channel utilizes 1 instrumentation amplifier and 2 operational amplifiers in active filter configuration (4^{th} order 1.6-33 Hz bandpass filter) to achieve a total voltage gain of 87 dB. A custom C program was implemented in the microcontroller to achieve signal sampling, processing, decoding, and output device control. More specifically, EEG was sampled at 256 Hz, and the average α- and β-band power for each 0.25 s of data were calculated, resulting in 8 dimensional observations (4 channels $\times$ 2 frequency bands). These observations were then used to generate a logistic regression model that distinguished dorsiflexion from idling states. In the online operation, novel EEG data were processed, passed to the logistic regression-based classifier, and a binary state-machine determined the brain state based on the mode of the 3 most recent classifications. Our system was tested on 2 able-bodied subjects (AB1: 20 yo, M; AB2: 27 yo, M), and a chronic stroke subject (ST1, 60 yo, M, left-sided hemiplegia). Subjects were cued to alternatingly dorsiflex and relax their right (AB1-2) or left (ST1) ankle, while the system collected, processed, and stored the EEG signals, as above. Ten-fold cross-validation was then used to estimate the accuracy of the generated classification models. The classification accuracies were as high as 95% for AB1, 97.5% for AB2, and 97.5% for ST1. In addition, ST1 performed two trials of online BCI-FES dorsiflexion using the generated decoding model. The subject was again cued to dorsiflex or relax in 10 epochs over 1 minute, while the BCI system classified his EEG signals in real time and appropriately delivered or withheld FES to the ankle on the hemiplegic side. The online decoding accuracies were 77.6% (80.9%) with 0.829 (0.804) correlation and 1.0 s (0.75 s) lag for the first (second) trial, respectively.

***Discussion*:** We developed a BCI system that is portable and inexpensive compared to conventional counterparts. Despite the reduced channel number and processing power, preliminary testing suggests that it achieves high performance both offline and online. Also, these decoding accuracies were comparable to those achieved previously using a full-size system [3,4]. Future work will focus on testing the system in more subjects.

***Significance*:** This is the first low-cost, fully portable BCI system for post-stroke motor rehabilitation. This system has adequate performance and can be paired with commercial FES devices for in-home therapy.

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