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BCI-FES: could a new rehabilitation device hold fresh promise for stroke patients?

Brittany M. Young[1,2,3], **Justin Williams**[2,3,4,7], and **Vivek Prabhakaran**[1,2,3,5,6,7,8]

[1]Department of Radiology, University of Wisconsin – Madison, Madison, WI, USA

[2]Medical Scientist Training Program, University of Wisconsin – Madison, Madison, WI, USA

[3]Neuroscience Training Program, University of Wisconsin – Madison, Madison, WI, USA

[4]Department of Biomedical Engineering, University of Wisconsin – Madison, Madison, WI, USA

[5]Department of Neurology, University of Wisconsin – Madison, Madison, WI, USA

[6]Department of Psychology, University of Wisconsin – Madison, Madison, WI, USA

[7]Department of Neurosurgery, University of Wisconsin – Madison, Madison, WI, USA

[8]Department of Psychiatry, University of Wisconsin – Madison, Madison, WI, USA

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It has been known that stroke constitutes a major source of acquired disability, with nearly 800,000 new strokes each year in the United States alone [1]. While advances in public and preventative health have helped reduce stroke incidence in high-income countries, growth of the aging population, increasing stroke rates in low to middle income countries [2], and medical advances that have reduced stroke mortality [3] are all contributing to an increase in stroke survivors worldwide.

This growing population of stroke survivors constitutes an increasing need for new strategies in stroke rehabilitation. One of the most common deficits that persists after stroke is that of functional motor impairment. While most stroke survivors experience some amount of spontaneous recovery shortly after the stroke event, many encounter a “functional plateau” before full recovery is achieved and are left with some form of disability. Recent studies have suggested that clinically relevant recovery potential persists during the chronic phase of stroke despite this functional plateau. Motor gains have been demonstrated in

Brittany M. Young WIMR Room 1310-F 1111 Highland Ave. Madison, WI 53705-2275 bmyoung2@wisc.edu
Justin Williams ECB Room 3142 1550 Engineering Drive Madison, WI 53706 jwilliams@engr.wisc.edu
Vivek Prabhakaran University of Wisconsin Hospital & Clinics Department of Radiology 600 Highland Avenue Madison, WI 53792-3252 vprabhakaran@uwhealth.org

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chronic stroke patients using newer techniques such as training using brain-computer interface devices [4,5], creating a clear need to investigate new ways to facilitate additional recovery not currently achieved with traditional rehabilitative approaches.

Functional Electrical Stimulation (FES) is one treatment that can be used to help chronic stroke patients with persistent motor deficits improve motor function. FES involves the application of electrical current using non-invasive electrodes on the skin to facilitate movement of a paretic muscle. There is strong evidence for the efficacy of FES as an adjuvant to traditional therapies when administered within the first 6 months of stroke [6]. Improvements in motor function facilitated by FES after stroke have been attributed to a recovered ability to voluntarily contract impaired muscles , to reduced spasticity and improved muscle tone in the stimulated muscles, and to an increase in joint range of motion [7]. Multiple neural mechanisms may underlie these changes, with one model suggesting that proprioceptive sensory input, along with visual perception of the movement, may promote neural reorganization and motor learning [8]. FES is currently employed by some stroke survivors to stimulate a lower extremity to improve walking [9] and is sometimes applied to a paretic upper extremity to improve motor function of an arm or hand [10]. Regardless of the anatomical application of FES, one commonality among standard FES therapies is that the electrical stimulus from these devices is administered completely independently of concurrent brain activity. Therefore, standard rehabilitative therapies using FES are a largely passive process with minimal coordination between the FES and the mental tasks required of the patient.

In contrast, one class of newer therapies being investigated with the aim of improving motor outcomes in stroke patients uses brain-computer interface (BCI) technology. BCI devices allow for neurofeedback – real time feedback of neural activity that can be used to train the voluntary modulation of a brain rhythm. The key components of a BCI device include a means of detecting neural signals, a computer that translates detected neural signals into one or more feedback modalities, and a means of providing feedback based on the user's brain activity. Feedback modalities that have been incorporated into BCI devices include visual displays [5,11], FES [12], robot-assisted movement [13], and cranial nerve noninvasive neuromodulation [14]. When using BCI devices to facilitate motor rehabilitation, this feedback is often controlled using desynchronization of the Mu and Beta rhythms detected over the sensorimotor cortex [4,5,11,12,15].

The real time feedback provided when using a BCI device can then be used to reward the production of certain patterns of neural activity over others. This reward-based reinforcement, along with use-dependent, error-based, and Hebbian-like plasticity mechanisms induced by BCI therapies that incorporate repeated attempts at neuromodulatory tasks, teaches the user to actively and consistently modulate brain activity during imagined or attempted movement. This learned modulation, along with sensory input that may be provided through an assistive movement device, may then promote functional recovery by inducing neuroplastic change in a disrupted motor system to allow for more normal motor-related brain activity. It is this return to normal motor-related brain activity that is thought to mediate the restoration of more normal motor control [16]. In contrast to many standard rehabilitation approaches, the dependence on neuromodulation used to drive the feedback presented during therapy using a BCI device goes beyond passive motor practice and requires active patient engagement to modulate brain activity patterns associated with movement.

Some studies have shown that certain patterns of neuroplastic change correlate with improved functional gains achieved by chronic stroke patients receiving targeted rehabilitation therapy [17,18]. The use of BCI devices to target and train the modulation of neural activity during rehabilitative therapy may then encourage neuroplastic changes associated with improved functional gains and facilitate additional motor recovery. Currently, BCI technology is being incorporated into new devices intended to facilitate additional rehabilitation in stroke survivors with persistent motor impairments [5,12,15,18].

The combination of BCI technology with FES presents the potential to leverage the neuromodulatory and neuroplastic advantages of both modalities toward functional gains in stroke survivors. The use of FES as a feedback modality for a BCI device (i.e. a BCI-FES device) triggers FES only when appropriate brain signals are detected during the user's attempt to move, synchronizing facilitated motion with modulated brain activity. This approach builds on the neural reorganization thought to be induced by FES alone and couples it with the active neuromodulatory and neuroplastic motor learning aspects of the BCI. This combination may further strengthen the central-peripheral connections necessary for the recovery of motor function after stroke, making therapy with BCI-FES potentially more efficient and more effective than therapies that use either apparatus in isolation.

BCI-FES devices may hold fresh promise for stroke survivors struggling with persistent motor impairments in two key ways. First, some systems use intracranial or neuroimaging techniques such as electrocorticography (ECoG), magnetoencephalography, and fMRI, providing information not only from the neural signals upon which feedback is based but also information with high temporospatial resolution that can be analyzed offline when researching the underlying neural processes that occur during therapy. Although BCI-FES devices with these designs tend to be more expensive, and sometimes more invasive, this additional information can be used to study and characterize the neural mechanisms that precipitate functional improvements. These insights can guide the next generation of BCI-FES devices, allowing researchers to optimize both the design of new devices as well as the targeting of these therapies to those likely to derive the greatest benefit. Second, other systems take a more minimalistic form, using non-invasive EEG recording to detect the brain activity used to guide neurofeedback. One of the key advantages to EEG-guided BCI-FES devices is the relatively minimal investment in hardware, which translates to significantly lowered costs. The low-cost, non-invasive aspects of these designs allow for greater numbers of subjects to be studied using these devices more quickly and with minimal risk. Insights gleaned from studies of EEG-guided BCI may inform the design of future EEG-guided and non-EEG-guided BCI devices as well. Low costs, in combination with software improvements that further simplify the minimum skills necessary to operate these systems will also help open the doors for BCI-FES devices to be used as a rehabilitative option accessible in the home.

Although no controlled study has yet demonstrated the efficacy of a BCI-FES device as a stand-alone therapy, the efficacy of a similar therapeutic approach using EMG-triggered FES has been demonstrated [19], highlighting the potential for triggered FES to act as a beneficial biofeedback modality to support and reward attempted movement with the detection of appropriate motor signals. Furthermore, there is emerging evidence that BCI-FES devices can be used to help stroke patients recover motor function. Rehabilitation therapy using BCI devices has been shown to produce functional gains with corresponding brain activity changes in stroke patients when combined with FES [12,15,20] and to contribute an adjuvant effect when combined with traditional physical therapy in small feasibility studies [5,13]. Nevertheless, there remains a need for large-scale randomized controlled trials to establish the efficacy of therapies using BCI-FES devices and to advance the development of this therapy modality as a potentially low-cost, adaptable, and non-invasive option for stroke survivors still suffering from motor impairments.

Future studies will need to determine the optimal parameters for stroke therapies using BCI-FES devices, such as timing since stroke onset, severity of stroke, stroke location (e.g. cortical vs. noncortical), dosing, and system design. An understanding of the underlying neuroplastic processes that mediate functional improvements attained using these machines will also be key in furthering our understanding of the recovering brain and in the development of future neurorehabiliative strategies and devices. As the field grows, the potential for improvements in rehabilitation through BCI-FES devices remains promising and may someday contribute to improving the functional status, independence, and overall quality of life that stroke survivors achieve.

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