Published in final edited form as:

Arch Phys Med Rehabil. 2015 March ; 96(3 0): S1–S7. doi:10.1016/j.apmr.2015.01.007.

Brain-Computer Interface: Current and Emerging Rehabilitation Applications

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A formal definition of Brain-Computer Interface (BCI) is as follows: “a system that measures central nervous system (CNS) activity and converts it into artificial output that replaces, restores, enhances, supplements, [informs], or improves natural CNS output and thereby changes the ongoing interactions between the CNS and its external or internal environment”.¹ More simply, a BCI can be defined as a system that translates “brain signals into new kinds of outputs”.¹ After brain signal acquisition, the BCI evaluates the brain signal and extracts signal features that have proven useful for task performance. There are two broad categories of BCIs: implantable and non-invasive, distinguished by invasively and non-invasively acquired brain signals, respectively. For this issue, we will focus on BCIs that utilize non-invasively acquired brain signals.

There are two major ways in which BCIs can be employed. The first is straightforward and has been studied for more than 25 years; in this case, the BCI system acquires brain signal and allows the user, through feedback, to engage the BCI output for control of the environment (light switch, temperature control) or communication devices. A second and newly emerging BCI application involves using the system as a motor learning-assist device. In this case, the BCI may enhance motor control recovery by demanding more focused attention or guiding activation or deactivation of brain signals.²

BCI research has experienced a recent exponential growth, which can be attributed to a number of factors, as follows: 1) availability of rapid, real-time sophisticated signal processing methods; 2) a greater understanding of the characteristics and uses of brain signals; 3) an appreciation of the phenomenon of activity-dependent brain plasticity; and 4) a growing dissatisfaction with current rehabilitation methods and the need for improved methods for recovery of function for those with persistent motor impairment.²

Brain signals can be acquired in a number of forms, including electrical (e.g., electroencephalography (EEG)) or magnetic fields (e.g., functional magnetic resonance imaging (fMRI)) or functional near infrared spectroscopy (fNIRS).

It is important for those of us who are clinicians and clinician-scientists to be informed about the development and capability of BCIs, because these systems have potential to enhance rehabilitation methods. Even more importantly, it is critical for us to participate in the design and development of these systems so that BCI system designs are grounded in the needs of patients, framed within feasible technical interfaces, and constructed for practical delivery in a clinical environment. To that end, we present this Issue, entitled, “Brain-Computer Interface: Current and Emerging Rehabilitation Applications”. Within this issue, we are providing papers that arose from presentations at the 2013 International Brain-Computer Interface Meeting which was held June 3–7th, 2013 at the Asilomar Conference Center in Pacific Grove, California, USA.

The 2013 BCI Meeting was the 5th in the International BCI Meeting series with past meetings in 1999, 2002, 2005, and 2010. The purpose of the BCI Meeting series is to bring together the diverse contributors to BCI research and development in a distinctive retreat-style meeting that encourages interaction, collaboration, and discussion. Thus, the BCI Meeting series strives to push the BCI field forward, encouraging growth and translation of BCIs from the laboratory to the clinic. The 2013 meeting was supported by the National Institutes of Health and the National Science Foundation, as well as other governmental and private sponsorsⁱ. The meeting drew scientists from 29 countries, representing 165 research groups, with a total of 301 attendees, of whom 37% were students or postdoctoral fellows. There were over 200 extended abstracts submitted for peer-review, from which 25 were selected for oral presentationⁱⁱ, and 181 for poster presentation.ⁱⁱⁱ Accepted abstracts were published in the open-access conference proceedings^{iv}. The retreat-style format featured 19 highly interactive workshops,³ and an exhibit hall with formal poster session and technology demonstrations.

The 2013 BCI Meeting theme was ‘*Defining the Future*’. Compared to prior BCI conferences, attendance included an increased representation of clinicians, clinician scientists and people with disabilities. There were a number of ‘firsts’ for the meeting series. First, the Planning Committee was composed of BCI researchers from around the world. Second, both the Planning Committee and conference participants included people with severe disabilities who need assistive technology for communication. A woman with amyotrophic lateral sclerosis (ALS) who uses assistive technology for communication served on the Program Committee^v. She attended the Meeting remotely; she participated in a panel discussion and provided a presentation at a Virtual BCI User’s Forum. This forum provided a venue by which BCI users could speak directly to the conference attendees. A man with brainstem stroke attended the Meeting with his caregivers, presenting both in a

ⁱ<http://bcimeeting.org/2013/sponsors.html>

ⁱⁱ<http://bcimeeting.org/2013/researchsessions.html> (indexes individual abstracts)

ⁱⁱⁱ<http://bcimeeting.org/2013/posters.html> (indexes individual abstracts)

^{iv}http://castor.tugraz.at/doku/BCIMeeting2013/BCIMeeting2013_all.pdf

^v<http://bcimeeting.org/2013/meetinginfo.html>

workshop and in the Virtual User's Forum. Both are co-authors on a paper in this issue (Peters)⁴ summarizing the experiences of BCI users with the current state of BCI technology. A third new development was that attendees at the 2013 BCI Meeting voted to establish a Brain-Computer Interface Society, which will plan and oversee the Sixth International BCI Meeting to be held in 2016. Fourth, there was an increased in the number of venues for dissemination of results. This issue contains papers with a clinical or patient experience focus. A special section in the Journal of Neural Engineering published papers with an engineering focus.⁵ A summary of the conference workshops was published in the newly established BCI Journal.³

The papers in this current issue provide examples of work conducted using a variety of BCI technology applications, including communication, leisure activities, and motor learning.

Communication

Problem

Communication is an essential function for health care^{7,8}, function, and quality of life⁶. For those with neuromuscular impairments and difficulty with writing or speaking, augmentative and alternative communication (AAC) devices can compensate and provide device-assisted communication⁶. Most currently available AAC devices are controlled by available physical movements, and in the presence of volitional movement, they work well for performing a simple task. But there are limitations to currently available AAC devices. First, the capability of currently available AAC devices can be overwhelmed by task complexity or by the simultaneous task demands of a given function. Second, some individuals do not possess the required physical capability to control an AAC device, and others have progressive diseases which eventually preclude their use of any physical movement to control communication devices. Thus, the inability of some people to operate AAC devices is of particular concern⁷ and represents an area of vital need. A study on end-of-life decisions by people with ALS⁸ quoted a participant as saying *"as long as I can properly communicate with my voice, my eyes or a machine or whatever, I want to have a respirator...But as soon as I can no longer communicate, that's it! I don't want anything else to be done."*

Role of BCIs in Rehabilitation

In contrast to most available AAC devices, BCIs can be controlled through the direct use of brain signal, bypassing the need for volitional muscle activity as a control paradigm. For a number of years,^{9, 10} potential BCI users and caregivers have expressed the importance of BCIs for communication. In a focus group of potential BCI users with ALS and their caregivers, one caregiver described the promise of BCI as follows, *"I just think it is wonderful that you can give someone a voice who is losing theirs."*¹¹

BCIs have been developed and tested for use in controlling devices for communication. BCIs are most appropriate and most needed by people with few other options for control of assistive technology. These include people with late-stage ALS, people with disorders of consciousness who show signs of cognitive awareness but lack other means of communication, and other populations of people who cannot reliably operate physical interfaces or eye gaze systems to access assistive technology. In this issue, Kübler, et al.

discusses a decision process for determining who should participate in in-home BCI research studies, considering participant characteristics, support structure, and environmental factors. To date, BCIs have primarily been used in the laboratory or in controlled research studies. However, one commercial BCI device is now available (IntendiX from g.tec, Schiedlberg, Austria). Thus, as discussed in this issue by Hill et al., critical issues remain for the widespread adoption of BCIs as practical AAC devices for clinical use. The paper in this issue on the Virtual BCI User's Forum (Peters) describes both the promise and the shortcomings of BCI as a communication device, and compares BCI to conventional assistive technology solutions.

BCIs are increasingly being integrated with other commercial assistive technology on an experimental basis¹² and can form an interface that is based on brain signal and incorporated within the framework of other existing assistive technology, increasing the accessibility of such devices.¹³ There is a growing awareness that BCIs can be used in combination with physical input signals if the patient has such signals available, a concept described as a hybrid BCI design.¹⁴ In this issue, Schettini, et al. investigates the design of a hybrid BCI to provide people with ALS with a system that will adapt to meet their needs as their ALS progresses. People with ALS have been the predominate user group for non-invasive BCI communication systems to date^{13, 15–17} and demonstrations of home use have been published.^{18, 19} In this issue, Hill et al. draws on examples from a study of in-home BCI use by people with ALS and most of the participants in the Virtual BCI User's Forum had ALS (Peters, in this issue).

For patients diagnosed with disorders of consciousness, BCI may offer the only opportunity of demonstrating awareness. A recent review showed that 4 of 24 patients (17%) who had been diagnosed as being in a vegetative state were not only consciously aware but could answer yes or no questions²⁰. BCIs offer a method to evaluate awareness and to restore a communication channel. BCI use for disorders of consciousness is an emerging field of great importance. Studies in this area include BCIs using auditory-, tactile- and motor imagery-based designs^{20–29}. In this issue, Coyle et al. describes a study of BCI use with people in a minimally conscious state, demonstrating that it is possible to learn to use a BCI device even in the absence of any other method of communication.

People with spinal cord injury or brain-stem stroke represent other populations for whom BCIs may be important and useful. BCI studies with people with SCI have included both computer access tasks^{30, 31} and exoskeleton control.³¹ In this issue, Huggins et al. explores the BCI design priorities for people with SCI for the purpose of setting research goals and evaluating how close BCIs are to providing benefit for this population. Also in this issue, Riccio et al. evaluated a hybrid BCI design using BCI in conjunction with a muscle activity switch for error correction in a study that included people with brain-stem stroke.

Limitations

The primary concern for BCIs as an AAC is the reliance of most BCIs on visual presentation of options, with an associated concern about possible reliance on eye gaze³². Indeed, some people with ALS have trouble not only controlling eye gaze, but also with keeping their eyes open,³³ which poses potential problems in using a visual display in order to view options

and feedback results. To address this problem, BCIs operated with covert attention have been developed, proving that eye gaze control is not required for BCI use.^{34–38} However covert attention is associated with lower accuracy of BCI performance.³⁹ A BCI with a visual display has even been designed for use in an eyes-closed condition by using lights that are visible through the eyelids.⁴⁰ Alternative BCI designs using auditory^{29, 38, 41–44} and even tactile^{45–48} displays of information are under development. In this issue, auditory BCI feedback is mentioned by Kübler as part of the considerations for selecting BCI participants and it is also used in Coyle's study.

One other consideration is the ability to learn to use a BCI. There have been some reports of greater variability in success at learning to use a BCI device among those with disabilities as compared with non-impaired adults.^{49–51} However, most people are able to learn to use at least one of the BCI designs for communication.^{52, 53} Overall, BCIs for communication have been successful in the laboratory, and for long-term functional use.^{19, 54}

Leisure activities

Problem

Disability touches every aspect of human life, and therefore assistive technology is needed in order to provide access to all types of activities that contribute to quality of life.⁵⁵ Assistive technology can enable participation in sport and leisure activity, providing connection to others as well as improvements in self-esteem and self-confidence.^{56, 57}

Potential

BCIs have the potential to provide an array of leisure pursuits, and applications in this area are just emerging. BCIs have enough flexibility to provide useful computer access, which can be utilized for leisure activities.¹³ In this issue, Peters et al describes the need for this type of flexibility, as articulated by potential BCI users. In Huggins' survey, respondents also suggested game-playing as a desirable BCI-assisted activity. We can also note that some leisure activities are served by existing BCIs, which provide for environmental control functions, such as TV control. BCIs based on sensorimotor brain activity have used games as part of user training protocols.⁵⁸ BCI applications for leisure activities have also been developed either as primary applications or additional functions for BCIs.^{59–61} In this issue, Holz et al. describes the positive impact of a BCI-operated painting program.

Recovery of function

Problem

It is important to develop innovative methods, such as BCI neural feedback systems, in order to restore motor function to those with neural injury or disease, because current standard care and research approaches do not restore normal function. Generally, there are two research approaches currently studied for treating motor impairment after neurological injury or disease: peripherally directed treatments such as exercise or exercise-assisted technologies^{62–67} or centrally directed treatments involving brain stimulation methods such as transcranial magnetic stimulation (TMS),^{68, 69} transcranial electrical stimulation (TES),⁶⁹ or transcranial direct current stimulation (tDCS).^{69, 70}

Peripherally-directed interventions are promising, for example, for stroke survivors. Interventions tested include robotics,⁶³ functional electrical stimulation,^{65, 67} coordination and functional task training,^{62, 65, 67} and body weight-supported treadmill training.^{64, 65} Even for those with moderate to severe impairment, some studies are showing clinically and statistically significant gains in response to innovative treatment in measures of Fugl-Meyer lower limb coordination scale⁶⁵ and the Arm Motor Ability Test (AMAT) Function score,⁶⁷ as well as significant gains in quality of life,⁶⁶ or in proxy function measures such as gait speed.⁶⁴ Though promising, these peripherally-directed interventions do not restore normal function in most study participants and some participants do not respond to treatment. Therefore, it is critical to develop other more effective treatment methods.

Though less studied than peripherally-directed interventions, brain stimulation methods have been more recently applied to the problem of motor re-learning for those with dyscoordination from neural injury or disease. The motor skill acquisition process (motor learning) is driven by neuroplasticity in a number of cortical centers including the motor cortex,^{70, 71} cerebellum,^{72–74} and cerebellar pathways through the thalamus to the cortex.⁷⁵ Engagement of these neural centers and pathways, during the motor learning process, is thought to produce a motor memory, or ‘motor engram’, which includes the neural substrate engaged during the task.⁷⁰

Brain stimulation methods hold some promise. But, as applied to the problem of motor re-learning after neural injury or disease, results are currently mixed. In the study of stroke treatment, scientists are reporting transient (days to a few weeks) motor gains in response to the application of TMS, but it is difficult to evaluate the body of literature due to heterogeneity of both subject and intervention variables. These include time since stroke (acute/chronic); rTMS frequency variability (1 – 25Hz rTMS); treatment duration variability (1 – 10 sessions); and measures of motor function for which the value is unknown regarding the minimally clinically significant improvement.^{68, 76, 77} In the application of tDCS, results are generally positive for ‘improving’ motor function in older adults^{78, 79} and stroke survivors (e.g.,^{80, 81}). tDCS application for those with Parkinson’s disease ranges from mixed (e.g.⁸²) to no response on most motor measures.⁸³ In this issue, Ang et al. present a study of the effects of tDCS on brain signal during training with an EEG-BCI; findings suggest that tDCS can enhance brain signal features that are used during EEG-BCI training, but further work will be needed in order to determine the actual role and benefit of both EEG-BCI and tDCS in physical recovery. Similar to the difficulties in evaluating response to rTMS treatment, the same or similar difficulties exist in evaluating response to tDCS. Further, reported results are not currently greater than peripherally-directed treatments. Some have proposed that the problem arises from the variability of neural networks across individuals, leading to a lack of certainty as to whether the applied stimulus did not work well in general or only for a given individual (who did not exhibit change).⁶⁹ One suggestion put forth for future work⁶⁹ is to combine the new information regarding modeling the electrical fields induced by brain stimulation⁸⁴ and the emerging information of cortical circuits,⁸⁵ in order to more specifically and accurately target brain stimulation.

Justification

Given the promise of direct brain stimulation, but its limited results, to date, it is important to continue to develop interventions for motor recovery that more directly target or engage the brain in the location where the pathology occurs. And given the individual variability of brain structure, neural networks, and alterations after brain injury or disease, one promising avenue of working directly with the brain itself, is to employ a neural feedback training system, which engages the individual's central nervous system encompassing all its individual uniqueness.

Biofeedback has been a useful intervention for a number of different types of health problems. Biofeedback systems can be based on non-invasively acquired brain signals such as 'real time' functional magnetic resonance imaging (rtfMRI), functional near infrared signal (fNIRS), and electroencephalography (EEG). The term brain-computer interface" has been applied to these non-invasive biofeedback systems, which are dependent upon brain signal processing that is sufficiently rapid to be of use in real time during training for cognition, emotion function, and motor learning. fMRI-BCI has been tested in several therapeutic applications. For example, fMRI-BCI was used in a preliminary study to train those with schizophrenia to more normally control emotion through modulation of the left and right insula brain regions.⁸⁶ Additionally, real time fMRI-BCI was successfully used to reduce pain perception, through modulation of the right anterior cingulate cortex (rACC).⁸⁷ Studies of rtfNIRS-BCI for application to motor function have focused on identification of usable signals in a BCI neural feedback system.^{88, 89} EEG-BCI systems have been successfully used to reduce seizure activity^{90, 91} and improve function in those with attention-deficit hyperactivity disorder (ADHD).⁹² With mixed success, EEG-BCI systems have been tested for use in motor learning after stroke.^{93, 94} Recently, a randomized controlled trial was conducted to compare physical therapy arm coordination/functional test training alone or in combination with EEG-BCI training.⁹⁵ Results showed a statistically significant additive advantage of the EEG-BCI treatment, according to the Fugl-Meyer arm coordination score (FM); but the absolute group difference was only 3 FM points, which is not clinically significant.⁹⁶ In this issue, the Marone study looks to the future with a study to test the feasibility of using non-invasive EEG-BCI systems in the clinic.

Future challenges and directions

Though an EEG-BCI proved clinically feasible for motor training, other factors must first be considered before clinical deployment should or can be realized, with efficacy of treatment being the foremost unproven factor. There are many sources of difficulty in developing an efficacious non-invasive brain neural feedback system. For example, rtfMRI-BCI is not practical for daily biofeedback sessions. rtfNIRS-BCIs and EEG-BC are more practical and portable; but they depend upon brain signals that are a summation of complex neural activity; the summated signals obfuscate the signal features that are likely most desirable and most reflective of the neural activity that should be targeted for treatment. In response to this difficulty, there is a growing literature that seeks to derive more specific meaning from EEG signals so that EEG-BCIs can be more effectively applied to training recovery of motor function after neural injury or disease (e.g., ⁹⁷⁻¹⁰¹). At the same time, the future development of BCI feedback systems should leverage knowledge of the neural mechanisms

of motor learning and how to engage those mechanisms specifically with BCI neural feedback systems. We can learn this process from the example provided in the study of tDCS brain stimulation. That is, Orban de Xivry and Shadmehr⁷⁰ have synthesized a body of work and derived three major principles of tDCS and treatment response, as follows: 1) “Firing rates are increased by tDCS anodal polarization and decreased by cathodal polarization, accounting for the effect of tDCS on motor behaviors that do not involve learning”; 2) “Anodal polarization strengthens newly formed associations, accounting for facilitation by tDCS of sequence-learning”¹⁰² “and speed/accuracy trade-off skill”,¹⁰³ requiring the formation of new patterns of motor activity”; 3) “tDCS polarization modulates the memory of new/preferred firing patterns, accounting for tDCS alteration of the rate of motor adaption” (e.g.^{104, 105}). Theories have been put forth to explain some of the positive response to tDCS; these theories include modulation of long-term potentiation,¹⁰⁶ a decrease in GABA;¹⁰⁷ and increasing or decreasing the level of noise in neural activity;¹⁰⁸ though none of these theories alone adequately explains experimental results. Once proven, mechanisms of motor learning may form the basis for a BCI that could deliver neural regulators to a particular brain location or to specific neural substrates, in order to enhance motor skill acquisition after neural injury or disease; though seemingly impossible, others¹⁰⁹ have recently designed and tested an EEG-BCI that uses brain-state in a mouse model to control a wireless-powered optogenetic designer cell implant for ultimate induction of synthetic interferon-beta (balances the expression of pro-and anti-inflammatory agents in the brain and protects the brain).

The application of brain stimulation and the use of brain neural feedback training both depend upon our knowledge of motor skill acquisition, the function of the neural centers involved, the mechanisms of the interventions, and the mechanisms of neural recovery of motor control. The synthesis of these discoveries will provide the platform for future BCIs.

Conclusion

BCIs are emerging as interventions to restore function through assistive technology and to promote recovery. Success in these applications has been observed in the laboratory and in limited in-home studies for communication applications. However, BCI technology is still clinically immature and further development with the participation of clinicians and clinician-scientists is needed before the full potential of BCIs for rehabilitation can be realized.

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