PM R 10 (2018) S233-S243

www.pmrjournal.org

Innovations Influencing Physical Medicine and Rehabilitation

Brain Computer Interfaces in Rehabilitation Medicine

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Abstract

One innovation currently influencing physical medicine and rehabilitation is brain—computer interface (BCI) technology. BCI systems used for motor control record neural activity associated with thoughts, perceptions, and motor intent; decode brain signals into commands for output devices; and perform the user's intended action through an output device. BCI systems used for sensory augmentation transduce environmental stimuli into neural signals interpretable by the central nervous system. Both types of systems have potential for reducing disability by facilitating a user's interaction with the environment. Investigational BCI systems are being used in the rehabilitation setting both as neuroprostheses to replace lost function and as potential plasticity-enhancing therapy tools aimed at accelerating neurorecovery. Populations benefitting from motor and somatosensory BCI systems include those with spinal cord injury, motor neuron disease, limb amputation, and stroke. This article discusses the basic components of BCI for rehabilitation, including recording systems and locations, signal processing and translation algorithms, and external devices controlled through BCI commands. An overview of applications in motor and sensory restoration is provided, along with ethical questions and user perspectives regarding BCI technology.

Introduction

Brain—computer interface (BCI) technology provides novel neuroengineering solutions to rehabilitation problems caused by amputation or neurologic injury. As a result, neural interfacing techniques are being incorporated in rehabilitation strategies across patient populations. This review introduces the concept of BCI, describes how BCIs are being used to compensate for lost function or to facilitate rehabilitative therapies, and discusses BCI applications in motor and sensory restoration.

The term "brain—computer interface" was first officially defined in June 1999 at the First International Brain—Computer Interface Technology Meeting as "...a communication system that does not depend on the brain's normal output pathways of peripheral nerves and muscles" [1]. At the time, the definition was created to distinguish it from other existing forms of augmentative communication devices that depend on spared motor pathways, such as facial or oculomotor movements. Since that meeting, interest in BCI has grown beyond solely a communication device, and now its usage includes augmentation of motor, sensory, and other functions.

BCI Technology

The core functions of most current BCI systems are recording neural signals from the brain, processing these signals through a computer algorithm, and translating processed signals into an intended action using an end effector device (Figure 1).

Recording and Decoding

While one could theoretically access any level of the central nervous system with BCI technology, some areas confer practical advantages over others. The cerebral cortex has a functional topography that enables comparatively easy targeting of specific motor and sensory subsystems. For example, the hand area of the primary motor cortex has a distinct anatomical morphology that is also conserved across individuals and

https://doi.org/10.1016/j.pmrj.2018.05.028

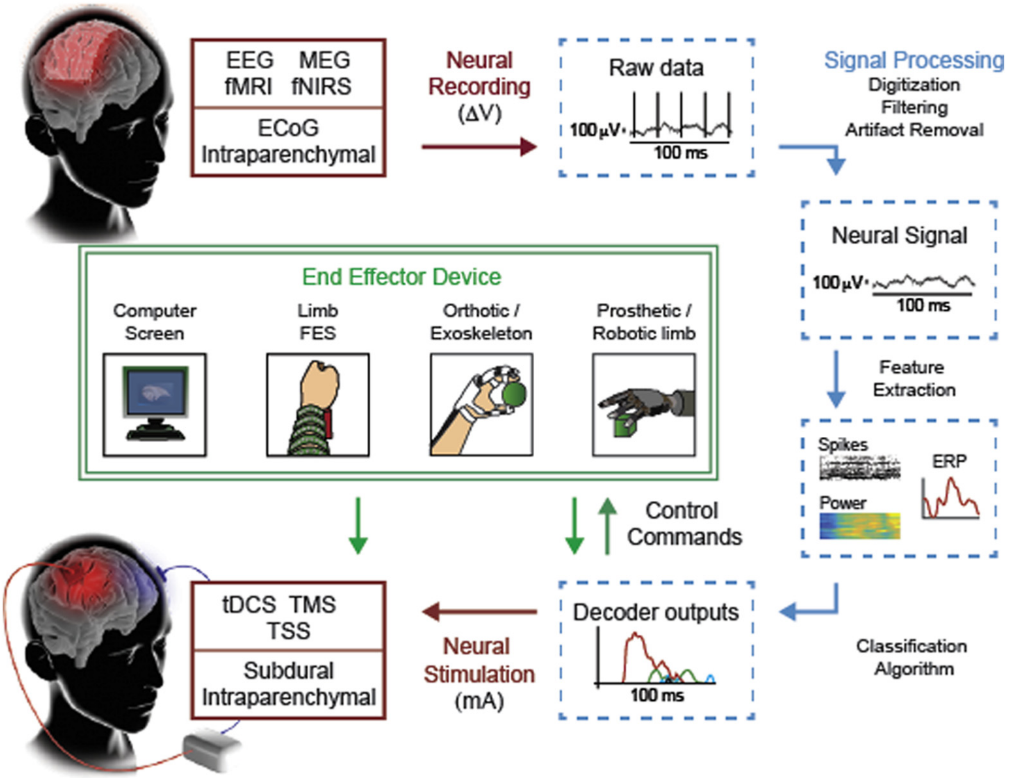

Figure 1. BCI architecture. Red boxes (solid lines) represent BCI components that interface with the central nervous system to capture neural activity (eg, via noninvasive EEG or invasive electrocorticography array) or provide feedback (eg, via noninvasive tDCS or subdural stimulation). Blue boxes (dotted lines) show signal processing steps that translate neural data into commands reflecting the user's intent. The green box (double lines) depicts examples of end-effector devices that can be controlled with a BCI. Arrows indicate directional flow of information. Note that end-effector devices may provide sensor feedback to the BCI decoder, produce actions that trigger neural stimulation, or be a source of sensory and meta-cognitive feedback to the BCI end-user. BCI, brain—computer interface; EEG, electroencephalogram; MEG, magnetoencephalography; fMRI, functional magnetic resonance imaging; fNIRS, functional near-infrared spectroscopy; ECoG, electrocorticography; FES, functional electrical stimulation; ERP, event-related potential; tDCS, transcranial direct current stimulation; TMS, transcranial magnetic stimulation; TSS, transspinal stimulation. Figure by M. Bockbrader. Brain/interface images by Seth Olson.

is conveniently located on the lateral aspect of the cerebral convexity, allowing for easy targeting with either invasive or noninvasive systems [2]. Similarly, the spinal cord has a topography that is grossly conserved across individuals and allows for recording and stimulation of the motor corticospinal tracts and sensory dorsal columns [3].

A key practical differentiator in neural recording technologies is the level of invasiveness of a specific technique, generally classified as "noninvasive" or "invasive," depending on whether placement requires penetrating the integument. Noninvasive recording techniques include direct measures of electrical activity resulting from neuron depolarization, such as electroencephalography (EEG) recordings, or indirect measures of neuron firing such as functional magnetic resonance imaging, magnetoencephalography (review in Thakor [4]), or functional near-infrared spectroscopy (review in Irani et al [5]).

In contrast to noninvasive techniques, invasive recording methods confer the benefits of greater spatial and temporal specificity but incur the added risks of surgically implantable devices. However, there are varying degrees of invasiveness. In the least-invasive level of recording techniques, electrodes can be placed just below the skin surface, decreasing the distance from the nervous system to the recording electrode and improving signal quality [6,7]. Alternatively, electrodes can be placed beneath the bony structures in the epidural or subdural space, lying as a net of electrodes over neural tissue of interest, as in electrocorticography (ECoG). In the most invasive case, multiunit microarrays of 100+ electrodes can be implanted into the neural parenchyma to record directly from individual neurons or small neuronal populations (review in Thakor [4]).

Regardless of the recording method, once raw neural signals are acquired, they are processed with amplification and digitization. Key features of the digitized neural signals include both amplitude and spike train frequency [8]. Salient features are then extracted using an algorithm and translated into device commands. These pertinent, extractable features vary based on the neural recording technique, with noninvasive techniques like EEG generally using averaged signals from a