5 Therapeutic Applications of BCI Technologies

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Abstract
There has been considerable recent interest in applying brain–computer interface (BCI) technology for the rehabilitation of nervous system disorders. This survey considers possible ways that BCI technology can be applied to motor rehabilitation after stroke as well as other disorders of brain functioning. To date, there have been a number of studies demonstrating proof of principle, but definitive evidence of efficacy is lacking. This area may advance as research identifies new signals to train, more effective means of training, as well as improved paradigms for applying this technology.

5.1 INTRODUCTION
A brain–computer interface (BCI) is a system that measures central nervous system (CNS) activity and converts it into an artificial output that replaces, restores, enhances, supplements, or improves natural CNS output (Wolpaw & Wolpaw 2012). A number of studies have been successful in training individuals to control electroencephalogram (EEG) signals to replace lost communication or control abilities (e.g., Kostov & Polak 2000; McFarland et al. 2010; Pfurtscheller et al. 1993; Wolpaw et al. 1991). More recently, there has been increased interest in developing BCI methods for improving motor, cognitive, or emotional function (e.g., Daly & Sitaram 2012; Dobkin 2007). This chapter considers some of the possible ways that BCI technology might be applied to promote neurorehabilitation.

As noted by Dobkin (2007), both traditional rehabilitation and BCI control rely on learning to modify spared neural ensembles. Dobkin (2007) suggested that practical BCI systems could be used as a tool to reinforce the use of spared neural representations or to ensure that subjects were optimally prepared to execute a particular movement. Silvoni et al. (2011) identified three potential approaches to the use of BCI technologies for rehabilitation: the substitutive strategy, classical conditioning, and operant conditioning. The substitutive strategy refers to all technologies that bypass interrupted neural pathways. Classical conditioning promotes neuroplasticity through establishing a contingency between stimuli. Operant conditioning promotes neuroplasticity by establishing a contingency between a response and reward/feedback. Daly and Wolpaw (2008) distinguished between applications of BCI technology that bypass an impaired neuromuscular system and those that help guide activity-dependent brain plasticity to improve function. Use of BCIs to improve function...
more closely fits the logic of traditional rehabilitation whereas substitutive strategies correspond to providing an orthosis. Huster et al. (2014) stated that neurofeedback likely represents the earliest application of BCIs and suggest that the extent of EEG data processing is the difference between BCIs for communication and control and those for neurofeedback.

While BCI technologies have generated a considerable degree of interest as potential agents of rehabilitation, critical issues for their successful application include what signals will be used and how these signals should be used. Use of neural signals for rehabilitation involves the context in which they are used (i.e., the training paradigm), whether feedback is provided, the goal of training, and the way brain states are conceptualized. For example, traditional neurofeedback paradigms occur within a context where the task of the patient is only to regulate their brain activity based on feedback provided (Walker 2010). In contrast, if the intent of training is to ensure that patients are optimally prepared to execute a particular movement (Dobkin 2007), then BCI training should be associated with that specific movement.

In the following, we will consider some of the paradigms that have been suggested as ways to apply BCI technologies to rehabilitation. The emphasis will be on their similarities and differences. Then, we will briefly consider some of the research findings to date.

### 5.2 CURRENT BCI REHABILITATION PARADIGMS

Neurofeedback (also referred to as neurotherapy or biofeedback) has been used for many years to treat a large assortment of conditions including attention-deficit/hyperactivity disorder (ADHD; Lubar & Shouse 1976), depression (Hammond 2005), substance use disorders (Trudeau 2005), insomnia (Hammer et al. 2011), autism (Friedrich et al. 2015), and stroke (Bearden et al. 2003; Reichert et al. 2016). Neurofeedback involves providing feedback in the form of some visual or auditory stimulus based on some predetermined EEG feature (Micouland-Franchi et al. 2015). As noted above, the patient’s task is only to regulate the specific brain signal and no additional behavior is required. Thus, there is no specific context in which neurofeedback occurs, other than a therapist’s office. As a result, neurofeedback protocols implicitly assume that the effects of training persist as a permanent change in brain state that is sustained beyond the therapeutic context.

BCI technologies have been used for rehabilitation, for example, to enhance motor imagery. The rationale for this approach is that motor imagery may provide an effective means of therapy for stroke-related dysfunction (Sharma et al. 2006). Since brain lesions may impair imagery (McInnes et al. 2016), methods to facilitate imagery might enhance recovery. BCI-facilitated motor imagery involves providing feedback based on sensorimotor rhythms (SMRs) while users are given the task of imagining movement of affected limbs (Pichiorri et al. 2015; Prasad et al. 2010). Enhanced motor imagery training assumes that motor imagery activates some of the same neural systems as are used in actual movement. SMR training, in turn, is used as a method to enhance motor imagery. Thus, the EEG is seen as an index of a cognitive task, the rehearsal of which facilitates recovery from motor deficits after stroke.

Another paradigm for use of BCI technology to rehabilitate the motor deficits resulting from stroke involves closing the sensorimotor loop (Gomez-Rodriguez et al. 2011; Ramos-Murguialday et al. 2013). With this paradigm, SMR desynchronization is rewarded by the operation of an orthosis that produces actual movement of the affected limb. Closing the sensorimotor loop assumes that activation of motor areas will be associated with the proprioceptive feedback produced by limb movement. Several alternative explanations have been provided for the effects of closing the sensorimotor loop, including Hebbian learning (Gomez-Rodriguez et al. 2011) and priming of subsequent physiotherapy (Curado et al. 2015).

BCI technology has also been used to train users to produce brain states that ensure optimal preparation to execute a particular movement (Boulay et al. 2011; McFarland et al. 2015b). In this paradigm, users learn to modulate SMRs in advance of the motor task to be practiced. This approach assumes that advanced preparation facilitates subsequent motor performance. Therapeutic benefit
can then result from the correct performance of the facilitated motor behavior and also from the user potentially learning task-appropriate preparatory responses.

Task-appropriate brain states have also been produced without training by making trial initiation contingent on the desired brain state (Burke et al. 2015; Griffin et al. 2004; Salari & Rose 2016). In contrast to the methods previously discussed, the state-dependent trial presentation paradigm does not provide feedback for the BCI user to learn control of the targeted brain state. It only assumes that the task-appropriate brain state facilitates performance.

Table 5.1 shows some characteristics of each of these approaches. The second column of Table 5.1 lists the context in which BCI technologies are applied. Neurofeedback has no particular context, imagery enhancement occurs in the context of practicing imagery, closing the sensorimotor loop occurs in the context of patients attempting control of an orthosis, and both trained preparation and state-dependent trial presentation occur immediately before the task to be practiced. The third column of Table 5.1 lists whether or not feedback is provided. All of the methods except state-dependent trial presentation provide feedback in order to enhance brain plasticity. While feedback will enhance learning, a method that does not provide feedback may allow for shorter training sessions. The fourth column of Table 5.1 indicates that the goal of these methods differ. Neurofeedback is generally conceptualized as a means to normalize the EEG (Walker 2010). The goal of imagery enhancement is to reinforce weak imagery (Prasad et al. 2010). Closing the sensorimotor loop strives to associate intention with haptic feedback (Gomez-Rodriguez et al. 2011). Both trained preparation and state-dependent trial presentation seek to ensure optimal preparation for the task to be practiced. Neurofeedback differs from the other approaches by implicitly assuming a static view of the EEG and the brain states it reflects. Finally, imagery enhancement and closing the sensorimotor loop are probably only applicable to the rehabilitation of motor impairments while the other methods may have broader application.

The list of methods and their characteristics shown in Table 5.1 is not exhaustive. Additional paradigms may be developed and additional ways in which paradigms differ may be identified. However, Table 5.1 provides a framework for consideration of design issues that will ultimately affect the efficiency of methods for rehabilitation.

### 5.3 BRIEF OVERVIEW OF RESEARCH FINDINGS

Neurofeedback has been a topic of extensive published research and is the only paradigm listed in Table 5.1 that is currently in widespread clinical use. In contrast, most of the research with other
BCI paradigms has been focused on rehabilitation of motor function. Perhaps the most common application of neurofeedback is for the treatment of ADHD, and this will be the focus of most of our discussion of neurofeedback.

In a review of the literature on neurofeedback for the treatment of ADHD, Monastra et al. (2005) stated that controlled group studies of ADHD have demonstrated beneficial effects on a number of outcome measures. The study by Fuchs et al. (2003) that they cite is typical. This study compared the effects of neurofeedback (SMR [12–15 Hz at C4] or beta training [15–18 Hz at C3]) and stimulant medication in children with ADHD, with treatment assignment based on the parent’s preference. SMR training consisted of providing visual and auditory feedback when activity was 60% above pretraining baseline for 500 ms. Improvements were found for both groups on performance of several psychometric tests of attention and ratings of symptoms. No information was provided about the nature of changes in the EEG that might have occurred with training.

One issue with the Fuchs et al. (2003) study is that the changes observed over time could possibly be due to nonspecific effects (i.e., symptoms may get better simply with the passage of time or may be due to placebo effects). Since information was not provided about changes that occurred in the EEG in the Fuchs et al. (2003) study, it is not possible to infer what the patients in the neurofeedback group might have learned. This is a concern with the interpretation of many neurofeedback studies since the nature of the EEG changes that occur with training is typically not documented (Zuberer et al. 2015). If the effectiveness of neurofeedback is based on the premise that treatment produces a relatively permanent change in the EEG, then studies should minimally provide evidence that a change has in fact occurred. The lack of clear evidence for learned changes in the EEG may be due in part to the difficulty of doing controlled comparisons when training is in one direction only (i.e., to only increase or decrease the EEG feature in question). In contrast, the use of multiple states, as is the case with most BCI communication applications, provides a controlled within-subject comparison (McFarland et al. 2005). What is being learned with neurofeedback is important for evaluating its impact, as originally discussed by Black and Cott (1977). For example, in a double-blind study, Logemann et al. (2010) found only nonspecific effects of neurofeedback in patients with ADHD as essentially equivalent effects were observed in a sham feedback control group. These results suggest that nonspecific effects may occur with neurofeedback paradigms independent of any changes in the EEG.

Some neurofeedback studies have documented changes in the EEG that occur with training. For example, Reichert et al. (2016) trained a stroke patient and healthy controls to increase SMR (12–15 Hz at Cz) over 10 sessions on different days, each consisting of a baseline and six training runs. Feedback was also provided on the presence of artifacts, which participants were instructed to minimize. Reichert et al. (2016) showed that both the patient and controls increased the SMR signal within daily runs as compared to baseline. In addition, there were pre–post increases on several measures of cognitive performance. However, Reichert et al. (2016) did not provide information about changes in SMR across days, nor did they provide spectral and topographic information that could characterize what participants were controlling during training sessions.

EEG features targeted for a given behavioral disorder by advocates of neurofeedback vary considerably. Recommended signals for treatment of ADHD include SMR, theta/beta ratios, and slow cortical potentials (Monastra et al. 2005; Strehl et al. 2006). Specific EEG features are also recommended for multiple disorders.

The neurofeedback literature contains recommendations for signals to train that often involve elaborate schemes that have minimal empirical support. For example, Walker (2010) associates specific brain areas, behavioral functions, and corresponding clinical symptoms to each of the 19 electrode locations of the 10–20 system. These associations are not supported by citations to the scientific literature. Consider the case of electrode FP1. Walker (2010) associates activity at this electrode with left frontopolar cortex and attention. However, it is important to recognize that activity at surface electrodes does not simply reflect the activity of the neural tissue in the immediate vicinity. Rather, it is the superposition of many sources resulting from volume conduction.
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(Hansen et al. 2016; Srinivasan et al. 2006). In addition, attention is a complex area of study reflecting multiple processes (Posner 1975) that are associated with several distinct neural networks (Scolari et al. 2015). Realistic identification of brain signals needs to consider both the nature of the EEG and that of brain organization. Also of particular relevance is a consideration of what sorts of artifacts might be present at a particular site. For example, both eyeblinks (Picton et al. 2000) and EMG (Goncharova et al. 2003) are prominent at anterior locations such as FP1. These artifacts are of particular concern given that neurofeedback studies typically do not provide a description of what the participants are actually using for control (i.e., spectral and topographic results).

Cortese et al. (2016) concluded that evidence from a meta-analysis of randomized controlled trials does not support the effectiveness of neurofeedback for the treatment of ADHD. However, summarizing the results of a randomized controlled trial, Steiner et al. (2014) concluded that neurofeedback is a promising treatment for ADHD. In a recent review, Thibault et al. (2016) noted that the clinical effectiveness of neurofeedback remains controversial. They suggest that factors other than the feedback may be responsible for observed effects. Likewise, in their review of the literature on healthy adults, Rogala et al. (2016) conclude that there is a lack of correlation between changes induced in the trained EEG signal and targeted behaviors. They attribute this to methodology that does not allow isolation of appropriate brain regions associated with the targeted behaviors. Zuberer et al. (2015) advocate more rigorous scientific standards in this research, which makes use of devices of uncertain quality.

Several recent studies have evaluated the possibility of using BCI technology to ensure, reinforce, or enhance motor imagery. Sharma et al. (2006) have reviewed studies suggesting that motor imagery may facilitate recovery from stroke. However, they note that it is difficult to ensure compliance with motor imagery instructions. Prasad et al. (2010) suggested that EEG might prove useful to verify whether patients are actually engaging in effective motor imagery. They evaluated the use of a two-target SMR BCI task and found that all five of their stroke patients were able to achieve moderate success. Some positive results were also obtained on outcome measures of motor function. However, it was difficult to isolate the cause of these effects as all five patients received both BCI-based motor imagery training and physical practice. Furthermore, this report did not include spectral or topographic information that would allow the reader to evaluate the nature of the signals being used for BCI control.

Pichiorri et al. (2015) used BCI-based feedback consisting of SMR-dependent movement of virtual hands in patients with stroke-related motor deficits. A group of 12 patients receiving BCI-based motor imagery training was compared to a group of 11 patients receiving only motor imagery training without feedback. Both groups additionally received standard care including motor, occupational, and cognitive therapy. Pichiorri et al. (2015) found significantly greater recovery on several outcome measures in the group receiving BCI-based feedback. They also provided information about the EEG bands involved and topographic location of the signals that the BCI group used for control. These results provide stronger support for the possibility that BCI-based imagery enhancement might be therapeutically beneficial in patients with stroke-related motor deficits.

A rationale for feedback that actually moves the affected limb is the suggestion that closing the sensorimotor loop produces Hebbian plasticity owing to the pairing of intention and proprioceptive feedback (Gomez-Rodriguez et al. 2011). Although Gomez-Rodriguez et al. (2011) proposed that closing the sensorimotor loop using within-trial activation of an orthosis might prove beneficial for stroke recovery, their study only involved showing that haptic feedback facilitated classification of the EEG. Buch et al. (2008) reported that magnetoencephalography (MEG)-based BCI training paired with post-trial activation of an orthosis had no significant effect on hand function, although patients successfully learned to control the device. Using a pre–post design, Shindo et al. (2011) reported some improvement in function after EEG-based BCI operation of an orthosis. Young et al. (2015) reported an improvement in a self-reported measure of strength after training with a BCI system that produced functional electrical stimulation of the hand and tongue. No information was provided about the specific EEG features used for training. Ang et al. (2014) found no significant
The difference between outcome measures for stroke patients receiving BCI-controlled robotic therapy and those receiving standard robotic therapy. Ramos-Murguialday et al. (2013) reported a significant improvement in functioning of stroke patients after training with an SMR-controlled orthosis as compared to a sham control group. Both groups also received behaviorally oriented physiotherapy. Information that would characterize the EEG features used by patients for orthosis control was not provided. Ramos-Murguialday et al. (2013) suggested that BCI training may have primed the effects of physiotherapy. Using a head-mounted neurochip in monkeys, Lucas and Fetz (2013) showed that making invasive stimulation of the primary motor cortex contingent on activation of a muscle resulted in reorganization of cortical outputs. The Lucas and Fetz (2013) study illustrates the bidirectional nature of the sensorimotor loop and provides an alternative method for creating associations between motor cortex and muscles.

The evidence for beneficial effects of closing the sensorimotor loop on motor deficits after stroke is weak at present and results are inconsistent. As with neurofeedback, the designs employed often do not allow isolation of the factors that might be responsible for any observed therapeutic effects. Furthermore, there is often a lack of concern for characterizing how training affects the EEG (or MEG).

As noted earlier, Dobkin (2007) suggested that one way that BCI systems might facilitate rehabilitation is to ensure that subjects were optimally prepared to execute a particular response. The possibility of training motor preparation was demonstrated in healthy controls by Boulay et al. (2011) using a go–no-go reaction time task and McFarland et al. (2015b) using a joystick movement task. Both of these studies used a three-phase design in which subjects initially performed the criterion task to identify pre-movement EEG features predicted movement. Next, these features were trained in a bidirectional BCI task. In the third phase of the Boulay et al. (2011) study, an auditory imperative stimulus was presented cuing a button press while subjects were also controlling a cursor to hit a target on a video screen. Voluntary desynchronization in SMRs produced faster reaction times than SMR synchronization. In the third phase of the McFarland et al. (2015b) study, subjects increased or decreased SMRs according to color cues in order to initiate the joystick task. SMR desynchronization facilitated performance in subjects with lower initial performance levels. Both of these studies provided spectral and topographic information to characterize the EEG features that were used by subjects for control. The results of both the Boulay et al. (2011) and McFarland et al. (2015b) studies showed that pre-movement voluntary modulation of SMRs affects behavior. They provide a rational for the development of rehabilitation protocols that target SMRs to ensure that subjects are optimally prepared to execute a particular response.

As noted earlier, neurofeedback studies have advocated the use of SMRs for the treatment of ADHD (Monastra et al. 2005), autism (Friedrich et al. 2015), sleep disorders (Hammer et al. 2011), memory (Reichert et al. 2016), and epilepsy (Sterman 2010). In each of these applications, SMRs are treated as a unitary index of some particular brain function. However, SMRs are recording site specific. For example, SMR effects are specific to the limb involved in both movement and imagination (Pfurtscheller & Lopes da Silva 2011). Furthermore, subjects can be trained to independently modulate three different SMRs differing in location (McFarland et al. 2010). In contrast to conceptualizations of EEG rhythms reflecting global functions such as mirroring the activity of others (Pineda 2008) or behavioral inhibition (Monastra et al. 2005), activity recorded at specific locations may reflect the activity of canonical cortical circuits whose functions vary with location (Bhatt et al. 2016). From this perspective, SMRs are analogous to rhythms at similar frequencies that reflect the activity of specific brain networks such as those involved in vision and hearing (Mazaheri et al. 2014; Scheeringa et al. 2016). Thus, spatial filtering operations are important to provide more precise localization of activity as well as to improve signal-to-noise ratios (McFarland 2015). Perhaps more important is an appreciation of the anatomical specificity of brain rhythms to specific neural networks.

At the same time that SMR modulations are topographically specific to a given limb, they are also extended across multiple brain areas. For example, recording with depth electrodes implanted...
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for deep brain stimulation reveals beta rhythm desynchronization with movement in the subthala-
mamic nucleus (Klostermann et al. 2007). These subthalamic beta rhythms are coherent with beta
rhythms recorded at the scalp (Kato et al. 2015). Likewise, beta rhythms can be recorded from spe-
cific muscles that are coherent with localized scalp beta rhythms (van de Steeg et al. 2014). Thus,
SMR beta rhythms represent a resonance extended over multiple components of an effector-specific
network. This provides a strong rationale for pairing specific SMR control tasks with specific move-
ments that are targeted for therapy.

Optimal task preparation can also be produced by delaying trial onset until spontaneous fluc-
tuations in the EEG indicate that a desired brain state is present. Griffin et al. (2004) showed that
state-dependent trial presentations could affect learning of classical eyelid conditioning in rabbits.
Trial presentation was contingent on the presence of hippocampal theta rhythm, as measured with
implanted electrodes. A theta-contingent group learned the task much quicker than a non–theta-
contingent group. State-dependent trial presentations were also used by Salari and Rose (2016) to
evaluate the effects of scalp-recorded activity on memory in human subjects. EEG was recorded at
frontal and temporal locations and spectral power was separately summed in theta or beta bands.
Presentation of visual images in a recognition memory experiment was dependent on either high or
low summed power in these bands. Subsequent recognition memory was better for high beta presen-
tations than low beta presentations while theta-dependent presentations did not differ significantly.

5.4 DISCUSSION

Which of the paradigms outlined in Table 5.1 will prove most useful for rehabilitation of brain
disorders is currently an empirical question. Their potential utility depends on the nature of brain
states, such as whether or not these represent static traits or transient configurations of labile net-
works. The paradigms outlined in Table 5.1 also differ in how they conceptualize the nature of
the rehabilitation process and the nervous system that is to be rehabilitated. For example, imagery
enhancement implicitly assumes that the EEG provides an index of a cognitive process and that it
is the strengthening of this cognitive process that is the goal of therapy. In contrast, the use of a
neurochip (Lucas & Fetz 2013) has the goal of establishing simple associations between brain and
muscle activity. The paradigms outlined in Table 5.1 also differ in their potential breadth of applica-
tion. Although there has been great interest in the use of BCI technologies to assist recovery from
the motor impairments resulting from stroke, the use of state-dependent trial presentations within
classical conditioning and recognition memory paradigms shows that some of these methods may
have broader application. Likewise, neurofeedback can be applied broadly as there is no dependence
on context. Paradigms based on optimizing patient preparation can also be applied in any situation
in which a preparatory period is feasible. However, imagery enhancement and closing the senso-
rimotor loop probably have less broad applicability. In addition, these methods may vary in ease of
implementation. For example, state-dependent training does not require extensive training of the
BCI user in brain state feature control.

Application of BCI technologies could potentially extend beyond stroke-related motor deficits to
include many other disorders (Daly & Sitaram 2012). However, application to any particular disorder
is dependent on identification of reliable neural signals that can be used in a suitable training para-
digm. This can be challenging as not all brain states are as well characterized as those associated
with movement. For example, some success has been obtained with functional magnetic resonance
imaging (fMRI) detection of emotional reactivity (e.g., Martino et al. 2016). However, detection of
emotional reactivity with the EEG appears to be less robust (McFarland et al. 2015a). As noted by
Kragel and LaBar (2016), the brain basis of emotions is currently poorly understood. While modi-

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107Therapeutic ... discussed so far, and these paradigms differ in how this has been done to date. The neurofeedback approach assumes an

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107Therapeutic ... discussed so far, and these paradigms differ in how this has been done to date. The neurofeedback approach assumes an

Selection of an appropriate brain signal is an issue facing all of the methods discussed so far, and
these paradigms differ in how this has been done to date. The neurofeedback approach assumes an
elaborate system that associates specific EEG features to specific functions and provides feedback accordingly (Walker 2010). Empirical support for such schemes is often not provided by those who advocate them. Selection of features for motor recovery by the other methods is generally based on the well-established association of SMRs with motor function (Pfurtscheller & McFarland 2012) but is much more limited in scope.

Even given the well-established association of SMRs with movement, there are still additional issues in selecting features for BCI systems. For example, in reviewing the use of transcranial magnetic stimulation (TMS) as a modality for motor rehabilitation, Plow et al. (2016) discuss the issue of whether ipsilesional or contralesional areas should be targeted. They suggest that the hemisphere targeted might depend on the extent of a patient’s lesions. The targeted hemisphere is also relevant for BCI-based methods that might be used to enhance the activity of specific brain sites that best participate in recovery. In this sense, there are certain parallels between the logic of using TMS and that of using BCI technologies. Both technologies could work by activating task-appropriate brain networks. Use of TMS has the advantage of being quicker and probably less expensive. Use of BCI technologies may be more precise in the aspects of network function targeted since TMS is likely to activate relatively broad expanses of cortex that may be involved in multiple functions. BCI methods may be able to target more precise activation of networks associated with frequency-specific signals.

Also reviewing TMS applications for rehabilitation, Chouinard and Paus (2010) noted that there are multiple components of the motor system that could serve as targets for activation, in addition to Brodmann’s area 4. This view is consistent with the results of Dum and Strick (1991) who examined the corticospinal projections to cervical segments of the spinal cord in macaques. Dum and Strick (1991) describe contributions from premotor and cingulate motor areas to the corticospinal tract. Although axons from these sites are generally smaller, they contribute a substantial portion of the pyramidal track. Dum and Strick (2005) suggested that the distinction between premotor and primary motor areas is not as clear as often supposed.

It is often assumed that SMRs arise from the primary motor cortex, but the exact neural circuitry generating SMRs are not precisely known. The hand area of the primary motor lies mainly on the anterior bank of the central fissure (Laakso et al. 2014). As such, the pyramidal cells would be aligned parallel to the scalp and would not be expected to provide a clear projection to central scalp areas. Thus, SMRs may represent the activity of areas other than the primary motor cortex. Although the motor system is perhaps better characterized than many other neural systems, much remains to be learned about how its various components generate the signals recorded from the scalp as well as their potential relevance for rehabilitation.

Although this chapter has dealt mainly with EEG, other neural signals can be used for rehabilitation. For example, Sitaram et al. (2012) used fMRI to provide real-time feedback on ventral premotor cortex activity to stroke patients and Rea et al. (2014) used fNIRS (functional near-infrared spectroscopy) to discriminate preparation of hip movement, also in stroke patients. Liew et al. (2015) provided feedback based on the correlation of fMRI activity between motor cortex and ipsilesional thalamus. This demonstrates the possibility of providing feedback on measures of connectivity. While measures of cerebral blood flow have less temporal resolution than EEG, they provide better spatial resolution. The paradigms discussed earlier (e.g., closing the sensorimotor loop or state-dependent trial presentations) could be applied to measures of cerebral blood flow just as readily as to electrophysiological indices of brain state.

5.5 SUMMARY

BCI methods developed for communication and control applications could also be a technology useful for rehabilitation. There are a number of different ways in which BCI technologies might be used for this purpose, depending in part on conceptualizations of nervous system functioning and therapeutic goals. Much of the work to date has been concerned with motor function after stroke, although there are many other possible applications. A number of studies have demonstrated proof
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of principle, but definitive evidence of efficacy is lacking. This may be partly because proof of efficacy is much more difficult to demonstrate than proof of principle. The use of BCI technology for therapeutic purposes may progress as research identifies new signals to train, more effective means of training, as well as improved paradigms for applying this technology.

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