

Developing a “hands-free” neuroprosthesis command system

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Introduction

People with spinal cord injury (SCI) face significant lifestyle challenges. Loss of independence due to the SCI can often be associated with depressive illness, pain, high levels of anxiety, frequent hospitalisation, drug dependency and so on (Craig & Hancock, 1998; Craig et al., 2002). They face severe restrictions on their ability to perform basic activities of daily living such as eating and drinking, and being wheelchair-bound restricts the user to limited terrains. Functional Electrical Stimulation (FES) involves developing technology that has the potential to help overcome some of these problems. For example, FES has been used to restore standing and stepping in people with paraplegia (Triolo & Bogie, 1999). Restoring leg movement using FES raises the problem of how the restored function is to be operated by the user. In many cases it is not possible for the person to operate a command system using their hands. Brain-Computer Interfaces (BCIs) provide a “hands-free” means of controlling electrical devices and is believed to have significant potential for the operation of neuroprostheses. The purpose of this paper is to evaluate briefly the ability of BCI interfaces to fulfill the requirements of neuroprosthetic applications, and highlight the potential of an EEG 8-13 Hz wave (called the Mind Switch) interface with an FES application.

FES command interface requirements

All lower-body FES systems currently require the use of a walking frame or crutches, and frequently involve the application of large forces through both arms to support the body against collapse. With both hands involved in the demanding task of postural support it is difficult for the person to issue commands to the FES system using their hands. Furthermore, as developments reduce the need for postural support it will be desirable to keep the hands free to perform tasks while standing. This raises the possibility of switch interfaces that do not require or involve arm/hand activity.

The status of development of lower extremity neuroprostheses has been reviewed by Triolo & Bogie (1999) and includes systems for standing, transfers, stepping, stair climbing/descending and bladder control. There are many degrees of freedom involved in the control of lower extremity FES tasks. Each function involves electrical stimulation applied to appropriate muscles in a specific sequence. Due to the complexity of this task, and the need to ensure user safety, the stimulation sequence is handled automatically, without the need for intervention from the user. However, the task of the user is to select a pre-programmed sequence to achieve a desired result, such as taking a step forward. Therefore, the primary nature of a lower extremity FES command system is to provide switches for selection, execution, and termination of these sequences. Graded or proportional command sources would also be useful for setting commands such as the angle of a turn, or the height of a step to be taken.

Brain-computer interfaces (BCIs)

BCIs offer “hands-free” control by allowing the user to employ their brain signals as a switch. The principle of BCI control is that a person can voluntarily change, or learn to change, neuronal activity in their brain. The brain activity generally used is the electroencephalogram (EEG) that is measured using surface electrodes. Detection of a specific change is then used to control some device. This general criterion has resulted in a wide variety of different strategies for BCIs (Wolpaw et al., 2000). BCI development has mainly focused on applications for

people with little or no voluntary movement, including devices for moving a cursor on a computer screen, selecting characters for writing, or using an Environmental Control System (ECS; Craig et al., 2002).

When choosing a BCI command system one must ensure that activation of the neuroprosthesis and movement of the limb do not adversely affect command signals used by the BCI. However, signals employed by BCIs often originate from motor areas of the cortex, and are affected by natural and passive movement of the extremities. Many BCIs use Mu (8-13 Hz) and Beta rhythms (13 Hz and above) located over sensorimotor areas. The signals used by these BCIs are reactive to movement preparation, execution, imagination and passive movement of the limbs, and form a spatial pattern of reactivity corresponding to the particular movement involved. Movement of the right hand for example, whether executed, passive, or imagined, principally results in reduced mu and beta-band power over the hand area of cortex on the left side of the head, prior to and during movement. It is difficult, therefore, to discriminate between mu and beta signals arising from movement and those arising from motor imagery of the same movement. This means that motor imagery of a particular limb cannot currently be used effectively as a command to activate a neuroprosthesis fitted to the same limb. Toe and feet movement and motor imagery have a predominant association with sensorimotor rhythms near the vertex. These signals are more difficult to detect on the scalp, probably due to the location of the cortical foot motor area in the mesial cortex. These signals have potential application for command of lower extremity neuroprostheses, provided that movement of the paralysed limb does not affect mu and beta rhythms at the vertex, which may be true for individuals with paraplegia involving complete lesions.

Mind Switch BCI interface

The Mind Switch BCI uses 8-13 Hz signals from the part of the cortex where reactivity is greatest to eye-closure. When a person closes their eyes, electrical activity within the 8-13 Hz frequency band is enhanced over the cortex, predominantly over visual areas. This increase in alpha amplitude measured is consistent with the hypothesis that alpha band activity is a correlate of a cortical area at rest. Heasman et al. (2002) recently reported a person with C5 tetraplegia using the Mind Switch to control a hand grasp neuroprosthesis. The subject toggled the open and closed state of the neuroprosthesis by closing their eyes for an average of 2.1 seconds. The main limitation of the Mind Switch is the necessity of closing the eyes to issue a command. However, as discussed below, the Mind Switch is the only BCI demonstrated to operate in an asynchronous control environment, which is an important requirement for neuroprosthetic applications.

BCIs can operate in continuous, synchronous, or asynchronous control environments. Those that operate in continuous control environments require the BCI to generate commands continuously to update the state of a device. This control has the limitation that the person must constantly attend to the task. In a synchronous control environment, stimuli are presented, say every 4.5 – 8 seconds, to indicate time windows when the user's response is measured. Synchronous control environments require the user to continuously produce appropriate responses in each time window, and allow command generation only during these periods. These environments are useful for communication applications where the BCI is used repeatedly, for example to choose letters for writing, but are less suitable for neuroprosthetic applications. A neuroprosthesis requires a command interface that can issue commands asynchronously, at a time of the user's choosing. To accomplish this a BCI must be able to detect specific brain activity at any time a command is intended, and disregard all other brain activity that arises when the user is performing other tasks. This is a much more difficult detection problem than encountered by BCIs in continuous and synchronous control environments. The signal used by the Mind Switch exhibits a much higher signal-to-noise ratio than other BCIs, and allows the interface to be used for periods exceeding 15 minutes without the generation of unintended commands.

Future directions of the Mind Switch

Our current research efforts are seeking to develop asynchronous BCI with multiple switches by combining the Mind Switch with alternative switches. For example, one potential combination is with the control of mu activity

at the vertex, reactive to motor imagery of the feet. In this arrangement a user activates the Mind Switch and then immediately imagines relaxing or moving the feet. The Mind Switch acts as the asynchronous switch, and the high or low level of mu activity indicates the BCI output. This BCI could potentially be used to toggle the state of two devices, such as the open/closed states of the left and right hands in a bilateral hand grasp neuroprosthesis.

The impact of artifact remains a challenge. The performance of BCIs is usually assessed in an environment where the user remains still and relaxed. These conditions are unrealistic in neuroprosthetic applications, and techniques to remove cable noise, muscular artifact, and ocular artifact from the EEG need to be incorporated to ensure adequate performance. Artifact in the EEG will also arise from FES stimulation currents. The stimulation frequency in FES systems is optimized to produce sufficient force and reduce the likelihood of muscle fatigue (typically 20 – 30 Hz) and often falls into the frequency range used by BCIs. Therefore, simple filtering in the frequency domain may not be an adequate tool to reject stimulation artifact. In a recent study, wavepacket analysis (WPA) was used to filter stimulation artifact from the EEG of a person with tetraplegia, using the Mind Switch to operate an implanted hand-grasp neuroprosthesis. Off-line signal processing using WPA significantly improved the reliability (from 77% to 100%) and speed (from 9.3 to 2.1 s) of the Mind Switch BCI (Heasman et al., 2002). Further studies are required to quantify stimulation artifact in the EEG due to implanted and surface stimulation systems in the upper and lower extremities.

For convenience, BCI development is usually conducted with able-bodied subjects. In order to optimize performance for people with SCI we need to know the impact the injury has on brain signals used by BCIs. We have recently investigated the impact of SCI on the EEG during eye-closure. Sign tests showed that people with SCI, compared to able-bodied individuals, have consistently lower activity in the alpha frequency band recorded from 14 out of 15 electrode sites. Furthermore, the group with tetraplegia had significantly lower ($p < 0.5$) alpha band magnitudes than the group with paraplegia, at central and posterior sites (74). These results will help to optimize electrode placement in the Mind Switch BCI for people with SCI.

Conclusion

Neuroprostheses require command interfaces where the user can switch the state of a system, or supply graded commands to control the device along one or more degrees of freedom. The user must be able to supply these commands asynchronously, at a time of their choosing, and the operation of the neuroprosthesis must not interfere with the user's ability to generate commands. Current command interfaces allow neuroprostheses to be operated to perform some activities of daily living, but often limit the potential functionality that can be obtained from the device. BCIs provide a means of generating commands "hands-free", and therefore offer the potential to overcome some of the limitations of existing command interfaces. Many signals used by BCIs are affected by extremity movement, and are unlikely to be suitable for neuroprostheses. Mind Switch is less affected by extremity movement and is therefore likely to offer suitable command signals. Furthermore, Mind Switch is presently one of the few BCIs that can potentially provide asynchronous commands for neuroprostheses. However, it does require users to momentarily draw their visual attention away from the task at hand.

Unfortunately, neuroprosthetic applications increase the likelihood of artifact in the EEG due to movement of the prosthetic limb, and increased muscle and eye activity. Stimulation currents from the neuroprosthesis are also likely to contaminate signals used by BCIs. Studies are needed to quantify these artifacts, so that appropriate signal processing strategies can be adopted to reduce the impact of these signals on BCI performance. Lastly, there is little data available concerning the deafferentation impact of SCI on the EEG. As many BCI have been developed using able-bodied subjects, it will be important to understand how SCI affects brain activity in order to optimize BCI – FES integration for people with SCI.

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