BME 5030 ELECTRONIC BIOINSTRUMENTATION

FINAL PAPER

ON

ELECTROCORTICOGRAPHY (ECoG) BASED BRAIN COMPUTER INTERFACE FOR CEREBRAL PALSY PATIENTS

BY

Mujtaba Javed Mir
(mjm528)

Department of Biomedical Engineering
CORNELL UNIVERSITY
New York, USA

(Fall 2009)

Understanding Cerebral Palsy

Cerebral palsy is a group of neurological disorders that affect the patient's ability to move and keep balance and posture as a result of an injury to parts of the brain, or as a result of abnormalities in parts of the brain that control muscle movements. The medical definition of cerebral palsy is a "non-progressive" but not unchanging disorder of movement and/or posture, due to an anomaly of the developing brain. Development of the brain starts in early pregnancy and continues until about the age of three. Damage to the brain during this time may result in cerebral palsy. This damage is usually to the motor cortex of the brain (figure 1) and is a onetime event. Thus, cerebral palsy does not worsen with time, however its effects may change over time. [1]

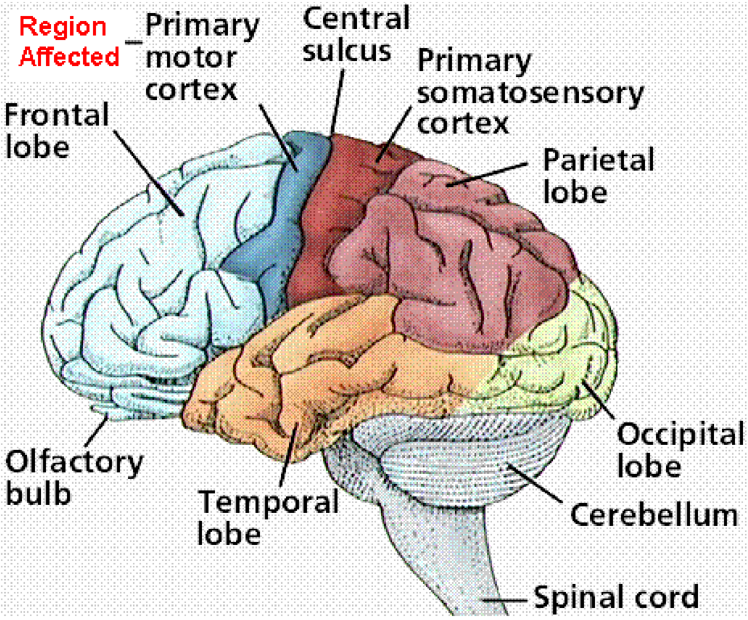

Figure 1[2]: Cerebral Palsy affects the motor cortex of the brain.

The damage to the brain interferes with messages from the brain to the body, and from the body to the brain. The effects of cerebral palsy vary widely from individual to individual. At its mildest, cerebral palsy may result in a slight awkwardness of movement or hand control and at its most severe, CP may result in virtually no muscle control, profoundly affecting movement and speech. Depending on which areas of the brain have been damaged, one or more of the following symptoms may be observed:

- Muscle tightness or spasms
- Involuntary movement
- Difficulty with "gross motor skills" such as walking or running
- Walking with one foot or leg dragging
- Walking on the toes
- Difficulty with "fine motor skills" such as writing or doing up buttons
- Difficulty in perception and sensation

Types of Cerebral Palsy

A. Classification by Number of Limbs Involved

- **Quadriplegia** – Here all the four limbs are affected.
- **Diplegia** – Here all four limbs are involved but the legs are more severely affected than the arms.
- **Hemiplegia** – Here one side of the body is affected. The arm is usually more involved than the leg.
- **Triplegia** – Here three limbs are involved, usually both arms and a leg.
- **Monoplegia** – Here only one limb is affected, usually an arm.

B. Classification by Movement Disorder

- **Spastic CP-** Spastic muscles are tight and stiff, and have increased resistance to being stretched. They become overactive when used and produce clumsy movements. Normal muscles work in pairs i.e. when one group contracts, the other group relaxes to allow free movement in the desired direction. However in Spactic CP, Spastic muscles become active together and block effective movement. This phenominon is called co-contraction.

  Spasticity may be mild and affect only a few movements, or severe and affect the whole body. The amount of spasticity usually changes over time. Therapy, surgery, drugs and adaptive equipment may help to control spasticity. Damage to the brain's cerebral cortex is generally the cause of spastic cerebral palsy.
- **Athetoid CP-** Athetosis leads to difficulty in controlling and co-ordinating movement. People with athetoid cerebral palsy have many involuntary writhing movements and are constantly in motion. They often have speech difficulties. Athetoid cerebral palsy results from damage to the basal ganglia in the midbrain. It was once common as a result of blood type incompatibility, but is now rarely seen.
- **Ataxic CP-** Ataxic CP is the least common form of cerebral palsy. People with ataxic CP have a disturbed sense of balance and depth perception. They usually have poor muscle tone (hypotonic), a staggering walk and unsteady hands. Ataxia results from damage to the cerebellum, the brain's major centre for balance and co-ordination.

Cerebral Palsy Treatment

Cerebral palsy cannot be cured, but treatment often improves the patient's capabilities. Treatment may include physical and occupational therapy, speech therapy, drugs to control seizures, relax muscle spasms, and alleviate pain; surgery to correct anatomical abnormalities or release tight muscles; braces and other orthotic devices; wheelchairs and rolling walkers; and communication aids such as computers with attached voice synthesizers.

However, in extreme cases the brain damage which caused cerebral palsy may also lead to other conditions such as seizures, learning disabilities or developmental delay. In such cases, the life of the patient becomes very hard and for helping such patients brain computer interfaces (BCI) are being designed that would provide communication and control the gait. The main target of these BCIs is spastic cerebral palsy as it directly involves the cerebral cortex and thus can be controlled by gaining access over the motor cortex of the brain, or as will be discussed later, by gaining control over the speech cortex.

ECoG and Brain Computer Interfaces

The terms 'ECoG' or 'electrocorticography' defines the technique of recording the electrical activity of the cerebral cortex by means of electrodes placed directly on it, either under the dura mater (subdural) or over the dura mater (epidural) but beneath the skull.

Brain–computer interfaces (BCIs) convert brain signals into outputs that communicate a user's intent. BCIs can be used by people with severe motor disabilities because this new communication channel does not depend on peripheral nerves and muscles. BCIs can allow patients who are totally paralyzed, have cerebral palsy or have other neuromuscular diseases to express their wishes to the outside world. However, practical applications of BCI technology to the needs of people with severe disabilities are impeded by the limitations and requirements of current BCI methodologies. [11]

Why choose the ECoG Signal?

The ECoG signal was zeroed in by understanding the relative merits and demerits of the signals or technologies that could be used for the BCI.

Techniques such as functional magnetic resonance imaging (fMRI), positron emission tomography (PET), and electrophysiological analyses such as ectroencephalography (EEG), magnetoencephalography (MEG), and electrocorticography (ECoG) could be used in brain computer interfaces, however, these techniques have some limitations.

The fMRI (using blood oxygenation level dependent contrast) and the PET (using $[^{15}O]H_2O$ tracer) assess changes in the physiologic processes such as blood flow, blood oxygenation, and glucose metabolism, which are believed to be coupled to local synaptic activity.[4] Both these technologies have provided new opportunities for spatically delineating regions associated with various aspects of human cognitive function. However, for these techniques the spatial and temporal resolution is quite coarse because they rely on metabolic and hemodynamic responses. Additionally, the precise relationship between underlying neuronal events and the metabolic hemodynamic responses sub serving fMRI and PET is not well understood. This implies that the fMRI and PET data can be difficult to interpret. Hence, I did not choose anyone of the two.

The next set of techniques involves using the electrical signals of the brain activity which forms the basis for methods such as EEG, MEG and ECoG. These techniques have an improved temporal resolution and a more direct assessment of the electro physiologic dynamics associated with various brain induced events, including the palsy relates complications that may occur in the brain. EEG is the most commonly used technique for acquiring the electrical signals of brain activity as EEG is non-invasive and thus low risk, is relatively low-cost, and is widely applicable. However, due to the signal attenuation by the skull and electrical noise contamination from muscle activity, the signal-to-noise ratio of EEG is low, the maximal spatial discrimination with EEG is approximately 3 centimeters and the frequency of resolution is poor (0-40 Hz). MEG is also non invasive and is much similar to EEG with a better spatial resolution of approximately 4 to 10 millimeters.

On the other hand, electrocorticography (ECoG) requires craniotomy for electrode placement. The ECoG signal magnitude is typically five to ten times larger (0.05-1.0 mV versus 0.01-0.02mV for EEG) than EEG, has a much higher spatial resolution as it relates to electrode spacing (0.125 cm versus 3.0 cm for EEG), and has more than four times the frequency bandwidth of EEG (0-200 Hz versus 0-40 Hz for

EEG). Though invasive, the ECoG platform provides a combination of huge spatial resolution on the order of 1-2 mm with a broader frequency range of around 0-200 Hz, also known as the χ band region.

Studies have proved that it is feasible to use electrocorticographic signal power in high spectral frequencies to get real time cortical mapping, from arrays of subdural electrodes. This suggests that high-frequency component (76–200 Hz, or “χ-index”) of the electrocorticogram can be used to provide a generic , reliable, clinically useful correlate of local cortical function .[5] This finding is demonstrated in figure 2 which shows power spectrum resulting from movement of the hand is picked up the ECoG and lies in the high frequency zone (χ Band Region) thereby strengthening the belief that ECoG is a better alternative for BCIs

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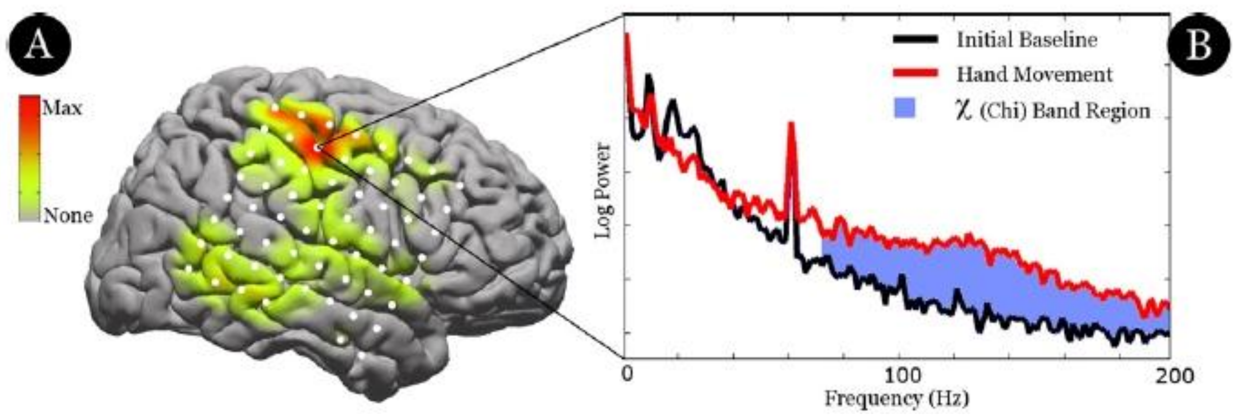


Figure 2 [5]: Electrocorticographic motor mapping. (A) Map of hand movement compared to rest. Electrode locations are shown in white. (B) The spectrogram (mean log-power vs. frequency) from a single, peri-central electrocoritcographic electrode placed , for hand movement (15 s) and resting baseline (10s). An increase in power occurs over a broad spectral range. This difference (shaded blue) is evident in even brief epochs of activity.

ECoG’s superior frequency range is attributable to two factors. First, the capacitance of cell membranes of the overlying tissue combined with their intrinsic electrical resistance constitutes a low-pass (RC) filter that largely eliminates higher frequencies from the EEG. [12] Second, the ECoG signals being closer to the cortex represent a smaller population of neurons than EEG, and discriminate across a broader range of frequencies including frequencies greater than 40 Hz. Thus, they are more prominent at electrodes that are closer to cortex than EEG electrodes and thereby achieve higher spatial resolution [14].

This advantage that ECoG signals have over EEG signals can be better understood by comparing the brain signals generated by ECoG and EEG. Figure 3 shows an example of a standard spectral analysis of variance of frequency changes for a human subject during a given active condition versus the rest, inactive condition. In this example the subject's task was to imagine saying the word "move" and that served as the active condition. The channels are the ordinate (y) axis and the frequency is the abscissa (x) axis and the ranges appreciable by EEG and ECoG are also shown. The figure demonstrates that the range of reactive frequencies extends into the ECoG range (0-200Hz) which is well beyond 40-50 Hz, the maximum value reported for EEG-based systems. Moreover, unlike EEG signals, the signal-to-noise ratio of the ECoG signal is improved by the skull rather than attenuated, and ECoG signals are not contaminated by muscle electrical activity.Thus, the ECoG signals, in contrast to the EEG signals, provide a much better frequency range and bigger spatial resolution. [6]

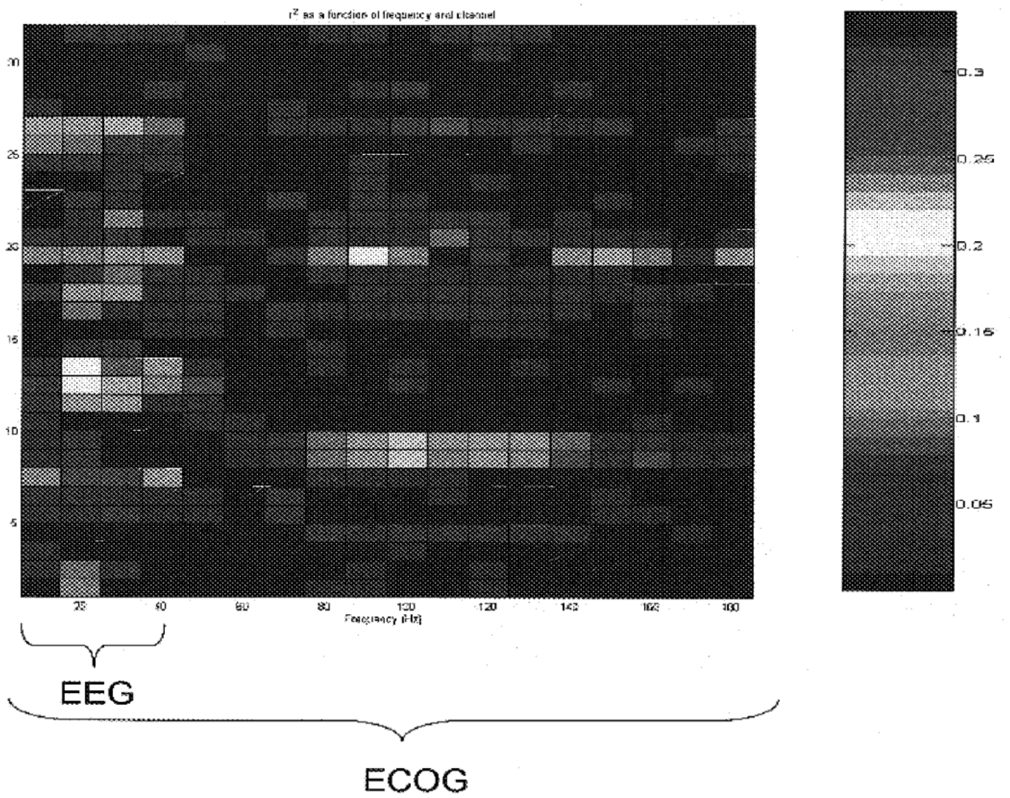


Figure 3 [6]: Comparison between the frequency spectrum of EEG and ECoG signals.

It is also worth mentioning that electrode locations or frequencies that are used in conventional EEG-based systems are not helpful in an ECoG-based system because the ECoG signals have a much higher frequency range, and higher spatial resolution.

ECoG based Brain Computer Interface

The brain computer interface that I have mentioned herein is partly based on the discovery that ECoG signals can be successfully used in a BCI to control an external device in real time, and further in part on the finding that ECoG signals can provide information required for control in at least two-dimensions. [3]

In order to get the signals from the cortex, subdural electrodes are used. These electrodes do not need to penetrate the cortex as is required with microelectrode systems. [2] Therefore, scarring and subsequently encapsulation of the recording sites is less of a factor with ECoG electrodes than with intra-cortical microelectrodes. These characteristics translate to increased implant viability over time, which is an important consideration for clinical applications. [11]

Thus, in this BCI system it is proposed to use ECoG signals as it has novel and un-expected advantages over EEG based systems. Also, the ECoG requires much less time, than required by the EEG based BCI system, for a user to learn to gain control and improve performance. The better spatial and signal resolution of ECoG relative to EEG gives us two or three more degrees of freedom of control. [11] For ECoG based BCI systems even with a very coarsely spaced electrode array, the information for twodimensional discrimination is present. On top of this, the movement of each finger can be distinguished with ECoG, which has never been seen with EEG. It is also very likely that more degrees of freedom can be achieved with a higher density electrode array. [7,11]

Use of Non-Sensorimotor Signals

The biggest advantage of using ECoG based Brain Computer Interface for helping CP patients is that this system can use the non sensorimotor signals to carry certain motor functions of the body. This is of particular importance in those types of CP where the motor cortex is damaged which is the case in spastic cerebral palsy.

This can be explained by the fact that the ECoG based system makes the use of speech tasks that drive brain signaling in speech cortex.[8] Thus a subject thinking about the word “move” generates signals in speech cortex that are accessible to ECoG, these signals are then used to gain overt control over an external device.[9]

The ECoG-based BCI system and related methods use ECoG signal from the brain and translate that activity into the intent of the patient. One such system is depicted in figure 4 where ECoG signal can be acquired using an electrode array that is either under (subdural) or over (epidural) the dura matter, although in an exemplary embodiment the electrode array is subdural. The signal is moved to the acquisition computer either through lead wires or through a wirelessly transmitted signal. [10] The computer is further programmed to analyze the ECoG signal so that the intent of the user is determined.

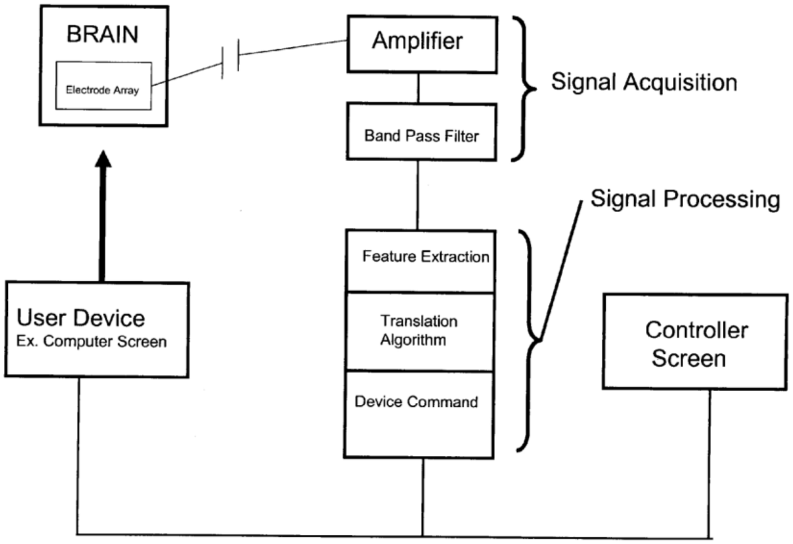


Figure 4[6]: Block diagram of the signal processing in an ECoG-based BCI.

The intent of the user is then communicated to a device, such as a screen cursor, or a gait controlling device or a wheel chair or a prosthetic device to control the device accordingly. Using closed loop feedback to the user, the BCI configuration makes this control continuously and in real time.

Signal Acquisition hardware is an electrode array implanted beneath the dura matter of the patient (i.e. subdural) and generates the raw ECoG signal. This signal is passed through an amplifier and a band pass filter. The signal is then provided as an input to a computer running software that extracts features of the signals, applies a translation algorithm to the signal features as they vary under varying behavioral conditions of the patient (user), and then generate a device command derived from the processed, translated signal. The device command is communicated to a user screen on a computer monitor, and controls the position of a cursor on the screen. For training of the user on the ECoG based BCI, the position of the cursor provides visual feedback to the patient as to the effect of the brain signals on the cursor position. The user then uses the feedback information to modify conscious instructions, thereby for improving accuracy of cursor position control. The device command is also communicated to a controller screen, which serves to manifest the intentions of the user. For example, the cursor moves up when the user intends for the cursor to go up.

Figure 5 is a block diagram of one embodiment of the ECoG signal based BCI in which the ECoG signal is routed through a network prior to being sent to a BCI computer. The feedback screen is meant for the user to see how accurate the machine is. Based on the feedback, the user trains the machine. Raw ECoG signals from the ECoG electrodes are passed to a data acquisition computer configured for collecting and storing the raw ECoG signal. Raw and processed signals from the acquisition computer, and the device command, are communicated via a local area network to a computer or computers configured to provide signals for monitoring, for example in a monitoring room or to an analog printing device. The signal is further passed through a low pass filter and to the BCI computer, which is configured for feature extraction, application of the translation algorithm, and generation of a device command. The device command is communicated to an output device, which is one embodiment is a feedback screen for viewing by the user. [6]

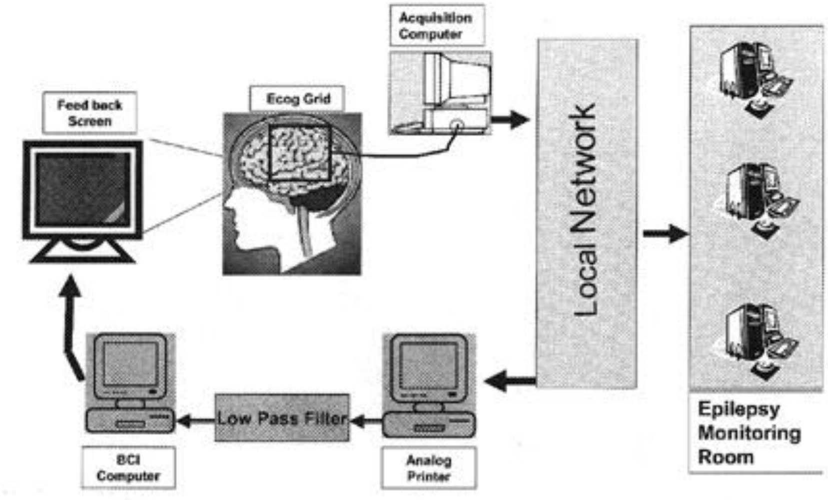


Figure 5 [6]: Block diagram of an ECoG based BCI that uses LAN for monitoring.

Figures 6 and 7 demonstrate the analysis of a given subject’s single electrode. In figure 6, a spectral analysis is performed to compare an active condition with an inactive one. In the case studied [6], the active condition is one in which the user/patient has been asked to imagine saying “move”. This example shows a pronounced decrease in power at 20 Hz in the active condition as compared to the resting one. Here, whenever the individual imagines saying the word “move”, a reliable depression in power exists at 20 Hz.[11]

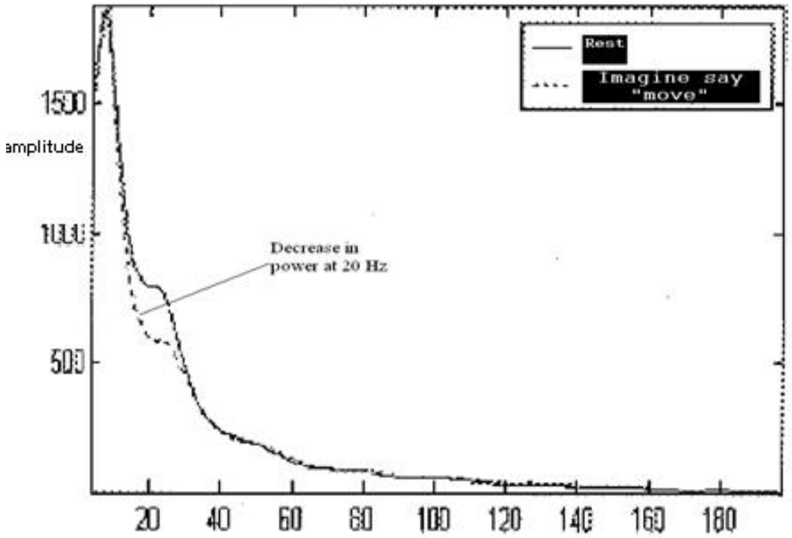
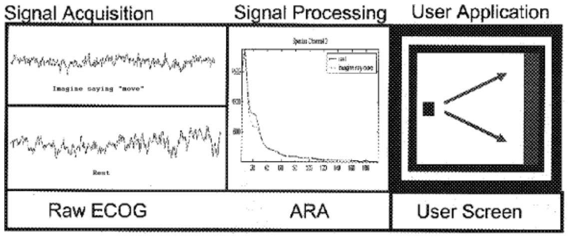


Figure 6 [11]: Decrease in Power due to the subject changing his position of rest and imagining saying the word “move”.

A graphical representation of an algorithm used to correlate specific brain signals to specific behavioral conditions of the patient using the ECoG based BCI is shown in figure 7. A reliable correlation between a power change at a frequency specific band once established (figure 6), is then utilized by the BCI system for device control. Here, as the BCI system continually gets raw data from the patient, any moment at which the system detects a specific depression in power at 20 Hz is the basis for generating a signal to direct the cursor upwards. On the other hand, a baseline level of activity at 20 Hz is the basis for generating a signal to direct the cursor downwards.



Condition 1. Imagine Saying Move, directs cursor upwards
Condition 2. Rest, directs cursor downward

Figure 7 [6]: Graphical representation of an algorithm used to correlate specific brain signals to specific behavioral conditions of the patient using the ECoG based BCI.

Thus, the protocol for using the ECoG based BCI system involves a screening process which is followed by a signal feature extraction process and then a process of closing a feedback loop to the user, by which the user adapts control of his conscious instructions to the output of the Brain Computer Interface.

Training the ECoG-based BCI

In order to use the BCI, it has to be trained first. The BCI is trained as per the feedback given by a specific user. In other words, training process personalizes the BCI. During the training sessions, the brain signals of the user are examined and the important postulates of the brain signals (i.e. frequency and locations) that are subject to user control are identified. The training sessions include, for example, multiple cognitive tasks that are selected on the basis of their activation of various, specific areas of cortex relative to the location of the electrode grid. Overt tasks are the ones that require an overt motor output by the user, for example, of a hand, the tongue, or the mouth. Examples of overt tasks are opening and closing of the hand, movement of other prosthetic body parts . Covert tasks, on the other hands, do not include motor output. These are tasks like thinking of closing the hands or thinking about saying a word. In the training process, each user is instructed to perform overt and covert tasks.

The ECoG signals that are generated during the implementation of each task and during the rest are collected, stored and analyzed. The signal frequencies and electrode locations, which vary with the behavioral changes of the patient are also identified. [5]

The software in the BCI system is then configured to related these features with the actions of the patient. For example, the spectral responses on doing a particular thing (say saying word) are compared with the responses obtained when the patient was in the state of rest. One or more electrode locations and one or more frequencies that were more closely involved with a certain task are pinpointed as shown in figure 8.

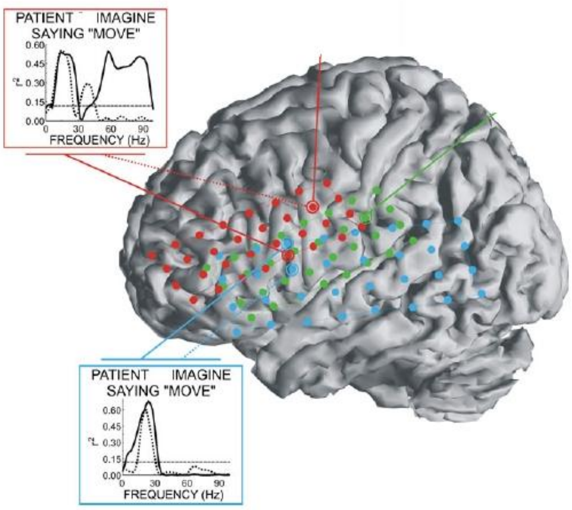


Figure 8 [11]: Spectral response at electrodes placed at different regions on the brain.

After this, offline study of the acquired data is done. The frequency spectrum at the rest state (inactive state) can be taken as the reference by the output device. Thus any change in the frequency spectrum while doing some work can be translated into output.

In the process of training or adapting to the BCI, the patient watches the computer screen (output device). After one second during which the screen is blank, a cursor appears on the screen and then a target also appears (on opposite ends). The cursor travels across the length of the screen at a fixed rate. The cursor's vertical movement is controlled by the control signal calculated by the signal processing component of the BCI. The offline assessment helps in identifying a signal that the user can control. The user now controls the cursor movement in one dimension (i.e. up or down).This movement of the cursor is dependent on deviation of the frequency spectrum from the reference spectrum. Suppose, the patient remains in the state of rest, then the cursor may move downwards and if the patient says the word "move" the cursor may move upwards (figure 7). The memory of the BCI would record the frequency spectrum for a particular action by the user and use this data in real time use of the device to identify that particular action. [11]

After the screening process and the offline feature extraction and analysis, the BCI computer provides the feedback output to the patient who is instructed to perform the same task that produced previously identified responses. The patient then employs the feedback as a basis for modifying the conscious instructions to the output device. Thus this feedback system would improve the accuracy of the BCI and the attached prosthetic device.

Conclusion

As cerebral palsy patients have gait problems in controlling their limbs, this BCI would be of immense use to them. CP patients who cannot control their hands and their grip can be trained accordingly on a BCI. More importantly, as stated earlier, the ECoG based BCI uses the signals from the speech cortex to gain control of motor functions. This is particularly helpful for cerebral palsy patients and they have little control over their motor functions. For example a CP patient who cannot control the closing and opening of hand could be trained in way such that the frequency spectrum of closing and opening is calibrated with the rest position. Any deviation from the rest position would trigger the cursor to the open position or the close position (of the hand) depending in the deviation of the spectrum. Thus, the movement of the cursor would tell if the patient wanted to open or close the hand and how tightly did the patient want to close the hand or grip on object. This information would be carried onto on artificial output device (say an artificial robotic hand) which would then hold an object accordingly. This is explained in the figure 9, where a prosthetic device is connected to the BCI.

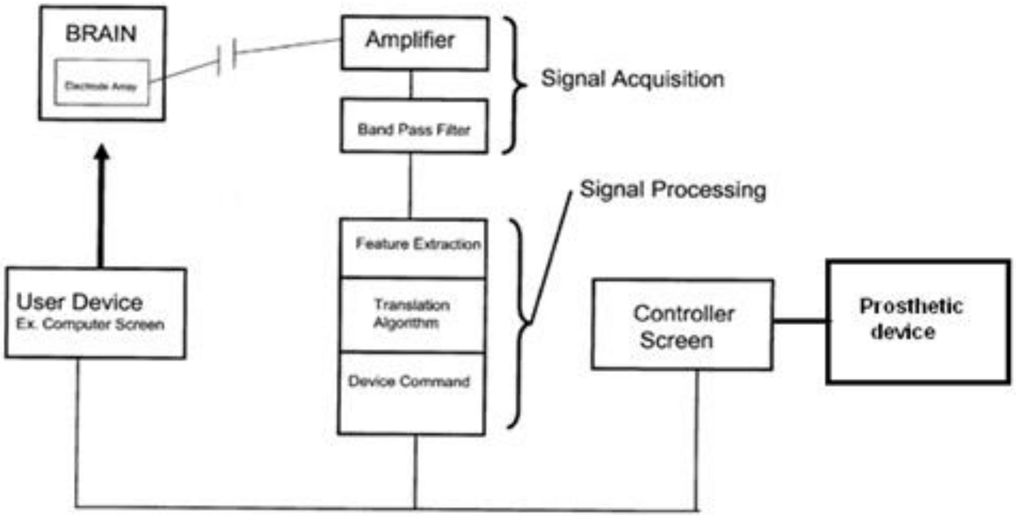


Figure 9: Prosthetic device connected to the BCI to help patients with Cerebral Palsy.

Thus in summary, ECoG is likely to be an excellent BCI modality that can be used to help severe cerebral palsy patients because it has higher spatial resolution, better signal to noise ratio, wider frequency range and lesser training requirements than scalp-recorded EEG, and at the same time may have greater long-term stability of signal quality over intra cortical recording. However, some ethical issues can be raised by the invasive nature of this technique. In future ways need to be found that would make the ECoG based BCIs more feasible for clinical use, this will involve research in reducing the invasive nature of this BCI. This development of ECoG-based BCI methodology could greatly increase the power and practicality of BCI applications that can serve the communication and control needs of people with motor disabilities.

References

1. National Institute of Neurological Disorders and Stroke (NINDS)

2. Webster., John, Medical Instrumentation Application and Design. Fourth Edition, Wiley, 1997

3. Taylor D.M., Tillery S.I., Schwartz A. B. 2002. Directic cortical control of 3D neuroprosthetic devices. Science 296, 1829

4. Villringer, A., and Dirnagl, U. 1995. Coupling of brain activity and cerebral blood flow: basis of functional neuroimaging. Cerebrovasc Brain Metab Rev 7, 240-76.

5. Miller, J. Kai, Shenoy, Pradeep, *et al* .2007. Real-time functional brain mapping using electrocorticography. NeuroImage 37. p504–507

6. Leuthardt *et al*.2006. Brain Computer Interface. United States Patent. Patent no: US 7,120,486.

7. Pfurtscheller, G., Berghold, A. 1989. Patterns of cortical activation during planning of voluntary movement. Electroencephalogr Clin Neurophysiol 72, 250-8

8. Bookheimer, S. Y., Zefliro, T. A., Blaxton, T. A., Gaillard, P. W., Theodore, W. H. 2000. Activation of language cortex with automatic speech tasks. Neurology 55, 1151-7

9. Friedman, L., Kenny, J. T., Wise, A. L., Wu, D., Stuve, T. A., Miller, D. A., Jesberger, J. A., Lewin, J. S. 1998 Brain activation during silent word generation evaluated with functional MRI. Brain Lang, 64, 231-56

10. Weiergräber, Marco *et al*. 2005. Electrocorticographic and deep intracerebral EEG recording in mice using a telemetry system. Brain Research Protocols 14. 154– 164

11. Leuthardt, Eric C., Schalk, Gerwin *et al* 2004. A brain–computer interface using electrocorticographic signals in humans J.Neural Eng. 1 63–71

12. Pfurtscheller G and Cooper R.1975. Frequency dependence of the transmission of the EEG from cortex to scalp. Electroencephalogr. Clin. Neurophysiol. 38 .93–6

13. Srinivasan R, Nunez P L and Silberstein R B. 1998. Spatial filtering and neocortical dynamics: estimates of EEG coherence. IEEE Trans. Biomed. Eng. 45 814–26