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Brain Computer Interface for Neuroprostheses – A review

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Abstract - *Even with all the technological advancements we see today in the field of medicine, people with spinal cord injuries or stroke patients face significant challenges when it comes to carrying out their day to day activities. Patients suffering with quadriplegia face many restrictions when it comes to performing their daily activities due to their limited hand use. However, if we are talking about restoring their motor capabilities, the question of how the user operates the command system comes into picture. As people with disabilities are our main focus here, we can agree to the fact that most of them cannot control the system using their hands. This is where a Brain computer interface (BCI) comes into picture. BCIs acquire the signals that arise in the brain using electrodes which can be placed on the skull or intracranially, process them and converts them into commands that can control a robotic arm or neuroprostheses or for cursor selection, etc. In this review, we discuss what a BCI is, it's history, components of a BCI system, what all types of signals can be used in a BCI system, a little deep dive into the non-invasive approach and discuss a few papers about the application of BCI in the field of neuro prostheses.*

Key Words: Brain Computer Interface, BCI, neuroprostheses, Electroencephalogram, EEG

1. INTRODUCTION

The thought of interfacing machines with minds has always been very intriguing. The recent advances in the fields of neuroscience and engineering are making this idea a reality. This might potentially allow us to augment human physical and mental capabilities. We can use the neural signals from the brain activity can be used affect their environment. The field of BCI (Brain computer interface) can enable patients suffering with quadriplegia and stroke patients to control prosthetic devices for walking or controlling their environment as it provides them means for hands free control of various electrical devices and have very significant applications in the operation of neuroprostheses. This review evaluates the BCIs and its applications and limitations in the field of neuroprostheses. It includes the history of BCIs, basic principles and the future of BCIs in the field of neuroprostheses.

2. WHAT IS BCI?

Brain-computer interfaces (BCI) are computer-based systems that allow communication between the brain and various machines [2]. They acquire signals from the brain using electrodes that may be placed on the skull or intracranially, process the signal and convert them into commands that may control various devices. The BCI systems use and measure the signals generated by the CNS by placing electrodes on scalp or cortex region of the brain and not the output from the peripheral nervous system or the muscles. The most popular principle of a brain computer interface control is that the individual can learn to voluntarily change the neural activity in their brain which is then acquired by the electrodes placed. The user is trained to come up with brain signal and therefore the BCI system is trained to decode the signal and translate them into commands which relies on the user's intention and control the output device.

3. HISTORY OF BCIs

- The history of Brain Machine Interface begins with Hans Berger's Electroencephalography (EEG) development[29], when he first observed brain activity. In 1924 he was the first to use EEG to track brain activity. EEG has been used for many years now as the most popular signal acquisition technology in the brain machine interface market.
- Researcher Philip Kennedy implanted the first brain-computer interface object in a human being in 1998. The object had very little functions. Yet a wireless di-electrode was a biproduct of this work
- A public company called Cyberkinetics was developed by John Donoghue from Brown University whose main aim was to develop BrainGate, a brain computer interface.
- Major progress in the field was achieved when the BrainGate of Cyberkinetics was implanted in Matthew Nagle.
- In 2004, Jonathan Wolpaw and his researchers fitted a patient with a cap that records the EEG signal from the part of the brain which controls movement. This experiment proved that a BCI system could control a computer
- Studies state that by 2050 BCI could play a very key role in helping men control objects with their mind.

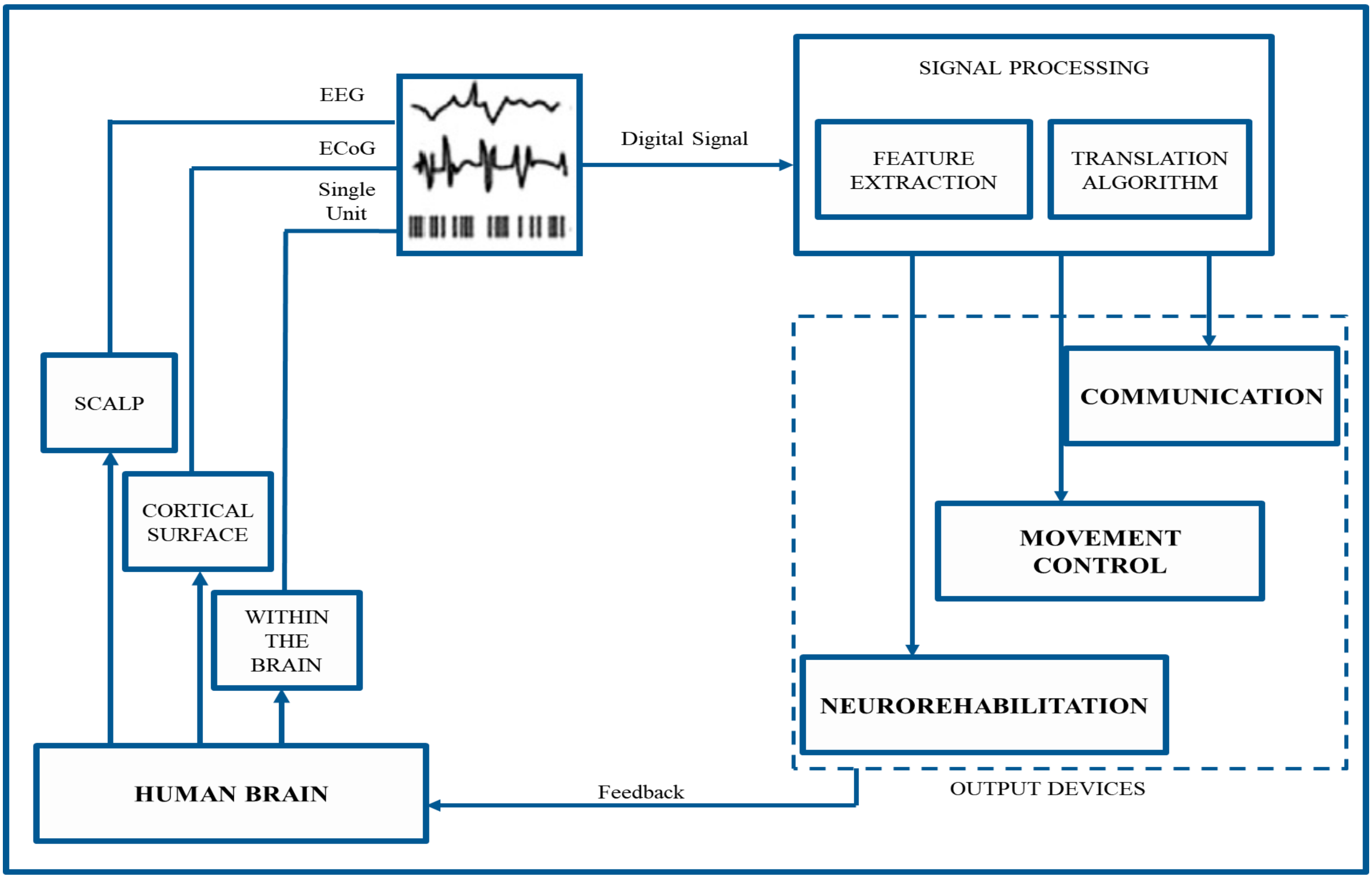

Fig -1: Elements of a brain computer interface

4. NEUROPHYSIOLOGICAL SIGNALS USED IN BCI SYSTEMS

There are different types of signals based on the source of the signal that can be used in BCI systems.

1. The most commonly used signals are the neuronal postsynaptic membrane polarity changes. The scalp EEG is extensively used in BCIs. This is extremely safe, easy and not expensive to acquire. The most important problem of scalp EEG is that the signal gets attenuated in the process of passing through the Dural region, skull and scalp tissues. This might lead to the loss of a lot of important information.
2. Intracortical microarrays which are embedded in the cortex can record the potentials of the neurons and the local field potentials produced by the nearby neurons and synapses. Although this picks up a more accurate signal when compared the scalp EEG, these implants have a high degree of invasiveness and require neurosurgical implantation and has a restricted area of recording. There is also the question of long-term performance of the electrodes that needs to be answered.
3. ECoG-based BCIs use signals picked up by electrodes placed on the cortical surface of the brain that read signals from within the ventricles. These electrodes, however, can record signals from a large area of the brain than intracortical microarrays. But they too have to be surgically implanted and their long-term risks are unknown.

5. ELEMENTS OF A BCI

The BCI system consists of 4 main components [30]. These components are administered by a protocol that defines all the minute characteristics pertaining to the BCI system including details of the signal processing, timings of the operation, the nature of the device commands and the performance. The operating protocol enables the BCI system to be flexible and adapt itself according to the user's needs.

5.1 Signal acquisition

This involves measurement of the brain signals using either a scalp or an intracranial sensor. These signals are filtered and amplified so that they are apt for signal processing. These signals are converted into a digital form so that they can be transmitted to a computer.

5.2 Feature extraction

The digital signals obtained are analyzed to extract relevant characteristics of the signal and converting them into form that can control prostheses. These features must have very high correlation with the user's intent.

5.3 Translation algorithm

An algorithm converts the extracted characteristics into instructions that can control various output devices. The algorithm must be dynamic so that it can adapt to changes in the signal characteristics and the subject's intent.

5.4 Output devices

The output instructions from the algorithm control the output devices and perform functions like letter choice, robotic arm control, cursor control, etc. The device output provides feedback to the subject, which closes the loop.

The components of the BCI system are shown in the Figure1. The electrical signals from the brain activity are read by electrodes which can be placed on the scalp, on the cortex or within the brain which are amplified and converted into a digital form. Significant signal characteristics are translated into instructions that can control prostheses. Feedback from the device allows the user to adapt the brain signals in order to improve the performance of the BCI system.

6. CURRENT ELECTROPHYSIOLOGICAL BCI SYSTEMS

6.1 Scalp-recording based BCI

Thanks to the minimal risk involved and the ease of performing research, EEG-based BCIs are the approach most used. They are therefore restricted to a small degree of freedom movement [31].
These BCIs can also be used in neurorehabilitation. Studies have shown that, EEG features in stroke patients change with improvement in motor function after a CNS injury. BCI combined with functional electrical stimulation (FES) or assistive robotics may help stroke patients with motor relearning.
Since these are the most commonly used BCI systems and have a more noninvasive approach we are going to discuss this type of system, the current methodologies used here and its drawbacks in detain in this review.

6.2 ECoG based BCI

Activity by electrocorticography or intracranial encephalography (ECoG) is reported from the brain's cortical surface [2]. Thus, it requires an epidural or subdural electrode array to be implanted surgically. Using the ECoG signal individual arm, hand, and finger movements were successfully decoded. ECoG is useful for long term applications.

6.3 BCI that use activity recorded within the brain

There are clinical trials using a microarray of 96-electrodes that is implanted in the right precentral gyrus of quadriplegic patients [22]. Using imaginary gestures, they showed control of robotic arm, television and lights etc. Current work investigates the use of BCI in conjunction with FES to control prosthetic limbs. Figure 2 shows the array and its placement in the brain.

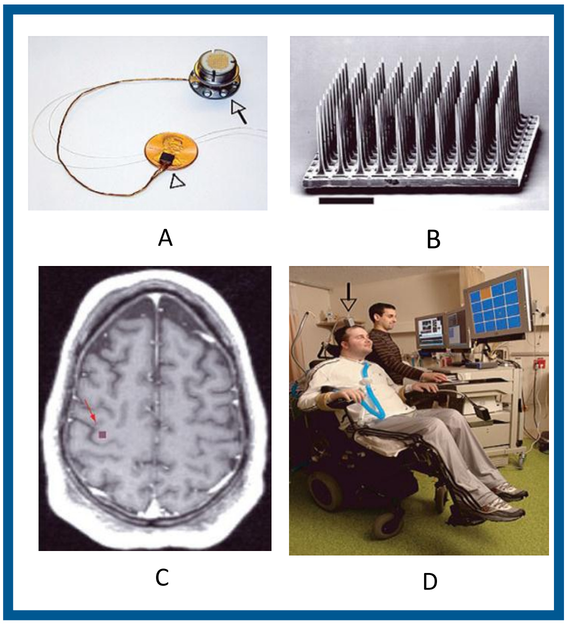

Fig -2:
Fig -2A: The intracortical microarray
Fig -2B: 100-microelectrode array
Fig -2C: The red spot shows the precentral gyrus
Fig -2D: Quadriplegic patient working on a BCI task
Reprinted from Macmillan Publishers Ltd.: Nature22, 2006.

7. NON-INVASIVE BCI SYSTEMS

Non-invasive scalp EEG is the most dominant methodology used in the analysis of brain signals and its performance in the real time interactions of humans with their surroundings. There are other non-invasive brain activity monitoring methods which include Infrared spectroscopy (fNIR), Functional Magnetic resonance Imaging (fMRI), position emission tomography (PET) and magnetoencephalography (MEG). Among all these, EEG is the only one that uses sensors that are portable and can be used for reading signals the user is moving [25]. It is also superior to the other modalities in terms of resolution and the areal of the brain that can be monitored.

Even though EEG has so many applications in the field of medicine, it is used much more in the clinical field than in daily life applications as it is considered to be too prone to noise [24]. As the current EEG technology is not sophisticated the researchers are also not very confident about the signal acquires and the sources of the signal. The current EEG monitoring practice has a complex procedure which involves the preparation of the skin, application of gel electrode and attaching a lot of sensors. The users don't have enough knowledge to handle these sensors on a day to day basis. Therefore, sizeable efforts are necessary to bridge this gap. A few commercial EEG systems have been developed [13]-[21] that are in used in investigations regarding the BCI systems and in gaming applications that use BCI technology. To make this system more efficient, we need better signal acquisition hardware, we must be able to validate the BCI system and the end product must be reliable.

7.1 Signal generation

The brain activity evolves along with age and maturity of the human brain. This is also affected by the number of personal attributes very heavily. It would be very useful if we could monitor the brain activity on a day to day level to study our cognitive evolution. But due to the impractical procedure of the current EEG technology it is not possible to monitor our brain activity. But having sophisticated EEG systems will enable us to monitor large populations who have diverse personal traits and create a large database.

An EEG is the signal obtained due to several simultaneous neural activities occurring in the brain. They are affected by the current mental state of the user and several external inputs and the signals which are an input or an output to the internal organs of the user [26]. Even having a person's eyes closed or open will completely result in a different EEG signature [27]. Therefore, understanding the current mental status of the user and considering contextual information plays a key role in the development of BCI systems using an EEG signal.

Surface EEG is not capable of capturing single neuron activity. This represents a summation of multiple neuron activity. The tissues present between the EEG signal and the source of the brain activity attenuates and smears the brain signal. This is mainly because of the difference in the conductive properties of the skin, skull, the cerebrospinal fluid (CSF), the dura and pia matter of the brain [28]. Understanding their properties is very essential when we are thinking of building a BCI system that lasts over a lifespan.

7.2 Signal Acquisition

The EEG design used in clinical applications is the use of electrodes are (Ag / AgCl) placed on the scalp using electrolytic gel [32]. The electrolytic gel closes the gap between the skull and the electrodes for the ionic current flow and it increases the adhesion of the electrodes to the scalp. This model is featured in Figure 3A.

But this setup is very complicated and involves a lengthy process of preparing the skin and application of the gel. The placement of the electrodes is also very critical, and the user might not have the knowledge to perform this process.

Therefore, the recent developments focus on the development of sensors that don't use conductive gel. These are called dry electrodes and they have pins that penetrate the hairy regions [22]. They contain electrodes which are Ag/AgCl or gold plated. These electrodes can be used until the conductive layer fades [33]. But the stabilization time needed for this type of electrode is larger. This system is more prone to noise and decreases the quality of the signal and is comparatively more fragile. This system is represented in Figure 3B.

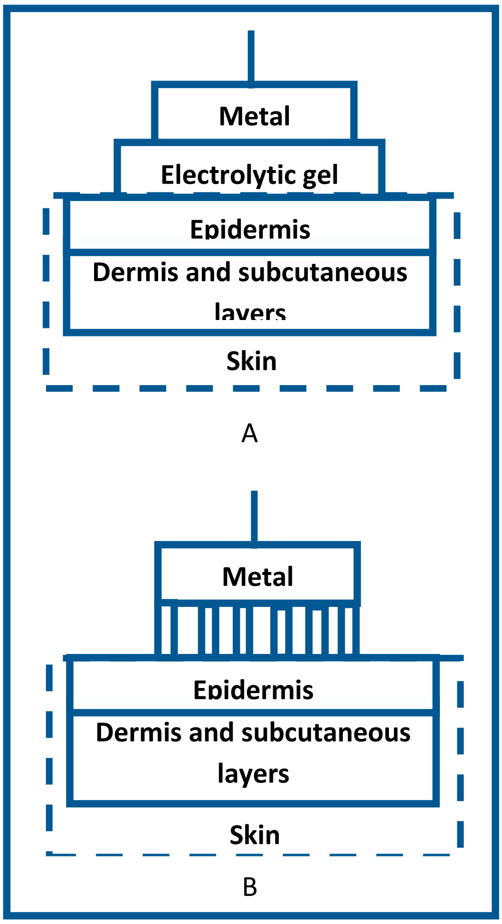

Fig -3:
Fig -3A: Electrodes using conductive gel
Fig -3B: Dry electrodes with pins

We have been seeing an increase in the number of products that do not use the conventional ways of EEG acquisition and mainly using dry electrodes. This may be used in long term applications. Here we are discussing several existent systems. They are shown in Figure 4.

Neurosky's [13] is a single channel measurement unit which uses dry electrodes. These electrodes are on the forehead. This can be used to measure frontal recordings. Data can be transmitted to any device wirelessly via Bluetooth. This is not very expensive and targets the low-end market

The Epoc (Emotive) [14] has 14 channels that can be put around the head and is inexpensive. It has the ability to transmit data wirelessly to the PC using a radio link is amongst the most widely available and used devices.it is very inexpensive and has 14 channels dispersed around the head. It provides a flexible and versatile research platform. Data is transmitted wirelessly, via a proprietary radio link.

Imec's headset [21] consists of an 8 channel wireless data acquisition platform and uses dry electrodes with pins to get rid of hair. It has low power and integrated electronics, therefore is miniaturized.

Quasar's [17] DSI is a 21-channel headset with EEG capabilities. It can reduce motion artifacts by including mechanical and electrical mechanisms. It can wirelessly transmit data but requires a USB dongle. It aims at achieving the highest possible signal quality.

g.Nautilus [16] is a platform which contains a cap and gold plated dry electrodes that can transmit data wirelessly through radio link. They can also operate for 8 hours without charging.

Fig -4 : Existing wireless EEG devices. [19]

These systems are either low-cost systems with the signal of a lower quality or are of higher quality and are robust which are costlier. But they do have a disadvantage. They might not for heads of all sizes and shapes. So more care need to be taken during the design of these systems.

Wireless transmission solutions include Bluetooth technology, Nordic Radio or Zigbee [19]. Bluetooth is the most used transmission technology but does have high power consumption. Low energy Bluetooth is not an appropriate option for EEG data transmission.

7.3 Brain signal Analysis

The EEG signal undergoes several steps before its analyzed and we discussed in an earlier section. During signal pre-processing the recorded signals are re-referenced, the signals undergo band-pass filtering and are resampled and epoched. The clean EEG segments are selected.

The extraction can be performed manually in the clinal environment but is impractical if we are extending its applications for a day to day use. For real time applications we need methods that can extract features from the EEG signal. This is considered as a part of the artefact handling process.

Artifact includes all the signals that are present in the EEG signal but Is not a part of the brain signal. There are different classes of artifact [24][29].

1. **Environmental Artifacts**: This includes interference from the power lines present in the environment or EMI produced by the body itself.
2. **EEG acquiring apparatus Artifacts**: This arises due to the interference of the circuitry present in the EEG systems.
3. **Artifacts arising from inappropriate use of the EEG system**: This is due to the improper usage of the EEG system leading to measurement error.
4. **Physiological Artifacts**: This is due to the distortions of the EEG because of the other electrical signals generated by the human body.
5. **Motion Artifacts**: This occurs due to the change in geometric measurement, coupling between the user's skin and the sensor and deformation of the user's tissue.

All these can be avoided using artifact reduction methods. This involves identifying the artifact components in the signal and isolating the original signal from the obtained signal. The features are then extracted from the clean EEG signal.

8. DISCUSSIONS

- Non-invasive asynchronous BCIs can be used for controlling neuroprostheses enabled by FES, which can be used to manipulate the environment of the subjects [34]. Novel and Experienced subjects and novel subjects were able to generate mental commands and manipulate their environment. The subjects were able to perform other actions while delivering the commands.
- The brain signals obtained from the scalp or the cortical region can be converted into outputs that communicate with prosthesis that will reflect the user's intent [35]. This can be achieved without the participation of muscles or peripheral nerves.

9. CONCLUSION

Years ago, BCIs might have been just a figment of our imagination. But with all the technological advancements in the field of neuroscience and engineering this has become reality. The BCI systems use brain signals which are recorded using electrodes and are processed to produce device outputs based on the user's intent. A few severely affected patients are now using BCI for basic control and communication. If the signal acquisition hardware improves and the applications of BCIs can be expanded with clinical validation and assured reliability.

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