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REHABILITATION SYSTEM FOR PARAPLEGIC PATIENTS USING MIND-MACHINE INTERFACE; A CONCEPTUAL FRAMEWORK

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ABSTRACT
Mind-Machine Interface (MMI) is a newly surfaced term in the field of control engineering and rehabilitation systems. This technique, coupled with the existing functional electrical stimulation (FES) systems, can be very beneficial for effective rehabilitation of disabled patients. This paper presents a conceptual framework for the development of MMI based FES systems for therapeutic aid and function restoration in spinal cord injured (SCI) paraplegic patients. It is intended to acquire thought modulated signals from human brain and then use these signals to command and control FES as desired by the patient. The proposed setup can significantly assist the rehabilitation and recovery of paraplegic patients due to the ease of control for the user.

Key words: Mind-Machine Interface・Functional Electrical Stimulation・Spinal cord injury・Paraplegic patients

INTRODUCTION
Spinal cord injury (SCI) is a medical complexity where the spinal cord of a person is disturbed due to certain reasons including accidents and others. Spinal cord is basically a bundle of nerves which is protected by the vertebrae. It provides a communication channel for the brain to transmit and receive signals from the rest of the body (Ibrahim, B. S. K. K., & Sherwani, F, 2014). Loss of this communication channel may result in partial or complete loss of movement according to the severity and level of injury. There are various medical terminologies that are used to define the type of injury with respect to the compromised limbs. These include Quadriplegia, Paraplegia, Hemiplegia and Triplegia. Paraplegic patients are such patients whose lower body is debilitated due to SCI within thoracic level. Functional Electrical Stimulation (FES) is an existing technique which is usually recommended for this patient population (Nielsen, G. et al., 2014). This technique uses minute electrical pulses applied through surface electrodes on the muscle surface to activate muscles.

Brain-computer interface (BCI) or MMI is a communication phenomenon where the brain acts as a transmitter and the corresponding device acts as the receiver. The connected devices detects the signals from the brain activity and perform the operations according to their design. Active research within this domain dates back to 1970s when some researchers experimented this technique successfully in monkeys (E. Fetz, 1969), (Schimidt, 1978). Since then, the scope of this investigation was limited to non-human counter parts such as monkeys. MMIs begun to be explored rapidly in humans during 1990s (Lebedev, Mikhail A. et al, 2006).

These studies, however, focused on ways to control the movement of artificial prostheses using brain signals. Researchers have been trying to efficiently acquire thought generated activities from the surface of scalp by using electroencephalogram (EEG) technique. This technique uses surface electrodes placed on the surface of human scalp. These electrodes are able to sense minute voltage due to brain activity. This is one of the most exploited techniques used for this purpose due to its operational simplicity. However, as the technology has developed and the systems are becoming more sophisticated than ever before, it is now becoming possible for scientists to use the thought modulated activity of human brain for different tasks. For example, interactive games are being designed which are derived by only thinking (Daly, J. J., & Huggins, J. E., 2015). Such systems are being developed which allows the user to control a number of home appliances by their intentions etc. It is now more than possible for disabled people to control their own limbs using their brain activity instead of artificial limbs.

Recent studies have shown that there is a strong need of such BCI based rehabilitative and assistive technologies which make use of brain signals to control their own muscle movements as this technique is non-invasive and allows user to control the maneuvers independently (Collinger et al., 2013). It has been observed through statistical analysis of the interviews of more than 500 paralyzed people that independent operation and non-invasiveness were the most important factors for disabled people (Collinger et al., 2013). These disabled people have posed that if the conventional FES system are incorporated with the BCI technique, it can significantly improve the standards of rehabilitative and assistive technologies.

A combination of BCI and FES can be an effective way to allow the SCI people to move their limbs using their own thoughts. When a user thinks that he or she wants to move his limb, a signal is generated in his brain and is collected on electrodes. This signal is then conditioned and transmitted to FES devices. These FES devices will read the signal and generate the electrical pulses accordingly which are sent to the surface of the muscle which is desired to be contracted hence eliminating the dysfunctional spinal cord (Ibrahim, B. S. K. K., & Sherwani, F, 2014) .
In this paper, human brain is introduced as a control system to be employed within BCI systems to generate the required

EEG signal activity. Finally, an incorporation of both FES and BCI is suggested to overcome the presiding issues regarding efficient control of the muscles.

PROPOSED SYSTEM DESIGN

The conceptual framework proposed in this study presents a system design for a MMI based FES system for rehabilitation of paraplegic patients. The aim of this research is to present such a system which is capable of providing efficient control of the limbs to the patients by introducing MMI into existing stimulating mechanism. It includes the fundamental methodology to be adopted while the execution of this system. Main contribution of this system is to develop an efficient control system to effectively analyze the brain waves and extract the required signals from the raw brain signals. Once the required signals are acquired, the system should be able to comply with the forward FES device in order to provide these signals as periodic pulses. The FES system then receives these signals and outputs the minute current pulses on the muscle surface. These minute current pulses of specific pattern will cause the paralyzed muscles to contract and extend in order to exercise the specific muscle or muscle group. The research plan for this study is basically divided in to five major phases. Block diagram of the first two phases of proposed system is depicted in Figure 1.

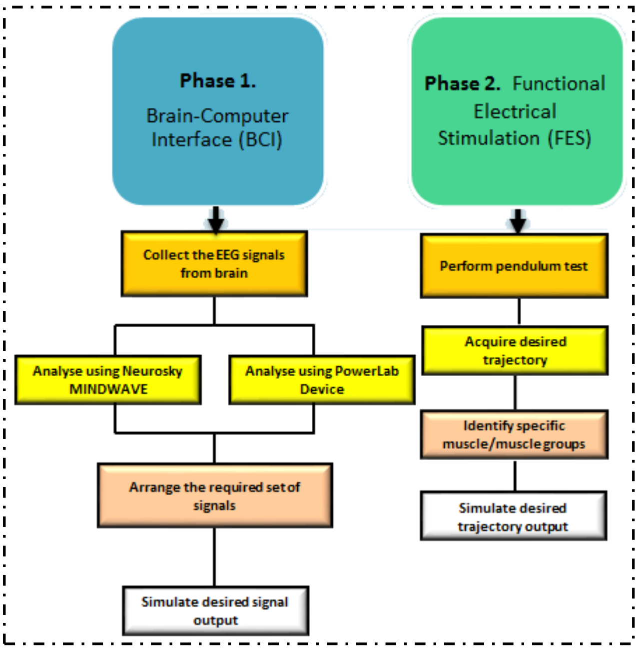

Figure 1: Research flow for phase 1 and phase 2

First two phases are the preliminary research phases. Phase one includes the identification and analysis of the signals from human brain to the limbs. At this stage, the signals are collected using two devices including Mindwave Mobile, Neurosky and PowerLab, ADInstruments. Both of these devices are capable of providing raw brain activity signal in terms of voltage differences. Mindwave Mobile device can extract the signal for three basic functional activities that are attention, meditation and blinking. While PowerLab can acquire the voltage difference between any two surfaces on the scalp. Once the raw signals are detected successfully, then these signals are arranged according to the required setting.

Following the first phase, the second phase is executed which contains the approximation of the natural trajectory of the human shank as in natural condition. It is achieved by rising the disabled limb to a certain angle and height and allowing it to fall freely. A goniometer sensor or an encoder can be used in this case which is placed on the knee joint to estimate the angle of movement of the human shank. This can be called as the desired trajectory that is needed to be followed by the FES driven limb movement. Once the required brain signals and the desired trajectory has been identified, phase three is started which consists of the integration of MMI with FES. To do so, a signal mapping mechanism is needed to be developed in order to provide a compliant communication platform between both devices. This is accomplished by implying MATLAB software as the control system. In the beginning, an open loop control strategy is implemented to test and verify the incorporated system as shown in Figure 2.

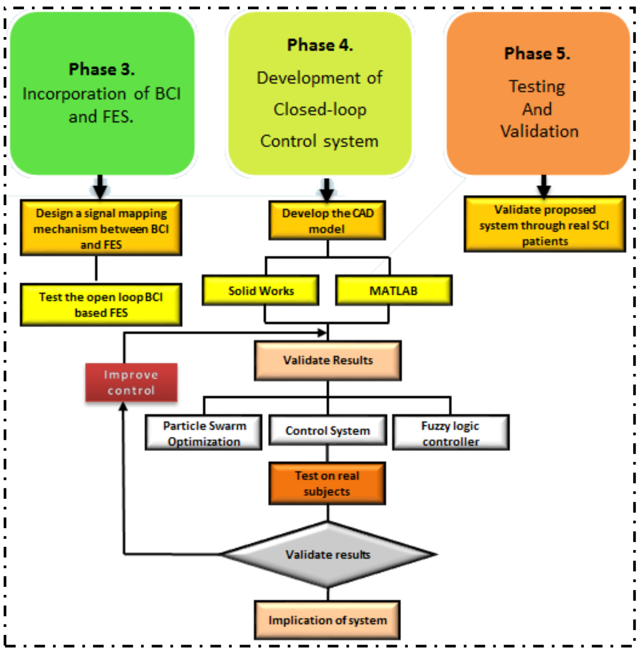

Figure 2: Research flow for phases 3, 4 and 5

This means that the system does not have a feedback and the input is not adjusted compared with the output. In case of the successful implementation of aforementioned open loop system, the overall system is then expanded to closed loop control. It is intended to utilize a combination fuzzy logic control (FLC) with particle swarm optimization (PSO) to command and control the proposed system. The system is tested on able bodied subjects primarily to become certain about the functionality of the system. If the results are satisfactory, then the system is validated lastly by testing it on an SCI paraplegic subject.

RESEARCH METHOLOGY

The main focus of this concept is aimed to assist and facilitate the paraplegic patients affected by SCI by enhancing their ability to contract and move their muscle

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groups. It is intended to develop a BCI based FES system for such physically and neurologically compromised subjects. The proposed system is objected to be autonomous in its self and is able to drive the FES devices by making use of the human brain as the central command and control system to contract specific muscles as desired. Three main targets needed to be met in order to establish the proposed setup. It includes analysis, quantization and arrangement of the EEG signals from the human brain to synchronize and comply with the BCI system. Secondly, to design a BCI based controller system to comply with the FES device to produce required muscle contraction. And lastly, to assess the performance of the proposed system based upon latency, accuracy, efficiency and error and omission through real paraplegic subject. Figure 3 shows the block diagram of the proposed system.

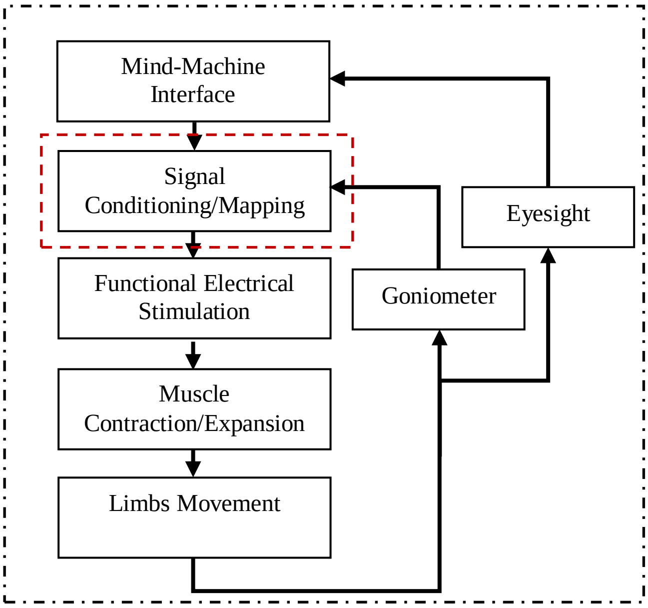

Figure 3: Block diagram of the proposed system (Ibrahim, B. S. K. K., & Sherwani, F, 2014).

The system flow can be observed in the proposed system block diagram. It shows that the closed loop system starts from the thought generated activity of the subject. The signals are then altered through the way with in the signal conditioning system to conform the FES configuration. FES, consequently, in a response to these brain signals triggers the current pulses to the surface of the skin of the specific muscle or muscle group which cause them to contract or expand and consequently produce desired movement at the target paralyzed limb. Figure 4 shows the graphical explanation of the proposed framework. It can be noticed that when the spinal cord is damaged due to SCI, then the brain signals are not able to parse through to the limbs, while it is possible to bypass the spinal cord by utilizing the BCI technology along with a suitable signal mapping mechanism system.

Mind-Machine Interface Stage

This step involves the extraction of signals from the human brain. Researchers have been investigating various recording mechanisms to collect brain signal activity in human applications.

These include scalp electroencephalography (Collinger et al,. 2012), electrocorticography (Wang W et al,. 2013), and intracortical microelectrode recordings (Collinger et al,. 2013).

Scalp surface EEG is the most common technique which is used to perform these recordings because it offers critical advantages such as non-invasiveness, less complexity, non-painful but at the cost of comparatively lower signal reception. Table 1 shows the fundamental classification of brain signals.

Table 1: Frequency based classification of brain EEGs

Band	Frequency (Hz)	Location
Delta	Up to 4	Frontally in adults, posteriorly in children; high-amplitude waves (Kirmizi-Alsan et al., 2006)
Theta	4-7	Found in locations not related to task at hand (Kirmizi-Alsan et al., 2006)
Alpha	7-14	Posterior regions of head, both sides, higher in amplitude on non-dominant side. Central sites (c3-c4) at rest
Beta	15-30	Both sides, symmetrical distribution, most evident Frontally; low-amplitude waves
Gamma	30-100	Somatosensory cortex (Kisley et al., 2006)
Mu	8-13	Sensorimotor cortex (Gastaut, 1952)

Signal Conditioning Stage

This stage comprises of mapping raw brain waves in to processed signals possessing understanding for the connected devices. It starts from receiving an input raw wave in the computer system as collected through EEG electrodes from the surface of the scalp. The signal is then forwarded for pre-processing where the main signal is further divided in to various according to different frequencies by applying filters within MATLAB. Next step is the feature extraction which interprets the meaning of different wave forms and their patterns. For example if the amplitude of a certain pulse exceeds a defined level, it could mean that the user wants to turn off or turn on the connected device. This setting can be adjusted and optimized with in the software based signal conditioning system. Lastly, the feature are classified as outputs and are parsed to the external devices. Figure 5 shows the block diagram of signal conditioning stage.

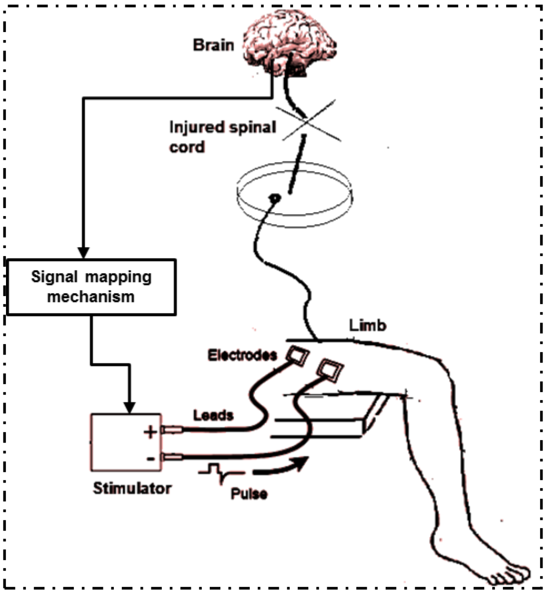

Figure 4: Graphical illustration of the proposed framework

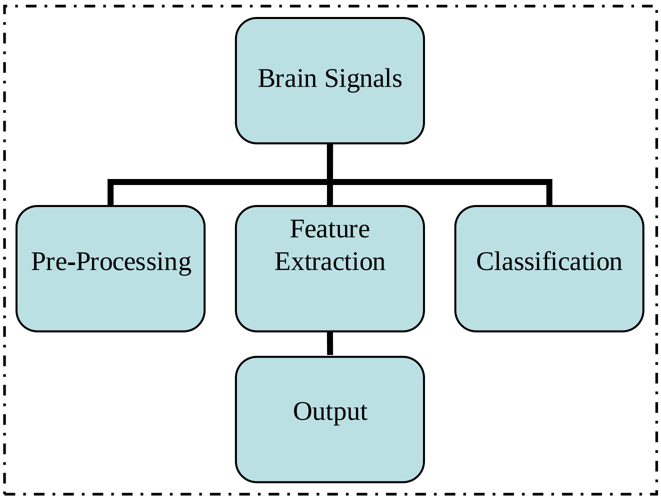

Figure 5: Signal conditioning

Functional Electrical Stimulation (FES) Stage

The FES phase includes the reception of the signal from the signal mapping system. Signal mapping system provides periodic pulses of thought modulated activity conveying the user intention on when and how to operate the device. FES device then accordingly generates the consequent current signals.

Muscle Contraction and Limb Movement Stage

Muscle contraction or prehension and the relative limb movement takes place, when the current pulses from the FES system are transmitted to the surface of the muscle. The angle of the knee movement is constantly monitored using a goniometer sensor device in case of hyper extension of the limbs. Second feedback is the visual feedback itself. The subjects can see their limb movement and can control the level of stimulation and the desired trajectory in real time just by altering their thoughts.

FUTURE TRENDS

Research and development in the field of rehabilitation engineering is progressing very rapidly. Until now, most of the researches has been carried out on providing therapeutic aid and utilizing artificial prostheses with their respective techniques to control them efficiently. According to the recent advancements within BCI technologies, it is easy to envisage that the future trends are bending towards the increase in the thought-driven systems. The systems which are able to cause less fatigue while providing efficient performance are becoming the question of the day where the researchers are trying to develop virtually fatigue free systems. The future of this domain seems to be highly interesting where further developments in this area can greatly facilitate the disabled patient population around us.

CONCLUSIONS

A rehabilitative platform for paraplegic patients using a combination of BCI and FES is proposed in this study. FES plays an essential role in the rehabilitation of the paralyzed patient population by strengthening their affected muscles through regular stimulation. This technique, however, is dependent on the pseudo brain alike signals generated by sophisticated control systems (Do et al, 2011). These devices are even after not able to produce the same EEGs as can be done by the patients' brain itself (Müller-Putz et al., 2011). A BCI is a direct communication pathway between the brain and an external device (Daly & Wolpaw, 2008). A major advantage of BCI over other user interfaces is that it can be operated independently from residual motor functions. A combination of BCI and FES can be a vital solution to help and facilitate the paralyzed patients because they are able to use their own brain EEG as a control signal to perform the required movements (Collinger et al., 2013).

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