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It's All in the Mind: Mind Controlled Prosthetics

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Abstract

The problem with prosthetics is a longstanding problem that researchers have been working on for many years. They are attempting to create a prosthetic that acts as if it is the original limb or body part. In recent years they have discovered a technology that has assisted many of those who are greatly in need of a prosthetic, such as an amputee or someone who is "locked in". "Locked in" refers to a person who is technically confined in his own body and has no methods of communication with the world. Brain-computer interface (BCI) has opened up a whole new world of prosthetics. It has opened doors for those who have been "locked in". BCI assists those with severe neural disorders. BCI links the brain to a machine, allowing for actions to be performed by circumventing the damaged or missing body parts. It captures the brain signals, interprets them, translates them and transfers them as control signals to the device being used. Using this technology, targeted-muscle reinnervation (TMR) has been designed to create a prosthetic for amputees as well. Altogether, it has been established that prosthetics controlled by the mind is possible.

Introduction

A prosthetic is a device that substitutes for a body part or function that is defective or missing. The aim of a prosthetic is to replace the missing or damaged body part so perfectly that when a function is performed it is as if the original body part performed it. The Brain-Computer Interface (BCI) is a device that captures nerve signals that the brain produces when there is an intention to act, translates the signals through algorithms and then produces the action through a machine; thereby, circumventing the damaged limbs or missing body parts (Leuthardt et al., 2006). The system requires no muscular control and it can consequently liberate someone who is paralyzed, or it can create a prosthetic limb that acts as the original limb. The following paper will discuss BCI and TMR, explaining the basics of how each works, demonstrating how BCI is helpful for those with severe neural disorders and TMR assists amputees.

How BCI works

The BCI works through a basic four step process: signal acquisition, signal processing, device output and operating protocol (Leuthardt et al., 2006).

Signal acquisition is when the brain signals are recorded and amplified, by electrodes. The brain signals can be recorded through many methods: non-invasively through Electroencephalography (EEG) and invasively through Electrocorticography (ECog), Local Field Potentials (LFPs), and Single Units. The non-invasive EEG is the safest method because it records the signals through the scalp and no electrodes penetrate the brain. The EEG mainly measures sensorimotor rhythms, slow cortical potentials (SCPs), and P300 potentials. The Sensorimotor cortex produces Mu (μ) rhythms which are typically 8-12 Hz and are found when the brain is not processing any new information, when it is "idling", and Beta (β) rhythms, which are typically 18-26 Hz. The μ and β rhythms decrease in activity when there is movement or preparation for movement. However, more importantly, these rhythms occur even

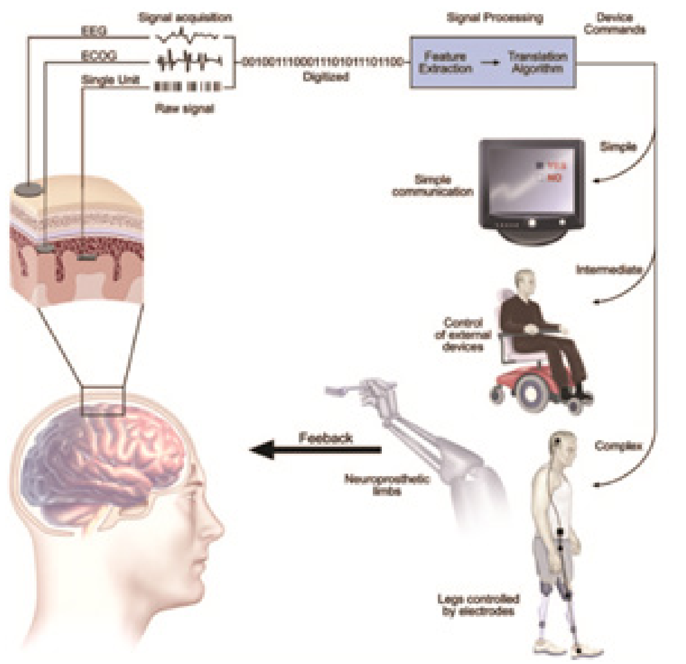

Figure 1:
This is a diagram of the BCI system. It shows the pathway of the signals (Leuthardt et al., 2006).

when there is only imagined movement and actual movements are not necessary for their activation. This makes them useful for the BCI because if someone imagines a movement, the μ and β rhythms will be activated and they can then activate the BCI without muscular contractions (Leuthardt et al., 2006). SCPs are the lowest frequency signals recorded over the scalp. They are slow voltage changes that are generated in the cortex over .5-10 seconds. Negative SCPs are associated with movement and cortical activation, while positive SCPs are associated with a reduction of movement and a reduction of cortical activity (Wolpaw et al., 2002). The SCPs are beneficial to the BCI because they are directly associated with movement and cortical activity; therefore, when a movement is desired, the SCPs will be activated and can power the BCI. The P300 potentials, otherwise known as "odd-ball" potentials are produced in the parietal cortex. The P300 is useful for the BCI because it differentiates the brain's response to a significant stimulus from a routine stimulus (Leuthardt et al., 2006). Additionally, unlike sensorimotor rhythms and SCPs, the P300 does not require any training of the user for control; it is a natural response to a preferred choice (Wolpaw et al., 2002). However, the system requires "training" to learn the user's preferences (Leuthardt et al, 2006). The EEG is the most commonly used signal acquisition system for the BCI as of now, because of its non-invasiveness (Leuthardt et al., 2006). However, the invasive methods are more accurate and specific in their recordings.

The next level of recording is through ECog, which measures the signals from beneath the cranium. The ECog was at first assumed to be very similar to the EEG; however, this is not true. The ECog can detect signals to a much higher frequency; up until 200 Hz versus the EEG which measures only up until 40 Hz. when the electrode is placed beneath the skull, as is done in the case of ECog electrodes, a higher frequency can be measured by the electrodes. This then allows for the recorded signals to be more precise and for there to be less other "distracting" signals (or a higher signal to noise ratio) (Leuthardt et al., 2006). Because ECogs are placed on the surface and do not actually penetrate the brain, they are considered more durable than the microelectrodes which measure LFPs, and Single Units (Schwartz et al., 2006).

LFP's are recorded through penetrating electrodes into the parenchyma. There the frequency can be measured typically from 300-5000 Hz, but can record lower frequencies as well (Schwartz et al., 2006). Single Units are recordings of individual neuron action potentials. The microelectrode is place deepest into the brain, and therefore, has the most accurate recordings. As a result, the use of Single Units can produce the most complicated actions. The further into the brain that the electrode is placed, the more accurate the recordings of the signals will be.

After signal acquisition, the signals are digitized and then the more complicated process of signal processing occurs. Signal processing is broken down into two components: feature extraction and signal translation (Wolpaw et al., 2002). Whenever there is signal acquisition, "noise", otherwise known as artifacts, such as other brain signals or even muscular movements, will get mixed in and can even sometimes be thought of as the target signal. Therefore, feature extraction removes the desired signals from the total signal; it identifies the meaningful signal that was produced from the combination of all the signals together (Leuthardt et al., 2006). The purpose of this step is to identify the user's intent, which is identified through the signals that are captured (Wolpaw et al., 2002). Different algorithms are used for feature extraction and artifact

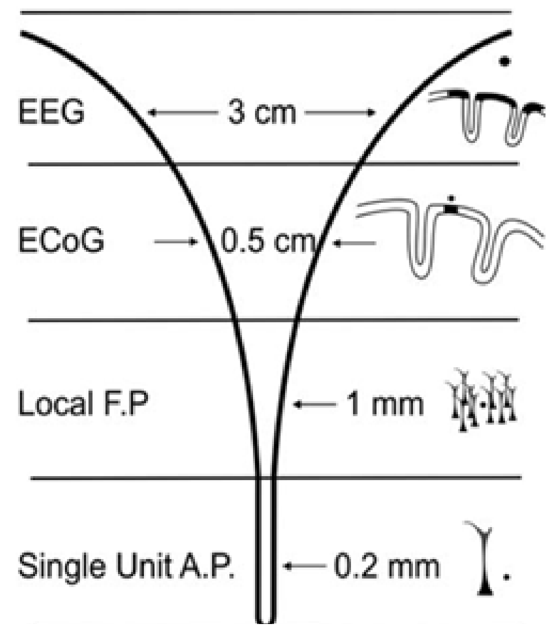

Figure 2:
The different kinds of signal acquisition methods and their distances from the neurons. The black dot in each picture symbolizes the electrode and its distance from the neuron (Schwartz et al., 2006).

removal (Vallabhaneni et al., 2005). The algorithms adapt to the user on three levels: first the algorithm adapts to the signal features that the user uses, for example if the user uses Mu rhythms, the algorithm will adapt to the user's characteristic amplitude of Mu rhythms. The second adaption is periodic adjustments to spontaneous changes, because the user will produce more than just one kind of signal and one intensity level of that signal. The third adaption of an algorithm is to use the brain's adaptive capacities. For example, as feedback occurs, hopefully the brain-computer interface will improve, as each "gets used to each other". This adaptive algorithm will assist the natural adaption of the brain by responding to the user with faster communication or other such "rewards" (Wolpaw et al., 2002). The more specific and exact the method for feature extraction and the better the adaptive algorithms, the more exact the signal to noise ratio will be (Wolpaw et al., 2002). Signal translation converts the signal features (rhythm amplitudes or neuron firing rates) that were extracted, into device commands (Wolpaw et al., 2002). Translational algorithms are used for this conversion. The signals are then converted into a different kind of signal that is appropriate for the device that is being used.

The signals are then sent to the device output section of the BCI which is the actual machine that produces the action. The action can be anything, whether it is controlling a cursor on a screen or the movement of a robotic arm (Leuthardt et al., 2006). The device output then translates the signals into physical control signals that can then power the device (Bashashati et al., 2007).

The operating protocol is how the device is controlled. How it is turned on and off, the feedback that is provided (such as the speed of the reactions), and the timing of the commands and actions. It is the basic operating manual of the prosthetic (Leuthardt et al., 2006).

How Targeted Muscle Reinnervation Works

Another method for a natural acting prosthesis is through Targeted Muscle Reinnervation (TMR). The prosthetics that are used in TMR are called myoelectric prosthetics. A myoelectric prosthesis uses residual muscles after an amputation or other, unrelated muscles, to amplify and supply signals to move the prosthesis. After a conscious thought to move that muscle, sensors relay the information to a controller which then powers the motor to move the arm. A myoelectric prosthesis works well and almost intuitively for an amputation that is below the elbow because Electromyogram (EMG) signals or motor action potentials are recorded from the residual muscles that formerly powered the amputated arm. However, for a shoulder amputation (and for some transhumeral amputations), TMR is performed to make the control of the prosthesis more intuitive. TMR is a process that takes the residual nerves from an amputated limb, the nerves that had innervated the limb before the amputation. They then transfer the residual nerves to another muscle group that had also "worked with" the amputated limb, but is no longer functional because it is no longer attached to the limb. As a result, when there is a thought about movement of a part of the amputated limb, such as a finger, the reinnervated muscle will contract. Nerves that would innervate the "recipient" muscles are denervated so that the muscles can be reinnervated by the transferred nerves and there will not be as much interference. The reinnervated muscles serve as biological amplifiers of the nerve signals that are sent to the limb. Subcutaneous tissue is also removed so that the myoelectric signals or the EMG signals can be recorded with relative ease. In this way TMR provides EMG control signals that are associated with the lost limb. This amplified, natural signal can then be used to power the prosthesis (Kuiken et al., 2007). After a signal is sent, through a mere thought or desire, to "lift a finger" or perform another action, electrodes record the EMG signals non-invasively, from the body surface. The electrodes are placed above the reinnervated muscles. Because the muscles amplify the signals, they are relatively easily recorded. The signals are then sent to a microprocessor chip that is in the prosthetic limb which interprets the signals and then powers the myoelectric arm to do what the signal was asking (Kuiken et al., 2007).

In most of the cases TMR was performed on someone with a shoulder amputation; however, some were performed on transhumeral amputations as well. In the cases of a shoulder amputation, the musculocutaneous nerve, median nerve, radial nerve, and ulnar nerve were transferred to the pectoralis major, pectoralis minor, latissimus muscle, and serratus anterior (each case was slightly different, but overall these were the nerves and the

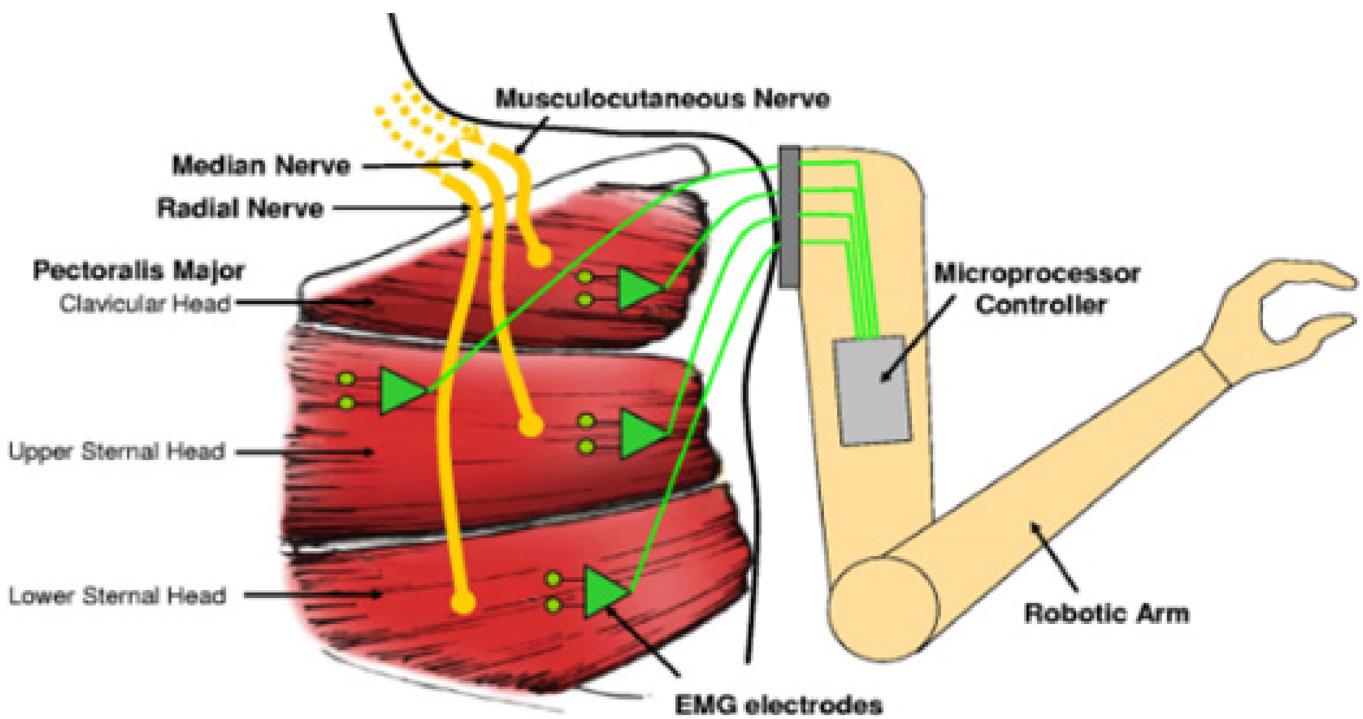

Figure 3.

Diagram of the TMR process. The 3 transferred nerves are yellow, the electrodes are green (and are in reality placed on the body surface, but the diagram places them on the muscles because the body surface was removed for the diagram's sake), and the microprocessor chip is in the prosthetic arm (Zhou et al., 2007).

muscles they were transferred to). In the transhumeral cases, the median and distal radial nerves were transferred to the medial biceps and the brachialis or lateral triceps, respectively (Kuiken et al., 2009). Approximately three months after TMR surgery, muscle reinnervation was felt and at approximately five months, strong contractions could be seen and palpated (Kuiken et al., 2007). At this point the muscle contractions can be used to power the myoelectric arm.

The capture of the EMG signals is the signal acquisition step of the BCI. Therefore, next is the signal processing step. In the case of TMR, there are artifacts that must be eliminated; however, they come from a different source. Most of the artifacts that disturb the signal in TMR originate from electrocardiogram (ECG) signals. Nonetheless, it was found that the ECG interference does not disturb the accuracy of the signals significantly when a pattern recognition algorithm is used for signal processing (Zhou et al., 2007). The microprocessor chip then sends the signals to the part of the arm that the signal was intended for, it powers the arm, performs the motion that was requested, and turns the arm off.

When TMR is done on a leg, the process is very similar. The sciatic nerve is separated into its two smaller branches; tibial and common peroneal nerves. The tibial nerve was then sewn onto the semitendinosus muscle and the common peroneal nerve was sewn onto the long head of the biceps femoris. In this way, the residual nerves reinnervated the hamstring group. The process is the same as by the arm prosthetic; however, there are more obstacles or details that need to be perfected with the leg than with the arm. Such as, the leg is required to bear weight, maintain balance, have the ability to change ambulation modes, and other such functions that the arm does not have to deal with. These functions are of vital importance and therefore, the error must be extremely low, because if not, the person is at risk of falling. Again a pattern recognition algorithm was used and it lowered the percent error from 12.9% to 2.2% (Hargrove et al., 2013).

Methods

Google Scholar and the PubMed database were used to search for information for this paper. Key words such as, "mind-controlled prosthetics" or "prosthetics controlled through thought" were used to find review articles. These articles gave a better idea of other key words to use, such as, "brain-computer interface" and "neural-machine interface" to find original papers. To find out about prosthetics for an amputee, key words like, "prosthetic limbs" were used and then "targeted muscle reinnervation" and "myoelectric prosthesis" were used to narrow down the search.

Discussion

Although each method for intuitive and natural control of prosthesis sounds like it can be a "perfect" prosthesis, each has its pros and cons which lends each prosthesis to a specific function. BCI is, in a technical sense, the perfect prosthesis because it captures the brain signal and performs the action through just a thought. However, there are some distinct issues that make it a useful prosthesis for someone with a severe neural disorder, but not for an amputee. One major concern is the problem and debate with signal acquisition. If the non-invasive EEG is used, the electrode is at a significant distance from the neurons because the scalp is 2-3 cm away from the cortex. Therefore, the signals recorded are limited and are not sufficiently effective to control a more complicated device, such as a device with more than two dimensional control (Schwartz et al., 2006). The information rate is only 5-25 bits/minute, which is so slow that it can take several minutes to insert a word into a computer and the average time for a task to be completed (including signal acquisition, signal processing, and device output) was an approximately 6.20 seconds (Cheng et al., 2002). In a different study performed in 2004, the average time for a cursor to be moved was 1.9 seconds (which is a significant improvement from the study in 2002) and the movement precision or the precision in hitting the target was 92%. Although these percentages are a significant improvement, they can still be improved in accuracy and speed, through better adaptive algorithms and other such reforms (Wolpaw, McFarland, 2004). In addition, EEG signals can only detect lower frequencies, frequencies that are less than or equal to 40 Hz, which again limits the complexity of what the device can accomplish. Furthermore, if sensorimotor rhythms or SCPs are used, only two dimensional control or at times three dimensional control has been proven to be possible, such as the movement of a cursor on a screen or a basic movement of a robotic arm (separate from the body). These rhythms do not have the capability of performing more complicated functions. Regarding the P300 signals it has not yet been determined if gaze fixation is necessary for the system to work. In this case the BCI would only be of assistance to someone with the ability of eye movement. However, with the P300 signals, only a simple word processing program can be used (Leuthardt et al., 2006). An invasive method of signal acquisition (such as, LFPs or Single Units) would solve the above mentioned problems with EEG signal acquisition; however, then the problems with implanted electrodes arise. First of all, surgery is required to place the electrodes in the brain and that in itself causes the risk of damage to the brain. Furthermore, if Single Units are used, the microelectrodes are placed beneath the cranium, which automatically causes blood vessels to be broken in the process. This causes a reactive response from the brain; astrocytes and glial cells will begin to aggregate there and they then basically insulate the microelectrode until no signals can be recorded after a period of time, so signal acquisition can only occur for approximately a year. Repeating the placement of the microelectrodes can cause scarring on the brain which can damage the person's cognitive status and can further damage the person's ability to function properly (Leuthardt et al., 2006). Additionally, the electrodes must remain stable for a long period of time and although algorithms can maintain the stability of an electrode, implanted electrodes have a limited time that they are functional (Leuthardt et al., 2006). The ECog system was tested and it was successful in many instances. In a stroke patient, for the movement of a robotic arm, the signal acquisition method decoded 61% of the ECog signals, at least one second before the movement was performed by the participant's functional arm. Selection of the movement that was desired (out of three different kinds of movements) was detected with 69.2% accuracy (Yanagisawa et al., 2011). In patients with epilepsy, the ECog signals had classification rates of 70-90% in selection of letters from a spelling system (Birbaumer et al., 2014).

Although the ECog's success rates are good, they are not good enough. In the real world there is not so much room for error, especially with people who cannot help themselves if something goes wrong. Success rate with the patients with epilepsy was high; however, this is only with a simple word program. Additionally, the problems with implanted electrodes still exist. However, they do not exist to the extreme that they exist in Single Units because ECog electrodes are placed on top of the parenchyma and not within. Therefore, the electrodes do not invade the blood brain barrier, which causes the inflammatory response that occurs in Single Units. In addition to the problems with the electrodes, in the BCI system the signals are easily interfered with through slight distractions, such as an eye movement. Because of all the above mentioned issues with BCI, BCI is limited to people with severe neural disorders, to someone whose only method of communication with the world is through their brain, such as someone with high level quadriplegia (Ohnishi et al., 2007). The BCI system is satisfactory for someone with a severe neural disorder because it provides adequate two dimensional control and even at times three dimensional control of a robotic arm. However, for an amputee two dimensions is not enough. Consequently, the problem of creating a "perfect" prosthesis for an amputee still exists. To solve this problem, TMR was designed. TMR unites BCI and existing prosthetics to create the perfect prosthesis. TMR solves most of the problems with BCI; however, it does have its limitations as well. First of all, TMR solves the problems of non-invasive electrodes because the signals are adequately biologically amplified through the muscle, and the signals are clear; however, they are not invasive and therefore overcome the problems of implanted electrodes as well. Compared to participants who used their own limbs as a control group in an experiment, the TMR patients performed exceptionally well, as seen in Table 1.

The motion selection time for arm function was very good, it was an average of less than or equal to 220 milliseconds. For hand grasps it was also pretty good; the motion selection time was an average 380 milliseconds. The average speed of an action was between 90°/second to 120°/second. For elbow and wrist function, the success rates were high. For hand grasps, the success rate was high, but not as high, most probably because this requires more cognitive control of the user (Kuiken et al., 2009). The TMR system does not have as much interference with the signal acquisition, with the exception of ECG signals which are easily taken care of through a pattern recognition algorithm. EMG classification accuracy has been shown to be in the range of 90%-100% (Kuiken et al., 2009). Users of TMR prosthetics have reported intuitive use, as one participant stated "I just think about moving my hand and elbow and they move." (Kuiken et al., 2007). TMR also provides multiple degrees of freedom. Until now, prosthetics

Table 1.

Performance Metrics for Virtual Prosthesis Testing Protocol With a 5.0 Second Time Limit:

	Mean (SD)	
Performance Metric	TMR Patients (n = 5)	Control Participar (n = 5)
Motion selection time, s		
Elbow and wrist[a]	0.22 (0.06)	0.16 (0.03)
Hand grasp[b]	0.38 (0.12)	0.17 (0.09)
Motion completion time, s		
Elbow and wrist[a]	1.29 (0.15)	1.08 (0.05)
Hand grasp[b]	1.54 (0.27)	1.26 (0.18)
Motion completion rate, %		
Elbow and wrist[a]	96.3 (3.8)	100 (0)
Hand grasp[b]	86.9 (13.9)	96.7 (4.7)

Abbreviation: TMR, targeted muscle reinnervation.
[a] For 108 attempted elbow and wrist movements.
[b] For 72 attempted hand grasps.

Table 1 is showing the time it took for each motion to be selected and completed and the motion completion rate, compared to the control group which used their natural arms. (Kuiken et al., 2009) required concentration for each movement to be performed, the myoelectric arm, without TMR performed, required a distinct thought about a muscle that was unrelated to the arm previously. Now one just thinks about moving his/her arm and it moves. In this way multiple degrees of freedom are possible, for example, now the shoulder can flex from -15° to 185° versus the conventional prosthetic arm that used gravity to swing forward from 0° to 90° (Miller et al., 2008). Additionally, more than one motion can be performed at once with TMR, for example, when grasping an object the wrist can be rotated and the elbow extended in one motion versus each motion having to be thought about and performed separately; however, executing this was not desired by the participants because of the cognitive burden it entailed. With the TMR prosthesis, the participant was almost four times as fast than with the conventional prosthesis (Kuiken et al., 2007). The level of classification accuracy here was found to be very similar to participants "using" their real arms, 95-97% (Zhou et al., 2007).Nevertheless, TMR has limitations as well. First of all, TMR is a surgical procedure which has the same dangers that every surgery has; however, it is not brain surgery which contains higher risks than other surgeries. Other side effects, such as, recurrence of phantom limb pain, permanent paralysis of the targeted muscles, and other painful neuromas are all risks of the TMR surgery (Kuiken et al., 2007). Secondly, TMR requires intensive therapy after recovery from surgery to gain control of the prosthesis. TMR of the arm is much more developed and reliable as of now than the leg. The leg prosthesis is still not available for clinical use because of some withstanding difficulties; such as, the leg must be made quieter, lighter, and more reliable. Additionally, for the leg to work properly the EMG signals must be of very high clarity and the electrodes must remain in contact with the residual limb without causing discomfort to the wearer which is hard to accomplish while movement is occurring, and lastly, improvement of the pattern recognition algorithm is necessary (Hargrove et al., 2013). Despite the limitations, TMR is in essence a perfect prosthesis for an amputee in that a signal meant directly for the limb is recorded through a residual muscle, processed and then used to power a prosthetic. In the case of a "locked in" patient, where TMR would not be of assistance, BCI is used. Through both BCI and TMR, prosthetics controlled through the mind is possible.

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