Evaluating the Plausibility of using Brain-to-Brain Communication to Create Neuromuscular Connection for Prosthetic Usage

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Abstract**—** When prosthetics are developed, they are created for traumatic amputees to restore quality of life so they can live as they did before their limb loss. However, for an individual with congenital amputation — an underdeveloped or nonexistent limb from birth — there are not as many options due to many prosthetics relying on the user's prior experience with the missing limb[1][2]. The purpose of this project is to investigate the possibility of using electroencephalogram (EEG) signals to control a prosthetic hand. Based on this knowledge, a prosthetic will be designed for an individual with a congenital amputation. Use of this device may be difficult for these individuals compared to those with trauma-based amputations because they lack experience with the limb in question. This can result in more difficulty during the rehabilitation process due to the neurological disconnect. This can be counteracted by utilizing brain-to-brain communication. By sending the neurophysiological signals of an able-bodied person to the individual with the amputation they can teach the amputee's brain these new motor skills. First, the biosignals responsible for the motor functions of the specific limb must be identified and analyzed[1][3]. By determining if the signals for moving one limb are identical to the signals for the other limb, they can be sent via brain-to-brain communication to the patient with the missing limb. Sharing these signals will help them learn how to use the prosthetic, thus making rehabilitation easier. The hypothesis is that using the EEG signals communicated to the congenital amputee via brain-to-brain communication will make the neurological connections needed to make moving the prosthetic easier. The end device would be equivalent to a myoelectric prosthetic controlled by Phantom Limb Syndrome (PLS), except it will utilize learned EEG signals instead of depending solely on PLS[1][2]..

Keywords: *Phantom Limb Syndrome, Myoelectric Prosthetics, Neuroprosthetics, Brain-to-Brain Communication, Rehabilitation, Congenital Amputation*

I. Introduction

Assistive technology and rehabilitation are broad and ever-growing fields. There are many assistive technology devices with varying levels of complexity available for individuals to choose from. They get more niche as the technology itself gets more complex. When it comes to individuals such as amputees the assistive technologies of choice are exoskeletons and prosthetics, and these devices are on the higher end of the technology spectrum as opposed to lower-tech devices such as canes or wheelchairs, which are less complex in design and function without a power source or specialized training[4]. An exoskeleton serves the purpose of aiding in the rehabilitation of the user's limb when they suffer from a partial or full loss of mobility. These devices can be powered by electroencephalography (EEG) sensors which use signals from the brain to move the exoskeleton[5][6]. The key difference between exoskeletons and prosthetics is that exoskeletons require the limbs in question to be present while prosthetics replace them completely. Oftentimes, prosthetics are meant for traumatic amputees for the purpose of restoring their lost motion. Though rare, some prosthetics have been developed for individuals with congenital amputation, which is when an individual is born with a limb underdeveloped or absent. There are not many instances of prosthetics specifically for people with underdeveloped limbs.

The overall goal of this literature review is to determine if it is possible for brain-to-brain communication to aid in the rehabilitative process for a congenital amputee equipped with a neuroprosthetic. The objective is to determine if an individual with a congenital amputation or underdeveloped limb would be able to control a prosthetic with EEG and EMG signals. To achieve this there must be an analysis of the current state of EMG and EEG-powered prosthetics. First, the capabilities and applications of brain-to-brain communication must be explored. Then an understanding must be found of the neurological differences between a traumatic amputee and a congenital amputee. Through this, the possibility of easing the rehabilitative process for a congenital amputee using an EEG-powered prosthetic can be determined.

II. EMG and EEG-Powered Prosthetics

The purpose of a prosthetic device is to restore the functionality of the amputated limb. In recent years, this technology has developed in such a way that it not only replaces that missing limb but makes it more efficient so the prosthetic fully mimics the original limb in both feeling and functionality[7]. The most notable way prosthetics have been improved is how the users are able to control them. Depending on the limb that the prosthetic is trying to emulate, it will require different styles of construction as each limb has differing degrees of function and freedom[2]. Recent developments in the technology include prosthetics that are powered by electromyography (EMG) signals from the body, electroencephalogram (EEG) signals from the brain, or both[2][8][9].

A. Myoelectric Prosthetics

Myoelectric prosthetics use a combination of the EMG signals that are emitted from the remaining muscles and Phantom Limb Syndrome (PLS) to control the device[10]. Phantom Limb Syndrome is a psychological phenomenon in which an amputee will continue to feel sensations in the limb that no longer exists. This is common in most, if not all, amputees and is incurable but the symptoms can be reduced by the presence of a prosthetic, even more so if the prosthetic is physiologically integrated with the individual[11][12][13][14]. Phantom Limb Syndrome often leads to Phantom Limb Pain, which is when those sensations are painful, leading to physical and mental discomfort for the patient[15][16]**.** Learning more about the capabilities of brains compensating for limb loss and amputated muscles is useful when developing prosthetics. However, even with good control of their phantom limb, the user's input may vary depending on their muscle condition. Research has been conducted to see how to best hone these biological signals and phenomena into efficient prosthetics.

In a study from 2018, researchers utilized the patient's EMG signals and conducted Phantom Limb Movements (PLM) training to create a more efficient experience for prosthetic users. In this study, like some others, the prosthetic was controlled by the user through noninvasive methods by using surface electromyogram (sEMG) signals that were collected from remnant muscle tissues at the residual limb of the amputee. The sEMG signals were then classified and isolated before being translated to the prosthetic. Researchers realized these control strategies were effective for prosthetic research because they tackled the difficulties that most prosthetic users have with simultaneous and proportional control of multiple degrees of freedom.[17] This is one of the issues that often arise in medical device development, in the transition from laboratory to clinical practice. The prosthetic may succeed in clinical trials but upon use in day-to-day life fails to mesh well with the user's actual routine. [a review on upper] It is assumed that if a prosthesis user's performance is excellent in the lab, they are more likely to use the prosthesis to perform everyday tasks. However, there is no evidence linking measures of user performance with usage. In fact, there can be a multitude of reasons as to why an individual would stop using their prosthetic, ranging from difficulty in practical use to discomfort caused by daily wear[18] [19].

Most studies that focus on developing prosthetics with more natural control utilize PLM decoding. So far they have been conducted on offline pattern recognition of pre-recorded myoelectric sequences or using simple computer interface control to perform simple free motions using a real prosthesis[10][20].In an ongoing study from the Institut des Systèmes Intelligents et de Robotique at Sorbonne Université, an experiment was conducted in which two patients had to attempt to move their phantom limb to make their arm prostheses mimic the phantom movements[10]**.** Despite having no PLM training beforehand both patients were able to control eight different movements of a prosthesis in a more efficient, simple, and dexterous way than conventional myoelectric control could offer. These results illustrated the baseline that patients can improve on. As the study progressed and the patients received more PLM training, their results improved noticeably.

B. Neuroprosthetics

Neuroprosthetics, on the other hand, utilize EEG signals to control the user's prosthetic. This is a non-invasive strategy for powering a prosthetic that is achieved by placing electrodes on the scalp, brain-computer interfaces (BCI) or brain-machine interfaces (BMI). EEG control of assistive technology has been recently developed over the years and there have been few systematic reviews of these studies. However, in this relatively short period of time, substantial discoveries have been made[21]**.**

In a study funded by the Defense Advanced Research Projects Agency (DARPA) in 2014, the advancements made for EEG-powered exoskeletons and prosthetics were analyzed. On top of this, they attempted to restore neural and behavioral function as well as improve human training and performance using BCI [22]. Recent research into EEG-powered prosthetics has found it possible to gain a significant amount of control of a prosthetic limb through peripheral nerve signals. This was achieved via nerve restoration, which conveys the somatosensory sensation of touch, temperature, pain, and vibration to these patients[22] .

Back in 2006, the Revolutionizing Prosthetics program began with the goal of restoring near-natural dexterity for people with loss of upper-limb control[22]. In that, it proved that gait assistance — a form of physical therapy that focuses on improving the patient's ability to stand and walk — on the basis of the EEG signals is feasible, though the level of assistance required often varied between healthy patients and those suffering from spinal cord injuries[21]. It is often the case that EEG-powered prosthetics are utilized in conjunction with virtual reality to help with assimilation and the rehabilitation process. Using a virtual reality environment aids the patient in relearning their missing motor skills, and the learning seems to happen in three stages: an initial phase, an intermediate phase, and an advanced phase[23]. The initial phase consists of combining knowledge of the instructions with the movements that are required to operate the controls and to produce the correct arm movement [23]. The intermediate phase focuses on sensory guidance for motor output and uses feedback from both the sensory systems and external sources, such as therapists, to identify and correct their errors. This helps ensure that the motor actions are less disjointed and start becoming more natural[23]. For the advanced stage the goal is to have the patient merge the knowledge from the previous steps to achieve continuous motor action. Users are proficient at the desired skill and are now concerned with speed and accuracy of performance. At this point, the user no longer must really focus on the thought of performing the action but can make adaptive changes to the action. At the advanced stage patients achieve the overall goal of prosthetic training, which is having the patient relearn their motor skills and demonstrate skilled operation of the prosthesis[23]**.**

C. Multimodal Prosthetics

Since PLS is a psychological phenomenon, myoelectric prosthetics are already technically using both EMG and EEG signals[2][15]. Choosing a prosthetic is not one size fits all. While myoelectric prosthetics have been shown to improve cosmesis and help alleviate phantom limb pain, they may not be the perfect solution every time. The device may not match up with their individual needs and as a result, they will be forced to compromise which will in turn make the device incompatible[13]. Nowadays work is underway to create prosthetics that utilize both EMG and EEG signals to improve the performance of the prosthetic. In a recent study from Pohang University of Science and Technology, it was shown that EEG signals can be trained using EMG signals. The researchers used a multimodal fusion algorithm to enhance the performance of motion classification[24]. They found that when combining EEG and EMG signals, the accuracy of the EEG signal increased while that of the EMG signal had a tendency to decrease[2]**.** This shows that while the EMG signals are relevant for making an efficient prosthetic, EEG signals are more important. This is because EEG signals are comparatively more useful when it comes to decoding complex motor movements. The more complex a motion is, like precise individual finger movements, the higher resolution of EEG signal characteristics required. To increase the resolution of the biosignals the number of electrodes must also increase. The information from EEG is crucial when it comes to reconstructing hand movements, and just having EMG information is not enough[2][25][26]. In the end it was concluded that combining multiple biosignals makes it possible to develop a more practical prosthesis for patients with upper extremity amputation[2][25].

III. CONGENTITAL AMPUTATION AND PROSTHETICS

In most cases, myoelectric prosthetics are aimed at recreating the function of a missing limb, controlled by the remaining muscles and nerves left after a traumatic amputation, and improved by using EMG and EEG signals that mimic the phantom movements of PLS. This can result in difficulty for congenital amputees, people who were born with an underdeveloped limb or no limb at all. There historically has not been a lot of research done on congenital amputees, let alone prosthetics made specifically for them. That being said, there has been a recent surge in studies exploring the neurological and physical capabilities of congenital amputees in regard to prosthetic use. This research is important because it may improve the medical rehabilitation that these individuals can undergo, permitting them to adapt well to their prosthetics and avoid some of the negative effects that may occur due to neglect[27].

A. Examining the Neuromuscular Capabilities

However, it must be noted that individuals who were not born with a certain limb rarely experience PLS because they do not have a limb to be a phantom and cannot feel sensation in a limb that never existed, in a brain that was never wired for that limb's presence. This was proven in a study from 1997, where researchers attempted to establish a connection between the brains of traumatic and congenital amputees. The results confirmed the idea that non-painful phantom sensations and phantom pain are rare and quite possibly nonexistent in congenital amputees[14]. The congenital amputees in this study also did not develop phantom limb pain. This is likely due to the lack of enhanced nociceptive input which provides the stimulation needed for phantom limb pain to develop in an amputee[14].

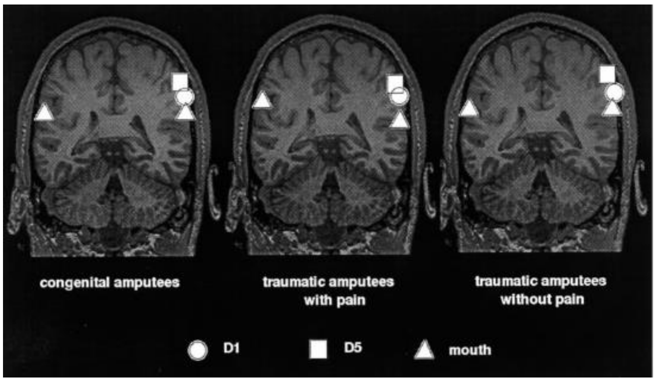

Figure 1: MR image comparing the cortical representation in different amputees[14]

There are rare cases where congenital amputees may experience PLS, as shown in a study from McGill University in the same year, where they found around 20% of people born with congenital limb deficiency developed a phantom limb compared to around 50% of children who lost a limb at the age of 5 years or younger developed a phantom limb[28][29]**.** Observations such as these are utilized in experiments evaluating congenital amputees' ability to control myoelectric prosthetics, which often rely on muscle contraction and pattern recognition. A study from as recently as 2019 showed that patients with congenital upper-extremity deformations achieved pattern-recognition control calibration of multiple degrees of freedom. Completion rates were higher for the congenital residual limb than the sound limb at higher levels of control complexity[30].

Despite this evidence, it is not substantial enough to validate giving myoelectric prosthetics to congenital amputees and expect them to work. After all, children under 5 who suffered a traumatic amputation are, by definition, not congenital amputees, and still had years to make neural connections to their limbs[31]. Furthermore, if around 20% of congenital amputees do nonetheless develop PLS, the more significant figure is that around 80% do not, and that 30% more of the traumatic amputees did. Even in the case of the congenital amputees successfully using a myoelectric prosthetic, their success was due to the immense amount of training required to circumvent the complexity of the task at hand.

Instead of relying on the congenital amputees to develop PLS to control their myoelectric prosthetic, some researchers have worked to strengthen their neuromuscular connections instead. This is achieved by utilizing computer-aided training (CAT) for motor tasks that would increase muscle activity and change its spatial distribution in a patient with bilateral upper-limb congenital transverse deficiency[32]. They recorded the difference in muscle activation maps of the trapezius muscles using CAT between an upper-limb congenital amputee and an able-bodied subject. The subjects were tasked with performing a series of movements including a reach-to-grasp movement. The data showed that congenital amputees were capable of imagining reaching for and grasping a book with the computer-generated hand without movements monitored by EMG[32]. This shows that technology such as the motor imagery-based CAT is beneficial in examining the plasticity of the neuromuscular system in patients such as these.

IV. Brain-To-Brain Communication

When developing a neuroprosthetic it is very important to assess the neurological signals of the user for the device to work. This is typically done by picking up the EEG signals via electrodes. The EEG signals are picked up and then cleaned and optimized in many ways[1]. Usually, computers are used to communicate with the brain for rehabilitative purposes. These signals can be used for brain-to-brain communication (BtB).

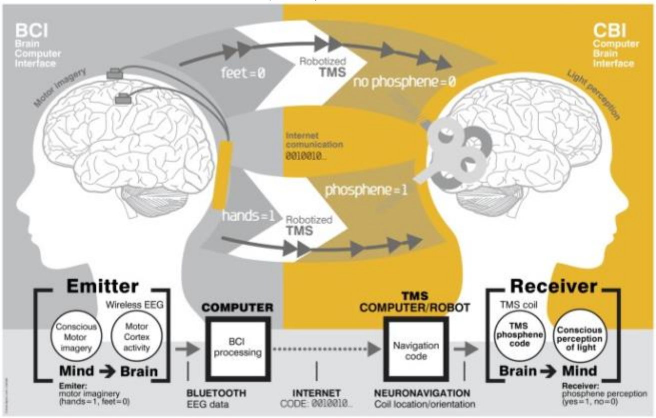

Figure 2: Brain-to-brain (B2B) communication system overview.[33]

BtB is a technique that directly connects two humans to each other's brains without using the common sensory channels used for communication. Some research even compares it to telepathy. It is achieved by connecting through a series of brain-to-computer interfaces (BCI), by which individuals can send EEG signals to stimulate the other's 'receiving' brain — sending a message. BCI refers to the hardware and software used to detect and translate brain activity that is then used to control computers or stored-program architecture devices without involving muscles or the peripheral nervous system[1]. Similar to EEG-powered prosthetics, in order to characterize this specific function of the brain, invasive means such as implantable cortical microelectrode arrays are used to directly detect the electrical field potentials/spikes from the somatomotor areas[34]**.** These electrodes are positioned primarily on the frontal lobe, which is theorized to house cortex neurons that produce large, synchronized outbursts. This area of the brain is involved in social cognition and produces electromagnetic fields around the brain. That makes it able to influence cortical neurons in the frontal lobe of another brain by inducing action potentials in large groups of neurons which can transmit information, such as emotions and cognition cues, to the other brain[3].

As it currently stands, there is no research that explicitly studies the possibility of whether motor signals can be transferred via brain signals. BtB often used for neurological therapy due to brain damage or a disorder to tap into locked-away potential[35][36][33][37][38] [39].

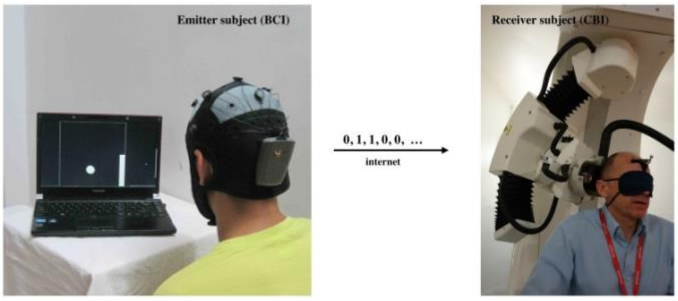

Figure 3: Emitter and receiver subjects with non-invasive devices supporting BCI based on EEG changes driven by motor imagery (left) and the CBI based on the reception of phosphenes elicited fromTMS (right) components of the B2B transmission system.[33]

However, a study from 2014 that focused on communication between the brains of two conscious subjects, determined that transferring motor signals via brain signals is possible to some extent. This was one of the first demonstrations of a functional brain-to-brain interface (BBI) in humans. The main differences found in this experiment compared to previous BtB research were the use of human emitter and receiver subjects, fully non-invasive technology, and the fact that both subjects were conscious when communicating. Factoring in these three differences in conjunction with precision technologies returned high-performance results for the subjects, which showed the necessity of the computer-brain interface portion of human-computer communication. This was achieved by using rotation-encoding TMS-induced phosphenes which acted as a method to exclude peripheral nervous system involvement [33] [34]**.** The results showed that information was in fact extracted from one brain using EEG and then conveyed to another brain using TMS, allowing both subjects to cooperatively perform a task solely using direct brain-to-brain interface[33].

A consensus is that there are three major developments when it comes to BtB communication research. First, the current technology is adequate and functional devices have been developed for brain-to-brain information transmission in humans. That technology may revolutionize how humans communicate and collaborate, as well as create opportunities to further investigate brain function and even utilize this technology in rehabilitation. Equally as important is the second fact that BBIs are now constructed using non-invasive technologies. Non-invasive technologies are simpler and safer for humans than invasive, surgically implanted devices. Also, they have a wider range of applicability and can be used to develop a wider array of tasks. The final development is that there appear to be more experiments involving human subjects. Historically, most tests were conducted on other mammals or primates and researchers would then hypothesize about how the results would affect human subjects. Having a proof-of-concept BBI in humans pushes the field to explore the future capabilities of information transmission technology[36][40][41].

Recently there has been research on utilizing BtB technology for rehabilitative purposes. In studies from National Institute of Mental Health and Neurosciences and Department of Industrial & Systems Engineering, North Carolina State University, BCIs have been used in a plethora of neurorehabilitation projects, most notably for visualizing the motor movements of stroke patients. The primary focus of this research was classifying the left vs. right hand/foot motor imagery of stroke patients. By analyzing the brain cortical activity that is associated with motor imagery, these EEG signals are decoded and transformed into the imagined hand movement directions in stroke patients[42][43].

V. Discussion

Based on the studies being conducted on congenital amputees, myoelectric and neuro-prosthetics, and brain-to-brain communication, it seems feasible that these topics can be combined. Specifically, it seems possible that utilizing brain-to-brain communication between an able-bodied individual and a congenital amputee could aid in building the neurological connections necessary to ease the rehabilitative processes for prosthetics.

The hypothesis is that using EEG signals communicated to a congenital amputee via brain-to-brain communication will assist them in making the neurological connections needed to make moving the prosthetic easier. As mentioned previously, there has been research into the neurological capabilities of individuals with congenital amputation in relation to their absent limbs. While their physical motor capabilities differ according to research that has been done their neurological capabilities are the same there was just be a slight learning curve. It has been found that some individuals with congenital amputations do experience Phantom Limb Syndrome[28], which would make learning prosthesis control slightly easier, but for those that do not, brain-to-brain communication could be a good solution to help with the learning curve of using a new device. As mentioned prior, there has been research focused on analyzing the EEG signals of motor imagery and decoding those signals to imagine hand movements for stroke patients. There are ongoing non-invasive studies, such as one by the National Institute of Neurological Disorders and Stroke begun in 2008, that provide evidence suggesting that surface-level EMG or EEG data contain sufficient information to presume movement direction and hand kinematics from recorded brain signals [37][44][45][46][47]. If this knowledge is used in conjunction with pre-existing EEG and EMG prosthetic technology, it could make the EMG signals that are the most focal part of the controls much stronger which in turn would make the prosthetic more efficient.

Making the rehabilitative process easier will make the patient stick to it longer. The harder a device is for someone to use, the less likely they are to continue using it, and the likelier they are to find a way to live their life without it, thus defeating the purpose of assistive technology in the first place [7]. Furthermore, it should be noted that when a patient possesses a prosthetic that works just as well as a natural limb, long term use tends to improve their body image. This ultimately shows that an effective prosthetic not only impacts the user physically but mentally and emotionally as well[48][49][50].

VI. Conclusion

In conclusion, the field of prosthetics and rehabilitative medicine is an ever-growing and adapting field and as scientists continue to decode the human body that information can be put back into creating peak medical care. The current state of myoelectric and neuroprosthesis continues to evolve especially as researchers continue to explore the neurological and neuromuscular capabilities of congenital amputees in respect to their missing limbs and improve upon brain-to-brain communication devices. When it comes to providing prosthetics for congenital amputees there will be more research in the future examining how to translate the motor imaging abilities from CAT device into a functional prosthetic. Furthermore, more research needs to be put into communicating motor movements to another brain, even seeing if BtB can help create those neurological connections in the receiving brain. As always with all research that contains human subjects, as the field advances it also introduces conversations between ethicists, neuroscientists, and regulatory agencies on the ethical, moral, and societal implications of BBIs. In the end, myoelectric and neuroprosthetics still have a long way to go in terms of effectiveness and accessibility before they can reach the commercial market. For that reason, it is predicted that future research will be more focused.

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