THE APPLICATION OF BRAIN MACHINE INTERFACES IN THE DEKA ARM

Katherine Dash kad179@pitt.edu, Sam Hunn sah207@pitt.edu, Anna Kelly amk307@pitt.edu

Abstract*—With the relatively recent invention of brain-machine interfaces (or BMIs for short), it is now possible for the human brain to send and receive signals from an electronic device. Using electromyography (EMG), the electrical activity of muscle tissue in the body is actually able to be recorded as signals and sent to the brain to be interpreted.*

These brain-machine interfaces have a number of applications, one of them being that you could functionally connect the brain to a device linked to or implanted in almost any body part. This idea is the key to perfect bionics and has greatly advanced what bionics can do. Currently, bionics users rely solely on visual feedback to successfully maneuver their limbs.

But, with the use of vibration-induced kinesthetic feedback, amputees are able to accurately control limbs with the sense of touch instead. Vibrational stimulation in conjunction with electromyography provides the user with kinesthetic feedback, allowing the prosthetic to be perceived as a functioning limb and not just a tool.

This mechanism is specifically used in a device known as the DEKA Arm System (also commonly called the Luke Arm). Combined with a new surgical technique, the brain-machine interface is able to send signals from the central nervous system to the prosthetic based off of feedback from various muscle movements.

These features would help amputees who struggle with mental illnesses, such as anxiety and depression, spurred by the loss of a limb and the frustration of adapting to a prosthetic. The successful implementation of BMI technology to prosthetics will provide millions of amputees around the world with an outstanding replacement for their lost appendage, thus improving their quality of life.

Key Words—Brain-machine interface (BMI), DEKA Arm system, Kinesthetics, Luke Arm, Electromyography

INTRODUCTION: AN EVOLUTION IN BIONICS

To one day have perfect bionics, scientists and researchers must utilize what are known as brain-machine interfaces (BMIs). Successfully linking the brain to a computer and allowing communication between the two is the future of the biomechanics industry. While this sounds simple, in reality, it requires engineers to account for numerous factors. Human limbs have many underlying mechanisms and capabilities that most people don't even think about, for example, kinesthetics. Current technology hasn't even been able to mimic the range of motion seen in human limbs. In order for our primitive bionics technology to evolve, engineers have a lot of work to do in several different areas.

One of these areas is the amputation surgery itself. A recent technique allows a patient's motor and sensory nerves to be rerouted to restore the function of, or reinnervate, proximal skin and muscle tissue. When a person attempts to move a missing limb, brain signals trigger the innervated muscles, causing them to contract [1]. Connecting a prosthetic to a user using electromyography (EMG) allows for these signals to be harnessed, thus providing prosthetic control and feedback.

Compared to now, where prosthetics users are only able to use visual feedback to successfully maneuver their limbs, vibration-induced kinesthetic feedback gives amputees the ability to have accurate control with the sense of touch instead. After a motion is performed, joint tendons vibrating at 70 to 115 Hz can generate a perception of movement, even if the patient is completely stationary [2]. This helps the prosthetic to be perceived as actually part of the body and not just an attachment.

A specific application of this is the DEKA Arm System (also known as the Luke Arm, after the character from Star Wars, Luke Skywalker.) Recently approved for commercialization, this prosthetic arm is the first arm that allows users to regain their sense of touch [3]. It comes with six pre-programmed patterns and four wrist movements, enabling better precision and flexibility for the user [4].

Prosthetics with features like these, and most importantly, the BMI component, will help amputees to not only regain full function of their limbs, but to return to the quality of life they had before.

INVASIVE BRAIN-MACHINE INTERFACES

A brain machine interface (BMI) is a system that allows for communication between the brain and an external machine. The newest, and also most invasive, BMIs employ cortical stimulation to control devices. In order to do this, a microwire array is implanted into the brain to record and extract motor control signals sent through cortical and subcortical interneurons. Interneurons, located solely in the brain and spinal cord, are responsible for communication between the central nervous system, sensory neurons, and motor neurons. BMIs use these nerves to record signals from the brain (part of the CNS), intended for motor neurons, and redirect them to a machine, thus initializing brain-machine communication. Long term use of an invasive BMI can lead to cortical and subcortical remapping, which leads to remapping of the body schema. This drastically improves the quality of control over the device, thus improving the quality of use. Cortical stimulation is proven to have the highest quality sensations experienced when compared to other brain-machine interface techniques [5].

Components of a Brain-Machine Interface

For a brain-machine interface to be effective, it must be what is known as a closed loop. This means that the neurons in the brain are able to send and receive signals from a designated body part, and in turn, that that body part is able to receive signals from the brain, act on them and send its own messages back to the brain based on sensory feedback from the environment. The BMI must also be real-time, that is, the signals being transmitted are done so with negligible or no delay and as fast as the body's natural nervous system [6].

An ideal brain-machine interface is comprised of several parts. The first is a multitude of chronically implanted electrodes that have the ability to pick up on extracellular electrical signals from populations of individual neurons. (Chronically implanted simply means that they are able to be within the body for a significantly long period of time, without breaking down or causing harm to the person's body.) These electrodes would be connected to a system that processes the signals and formulates motor commands based on them; this system also would be able to communicate back and forth with the many electrodes. The final component is an actuator device that responds to the motor commands and, in turn, is able to cause a movement and also give sensory feedback to the patient [6].

To expand on the second part of the brain-machine interface mentioned above, the device that processes the signals also would have multiple parts, which are as follows. First is either one or more neurochips that can communicate with the electrodes and are also able to be chronically implanted. Next would be a module used to acquire data and information that is able to be connected with at least one of the neurochips mentioned before. The third part is a unit that is linked to the data acquisition module and whose job it is to produce the motor commands. Lastly, it is necessary for there to be a supply of power for the neurochip(s) and for signals that are being transmitted and received throughout the system [6].

Longevity and Sustainability

When most people hear the word "sustainability," they think of recycling, "going green" and being environmentally-friendly, and finding alternative energy sources. However, there is much more to this concept than just that. Sustainability can be how a product or innovation makes the common person's life better. For example, does a device enrich someone's quality of life or make dealing with a disability easier for him or her? How long will the device last, and is the procedure to implant it invasive or dangerous to the patient? There are other factors, too, such as comfort level, ease of operation and accessibility.

When thinking about sustainability in this way, it is easy to evaluate how such devices as brain-machine interfaces could or could not be considered sustainable, especially with regards to longevity. A materials scientist and biomedical engineer at Carnegie Mellon University, Christopher Bettinger, notes that part of the reason current brain-machine interfaces are not long-lasting is because of the natural composition of the brain. Our brains have what can be described as a gelatinous consistency. But, comparatively, the majority of BMIs today are produced using such materials as silicon, which relative to our brains, is very hard and rigid [7].

Furthermore, Bettinger makes the comparison that the electrodes of the brain-machine interface being implante are like a plastic fork, and our brain is like a bowl of Jell-O. Following that analogy, then, implanting a BMI is like sticking a fork into Jell-O and hoping that it does not shift once it is there. Because of this, currently, it is not yet possible to make it so that BMIs will not move around on the surface on the brain. These small movements, or "micro-motion artifacts," can cause damage to tissue and inflammation and exacerbate tissue scarring from the initial surgeries. Such occurrences as these are natural biological reactions; however, over time, they decrease the signal quality and the amount of information that can be extracted from the brain. At some point, typically after about five years, the device becomes no longer functional, which describes why brain-machine interfaces are unfortunately not yet sustainable in the long term [7].

The Process Behind Brain-Machine Interfaces

Equally important to fully comprehending how brain-machine interfaces actually function is, not just their parts, but how those parts fit and work together. This process and the mechanisms of BMI's will be detailed below.

After a nerve signal collection device has been surgically implanted into the tissue of the patient's central nervous system, they are fitted with the actuator (that reacts with movement to received neural signals and also gathers data). Neural signals are now able to be collected and extracted to create motor commands, which are then transmitted to the actuator. Next, a specific corresponding movement is matched with the motor commands and sent to the nerves in the muscles of the designated body part. At the same time that all of this is happening, a sensory "report" is obtained by the actuator. The sensory formation is interpreted and then sent to the subject's biological systems [6].

The Technique of Osseointegration

According to Courtney Moran, a clinical prosthetist who works at the Johns Hopkins University Applied Physics Laboratory, the most important part of any prosthetic is the part that is attached to the body, or the socket. In instances where the socket does not fit properly, patients have reported experiencing pain, sores and blisters, as well as feeling like their prosthetic is heavy and burdensome [8].

Luckily, a new surgical technique called osseointegration is able to solve many of these problems. During osseointegration, the prosthetic device is able to be attached directly to the bone in the patient's arm. After a custom-made titanium post has been finished, it is implanted into the marrow space of the bone. Figure 1 compares the attachment of a traditional prosthetic to an osseointegrated prosthetic [9]. Gradually, the implant becomes a part of the body. And, several weeks after the first surgical procedure, an extension also made out of titanium is connected to the post and allowed to be brought through the patient's soft tissues and skin. The final step is when the prosthetic is actually able to be attached to the previously implanted extension [7, 9].

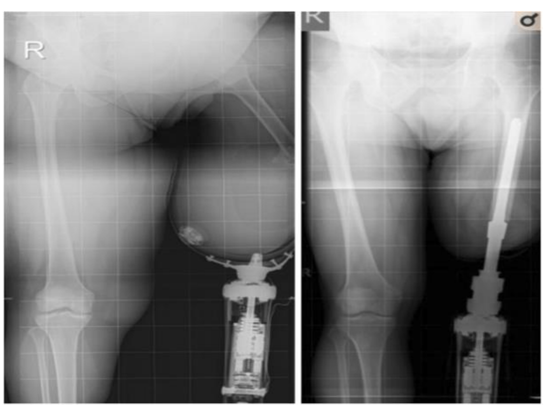

FIGURE 1 [9]
X-Ray of socket prosthesis (left) and osseointegration prosthesis (right).

Osseogration allows for the bone itself, not soft tissue, to bear any weight the user puts on their arm and gives the user an overall better quality of feeling. It also has the ability to alleviate pain and discomfort, decrease skin chafing and general breakdown, and allow for participation in activities that might cause other types of prosthetics to come unattached [10]. Johnny Matheny, who lost his left arm to cancer in 2008, was the first person in the United States to undergo osseointegration just seven years after that. When asked to describe the difference before and after the procedure, he said: "Before, the only way I could put the prosthetic on was by this harness with suction and straps; but now, with osseointegration, the implant does away with all that. It's all natural now. Nothing is holding me down. Before, I had limited range; I couldn't reach over my head and behind my back. Now, boom, that limitation is gone." Even more impressive was the fact that, upon arriving to the lab to run through some tests and test out his new prosthetic, Matheny was able to achieve all the goals set for him within only a couple of hours [8].

Not only does osseointegration improve patient experience, it drastically reduces the hassles associated with maintaining traditional prosthetics. Traditional socket prostheses require daily cleansing before donning. Being confined to a plastic shell, residual limbs sweat profusely, causing odor and bacteria growth, which can lead to skin irritation and damage. When the prosthetic isn't worn, the user must wear a shrinker sock to reduce the amount of swelling of the residual limb. With a swollen limb, the prosthetic cannot be worn without significant discomfort. The socket of a prosthetic often cause redness, pain, and chafing of the residual limb, discouraging the user from wearing it. Amputees with this older technology must carefully examine the residual limb to ensure no blisters or tender spots are present. In addition to these disadvantages, the socket of traditional prosthetics must be replaced every three to five years. Osseointegration is a much more sustainable option for amputees as it eliminates the need for constant upkeep and modification of the prosthetic, illustrating its superior longevity in comparison to traditional models [11].

IMPLEMENTATION OF NON-INVASIVE BRAIN-MACHINE INTERFACES TO PROSTHETICS

One of the most important components of a brain machine interface is the connection between biological systems and the machine. The success of prosthetics controlled by non-invasive BMIs rely on targeted reinnervation, electromyography, and vibrational stimulation to complete the loop of communication between the body and bionic. Targeted muscle reinnervation (TMR) is essential to the reception of signals by a device from the brain. TMR is a, "surgical procedure used to improve the control of limb prostheses" [12]. Principally, nerves from a patient are rearranged in a manner that allows muscles near the amputation site to regain function. This technique is absolutely imperative to the function of non-invasive BMIs. Rather than implanting a sensor into a patient's brain to receive signals directly, targeted reinnervation allows for the patient's native nerves to transmit signals from the brain to the site of amputation. At this junction, electromyography bridges the gap between human and machine.

Use of Targeted Muscle Reinnervation

Targeted muscle reinnervation (TMR) is a surgical procedure that was developed to give amputees a more natural control of their prosthetic devices, specifically with regards to the myoelectric process. In this process, functional nerves are taken from the amputated limb and transplanted into places, such as the chest or upper arm, where the muscles are not biomechanically functional anymore, because of the loss of that limb. At the same time that this is being done, those target muscles are cut off from their natural motor neural pathway, in order for the newly transferred nerves to reinnervate and restore function to them [12].

Over time, the nerves intertwine with and grow into the muscles they were implanted in, which allows them to produce signals that can then be received by the surface of the residual limb [13]. Those signals are then able to be used to control a prosthetic device, which not only makes for a much smoother and more natural operation of the prosthetic, but also creates numerous opportunities for the device to be used and in ways not previously done before.

For example, using targeted muscle reinnervation myoelectric signals with multiple nerves gives amputees the ability to control multiple joints at once [12]. This allows for a greater versatility and use of the prosthetic. One study, collaborated on by researchers from the Rehabilitation Institute of Chicago, Northwestern University and the University of New Brunswick, used electrode arrays to record electromyographic (EMG) signals from TMR patients as they attempted to perform 16 different movements that involved the elbow, wrist, thumb and fingers. The measured EMG signals were then analyzed electronically and used to make a "classifier" program, which had the ability to predict the specific motion based on the signal pattern. Using this technique of "pattern recognition," the 16 distinct movements could be recognized with an average accuracy of 95% [14]. This shows just how versatile upper-body prosthetics have become and what they are capable of doing.

Electromyography

Electromyography measures electrical activity in muscles in response to nervous stimulation with small electrodes attached to the skin. Previously, electromyography has solely been used to assess the health of muscles and their connection with motor neurons [14]. With an application to prosthetics, electromyography records the signals sent by the patient by measuring motor neuron activity in addition to muscle contraction, and relays them to the bionic, where certain signals correspond with certain movements. EMG Pattern Recognition (EMG-PR), a specific type of electromyography, deciphers signals from the brain by utilizing activation patterns of muscle each time the user "executes" a motion with the missing limb. Activation patterns are unique for each individual and are thus mapped to specific prosthetic movements through calibration [16]. Essentially, the patient mentally relays a command to the bionic via electric nervous signals, which are measured using electromyography and transmitted to the bionic, resulting in the desired motion. With the two-part system between reinnervated muscles and electromyography, the bionic will function properly. However, the lack of a kinesthetic feedback system in a bionic system reduces precision of movements and exponentially increases difficulty of control [17]. Kinesthetic sense helps the brain to learn the relationship between motor commands and outcomes to correct movement errors [17]. Spatial awareness of the body is supported by a plethora of sensory inputs from the skin, muscles, tendons, and joints. In prostheses these sensory inputs are replicated by vibrational stimulation, the third component of the communication loop between the body and bionic.

Application of Vibrational Stimulation

With each movement, the brain receives feedback on the positioning of the body, enabling us to move without visualizing our appendages at all times. The body sends signals to the brain, updating it on the position, movement, balance, and force experienced by the limbs. This phenomenon is called proprioception [18]. Having this sixth sense allows us to control our bodies without visualizing each movement. Unfortunately, current prosthetic users rely fully on sight to successfully position their artificial limbs. Visual feedback is not a sufficient substitute for the vast sensory inputs that normally provide the brain with information on motor execution and error correction. Traditional prosthetic systems have solely focused on returning joint mobility and function, which is why they are inferior to models employing a feedback system. Vibrational stimulation, a substitute for proprioceptive systems. is essential to full control and function of a prosthetic limb. Vibration-induced kinesthetic illusions are the key to perception of movement in bionics. To produce joint-specific sensations of movement, joint tendons are vibrated at 70 to 115 Hz. The kinesthetic illusion caused by vibrational stimulation is strong enough to give the patient the impression that their limbs are in impossible positions, though they have been amputated [17]. This system completes the loop of communication between the brain and the bionic, which is illustrated below in Figure 2.

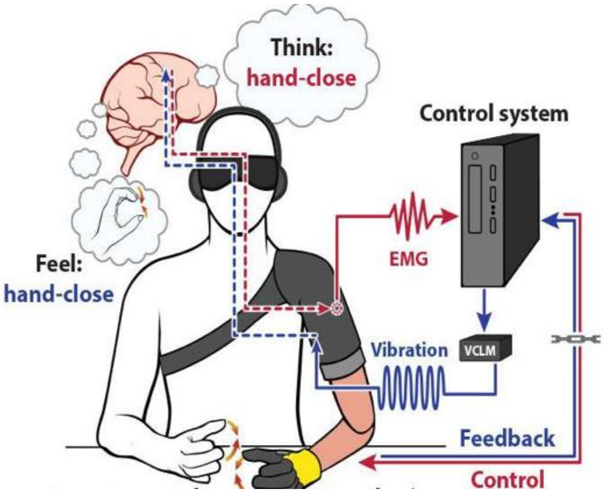

FIGURE 2 [17]
Schematic representation of the movement feedback paired to a real-time functional prosthetic hand clinically fitted to the participant with illusory feedback locked to their volitional control, which was used to explore clinical feasibility. Feedback pathways are represented in blue. Prosthesis control pathways are represented in red.

THE UTILIZATION OF BMI IN THE DEKA ARM SYSTEM

Brain machine interfaces are a vital aspect of the DEKA arm system (also called the LUKE Arm). This relationship acts in two distinct ways. First, body machine interfaces allow a patient to naturally control their DEKA arm as if it was their own. Second, the built-in functionalities of the DEKA arm system as well as its ability to be used on a variety of different amputees allows a BMI to be used up to its full potential. Our clarification of the relationship between BMIs and the DEKA arm system in the next two sections will provide a real-life example of the use of BMIs

Controlling the DEKA Arm System Using a BMI

While electromyography is used to receive control signals from the brain, it is the DEKA arm system's job to interpret these signals to control the DEKA arm itself. One of the ways it does this is through a process called "Endpoint Control" [2]. Essentially, endpoint control allows the user to think of a simple command based around the terminal point of the bionic device, and the software in the DEKA arm finds the most effective way to get to that point using a series of algorithms. These algorithms can be done using both cylindrical and cartesian coordinate systems [2]. This endpoint control is very useful because bionics are still very rudimentary. By keeping the user input to a minimum, the system stays simple and there is a lesser chance of any major problems with the control system

The DEKA arm system also has three different modes in order to simplify the input required for the arm to move. It has standby, hand, and arm modes. While at first glance, having these modes makes it seem the arm would be harder to control, it is necessary because of current technological restraints [19]. People's knowledge of electromyography is still in its infancy. These three separate modes almost act as training wheels for patients. By only allowing "certain degrees of freedom" [19], controlling the arm will be more forgiving to mistakes. Also, despite having distinct control modes, it still "can carry out several movements at the same time" [20]. According to Dr. Linda Resnick, who led the U.S. Department of Veterans' Affairs' study of the arm, these features and control systems are "'unprecedented'" [20]. These modes allow the DEKA arm system to be used in a wide variety of activities, drastically improving the quality of life of the user. The DEKA arm system provides a glimpse into how bionics will be controlled in the future.

The Mechanical Versatility of the DEKA Arm System

The DEKA arm system is a cutting edge bionic that has the capability of utilizing the full potential of BMIs. It is versatile in both what it can do and who it can help. First, the DEKA arm system has the ability to be used by a variety of different types of amputees since it has "three configurations: radial configuration, humeral configuration, and shoulder configuration"[2]. Colloquially, these are for people with below the elbow amputations, above the elbow amputations, and shoulder amputations, respectively. By having multiple different types of configurations, the DEKA arm system can work with almost any type of arm amputation allowing it to be used by a large number of consumers. This one innovation can improve the quality of life of millions of people.

The DEKA arm system has a wide range of capabilities that help to improve the lives of amputees. First, and foremost, it has up to ten types of movement, ranging from moving the entire arm, to multiple different wrist movements, to even individual finger movements [19]. Currently, the DEKA arm is the only commercially available prosthetic device with a powered shoulder, which actually gives amputees using the shoulder configuration the ability to reach behind their heads [21]. This allows for numerous more degrees of freedom and creates a variety of new opportunities in which people are able to functionally use their prosthetic device. By having all these different degrees of freedom, the system allows amputees to regain a lot of their quality of life similar to what they had before their amputation.

Another set of capabilities the DEKA arm system provides to users is its six different grip patterns. They are power grip, fine pinch open, fine pinch closed chuck grip, lateral pinch, and tool grip [2], all of which are displayed below in Figure 3. These different grips allow users to utilize the DEKA arm system in a variety of ways.

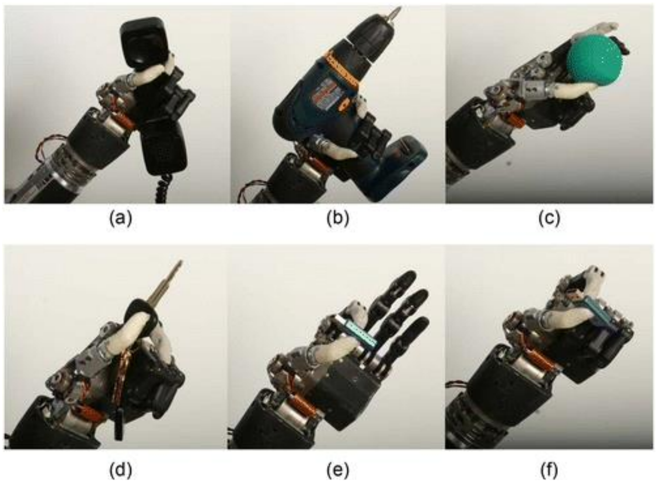

FIGURE 3 [2]
Six grips of the DEKA Arm: (a) power, (b) tool, (c) chuck, (d) lateral pinch, (e) fine pinch open, and (f) fine pinch closed.

These six grips were chosen specifically because of how versatile they are. For example, tool grip could be used if the user needed to use the index finger individually such as to point at objects. This also allowed users "to pick up a coin, use keys, prepare food, feed themselves, comb their hair, open an envelope and even handle such delicate objects as eggs" [3]. In Figure 4 below, performance of a number of everyday tasks is compared for users who use the DEKA arm system versus a current prosthetic device.

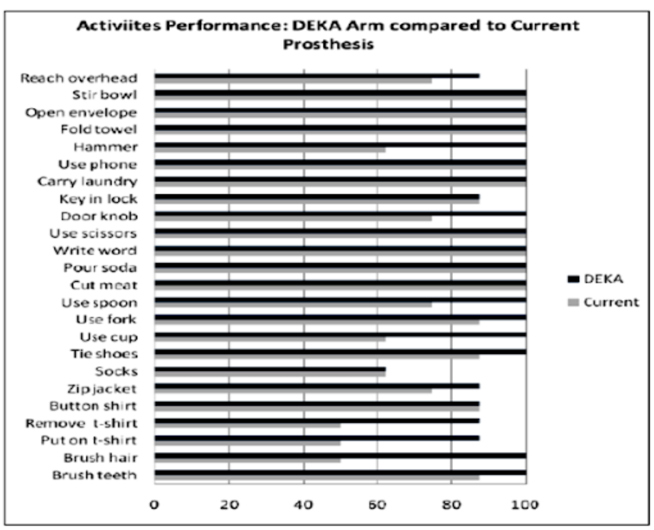

FIGURE 4 [19]
A bar chart comparing performance of various everyday activities using the DEKA Arm, as opposed to a current prosthetic device.

Also, the latest version of the DEKA arm system added a feature called detent which "[allows] users to separate the positioning/stabilizing and grasping aspects of grip from the precision portion and minimized unintentional finger movements while grasping, releasing, or manipulating a given object" [2]. In layman's terms, detent allows users to control the individual aspects of a grip without changing the rest of the grip, and to allow users to pause an opening or closing motion when transitioning to or from a grip. This feature allows amputees unparalleled precision and ease of use when using the DEKA arm system. With the DEKA arm system, amputees are able to live almost as if they were not missing a limb because of the arm's extreme versatility.

LOOKING AHEAD: AREAS STILL TO BE IMPROVED IN THE DEKA ARM

While what researchers and engineers have accomplished with regards to the DEKA arm system is truly amazing, as with most things in life, there is always room for improvement. One specific example of this can be seen by taking a deeper look at the chronically implanted electrodes that make up part of the brain-machine interface. For the 192 electrodes to be effective, each one had to individually mapped in concordance with the patient's nervous system so that the sensations they felt would correspond with real stimuli. Essentially, what those working on the DEKA arm did was ensure that, if pressure were applied to a specific location (for example, the tip of one's index finger), the user would that feel the pressure in that specific area and nowhere else. This provides the wearer with a fuller sense of control. However, it is still nowhere in the range of complete control. Looking solely at the numbers, there are approximately 500 million neurons that are connected in some way to any movement your arm makes. At present, the DEKA arm system is only able to utilize a couple hundred of those, which is less than a fraction of 1% of the possible neurons. What scientists and researchers have been able to achieve with the DEKA arm thus far is a great accomplishment in and of itself, although it is clear that their work is not yet done.

THE HOLISTIC VALUE OF BMIs IN THE DEKA ARM SYSTEM

Even though there is tremendous value of the work being done with BMIs and the DEKA arm system for research and scientific purposes, the main goal of these projects is to help people struck by disaster. Amputation is a huge issue in American society, and there is an increasing number of amputees every day. According to researchers, "in the United States in 2005, there were 1.7 million people living with limb amputations; that number is expected to double by 2050" [12]. Additionally, "from 2001 to 2010, over 1,000 U.S. military personnel suffered traumatic major limb amputations in the Iraq and Afghanistan conflicts," and "many of our wounded warriors are returning with multiple limb amputations, resulting in a much greater impairment."[12]. While amputation saves lives, patients are unable to live normally afterward, and amputation is becoming more and more common. It is urgent that engineers find a way to help amputees because the issue is not going away anytime soon. As for people individually, losing an arm can dramatically change someone's life for the worse and make simple day-to-day tasks a huge struggle. According to a recent study done by several researchers in the Department of Psychology at Tufts University in Massachusetts, amputees who feel depressed "may be well adjusted to the loss of a limb emotionally but may struggle with depression symptoms surrounding the more practical loss of mobility and activities. Indeed, in one sample, a regression analysis revealed that younger age, less satisfaction with social contacts, and perceived restriction of activities explained 40% of the variance in depression symptoms" [22]. Depression among amputees is a serious, yet preventable issue. Amputees have already gone through the traumatic experience of losing a limb, so making sure that the rest of their lives are as normal as possible is vital. Many amputees are struggles are out of their direct control, so it is important that engineers provide the tools to live normal lives.

A very effective way for amputees to regain a sense of normalcy in their lives is through the use of bionics. Amputation can very easily cause depression because it is a huge, life-changing event. This happens because of a physical loss of a limb and a sudden lack of mobility and freedom Currently, it is impossible for humans to grow limbs back. However, by the use of bionics, amputees can regain a lot of the freedom they had before the amputation. In a study done by the International Society for Prosthetics and Orthotics, it was found that in users of the DEKA arm system " who continued to use the device for approximately three months, there was evidence of medium to large improvements in some measures of dexterity and activity performance and small improvements in measures of self-reported disability"[23]. Also, "the findings demonstrate that use of the DEKA Arm at home was associated with improvements in community integration for the small number of persons in our sample who used [a shoulder configuration] device" [23]. The DEKA arm system, and the utilization of BMIs in the DEKA arm have proven to improve the mobility, the performance of day-to-day activities, and the quality of life of users. By improving the ability of amputees to live normal lives, engineers are lessening amputee depression, thus performing a major service in the lives of those who have been through the traumatic experience of losing a limb.

CONCLUSION: WHY DOES THIS MATTER?

After researching BMIs, and the DEKA arm system, it is important to analyze the point of all this development and research. BMIs are cutting edge technology that both helps amputees lead normal lives, and teaches us about how the human brain works. This development as well as the DEKA arm system, has positively impacted the lives of many amputees, helping them lead more normal lives than they would have without the aid of bionics. BMIs and the DEKA arm systems allow bionics to be so much more than they were only a few years ago. They can easily be integrated into the lives of amputees, because they feel more natural to use than ever before. BMIs have a profound impact on human lives, and the technology's continued development will further improve amputees' quality of life.

SOURCES

[1] T. S. Davis, D. T. Hutchinson, H. A. Wark, et al. "Restoring motor control and sensory feedback in people with upper extremity amputations using arrays of 96 microelectrodes implanted in the median and ulnar nerves." Journal of Neural Engineering. 06.2016. Accessed 01.23.2019. https://www.ncbi.nlm.nih.gov/pubmed/27001946?dopt=Abstract.

[2] K. Etter, S. L. Klinger, L. Resnik. "The DEKA Arm: Its features, functionality, and evolution during the Veterans Affairs Study to optimize the DEKA Arm." Prosthetics and Orthotics International. Vol. 38, no 6. 12.2014. Accessed 01.23.2019. https://journals.sagepub.com/doi/10.1177/0309364613506913. pp. 492-504.

[3] E. Guizzo. "Dean Kamen's 'Luke Arm' Prosthesis Receives FDA Approval." 05.13.2014. Accessed 01.23.2019. https://spectrum.ieee.org/automaton/biomedical/bionics/dean-kamen-luke-arm-prosthesis-receives-fda-approval.

[4] H. Knight. "Surgical technique improves sensation, control of prosthetic limb." MIT Media Lab. 05.30.2018. Accessed 01.23.2019. http://news.mit.edu/2018/surgical-technique-improves-sensation-control-prosthetic-limb-0530.

[5] M. Lebedev, M. Nicolelis. "Brain-Machine Interfaces: Past, Present and Future." Trends in Neuroscience. Vol. 29, Issue 9. 09.2006. Accessed 01.23.2019. https://www.sciencedirect.com/science/article/pii/S0166223606001470?via%3Dihub.

[6] "Closed Loop Brain-Machine Interface." United States Patent and Trademark Office. 04.24.2007. Accessed 03.05.2019. https://patents.google.com/patent/US7209788B2/en.

[7] https://www.theverge.com/2018/5/30/17408852/brain-implant-materials-neuroscience-health-chris-bettinger - Why it's so hard to develop the right materials for brain implants

[8] P. Campbell. "Titanium implant unlocks new levels of operability for prosthetic arm." Johns Hopkins University. 01.12.2016. Accessed 03.06.2019.

https://hub.jhu.edu/2016/01/12/prosthetic-limb-more-mobility-apl/.

[9] J. Frölke, R. Leijendekkers, H. Van de Meent. "Osseointegrated prosthesis for patients with an amputation." U.S. National Library of Medicine. 01.17.2017. Accessed 03.04.2019. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5371626/.

[10] S. Dutchen. "Life and Limb." Harvard Medicine. 01.01.2019. Accessed 03.06.2019. https://hms.harvard.edu/magazine/cost-conflict/life-limb.

[11] http://www.hangerclinic.com/limb-loss/resources/living-with/pages/limb-and-prosthesis-care.aspx

[12] J. Cheeseborough, L. Smith, T. Kuiken, G. Dumanian. "Targeted Muscle Reinnervation and Advanced Prosthetic Arms." U.S. National Library of Medicine. 02.01.2015. Accessed 03.05.2019. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4317279/.

[13] M. González-Fernández. "Development of Upper Limb Prostheses: Current Progress and Areas for Growth." Archives of Physical Medicine and Rehabilitation. Vol. 9, Issue 6. 12.18.2013. Accessed 03.03.2019. https://www.sciencedirect.com/science/article/pii/S0003999313012410.

[14] T. Kuiken, G. Li, B. Lock, R. Lipschutz. "Targeted Muscle Reinnervation for Real-Time Myoelectric Control of Multifunction Artificial Arms." U.S. National Library of Medicine. 02.11.2009. Accessed 03.06.2019. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3036162/.

[15] "Electromyography." Johns Hopkins Medicine Health Library. 03.17.2014. Accessed 03.01.2019. https://www.hopkinsmedicine.org/healthlibrary/test_procedures/neurological/electromyography_92,p07656.

[16] L. Resnik, F. Acluche, S. Klinger. "User experience of controlling the DEKA Arm with EMG pattern recognition." Public Library of Science. 09.21.2018. Accessed 03.03.2019. https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0203987.

[17] P. D. Marasco, J. S. Hebert, J. W. Sensinger, et al. "Illusory movement perception improves motor control for prosthetic hands." Science Translational Medicine. Vol. 10, Issue 432. 04.2018. Accessed 01.23.2019. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5906050/.

[18] U. Proske, S. Gandevia. "The Proprioceptive Senses: Their Roles in Signaling Body Shape, Body Position and Movement, and Muscle Force." American Physiological Society. 10.01.2012. Accessed 03.07.2019. https://www.physiology.org/doi/full/10.1152/physrev.00048.2011.

[19] "DeNovo Classification Request for DEKA Arm System." Decision Summary. 06.14.2012. Accessed 03.02.2019. https://www.accessdata.fda.gov/cdrh_docs/reviews/den120016.pdf.

[20] "DEKA Advanced Prosthetic Arm Gains FDA Approval." U.S. Department of Affairs. 05.16.2014. Accessed 02.25.2019. https://www.research.va.gov/currents/spring2014/spring2014-34.cfm.

[21] "LUKE Arm Details." Mobius Bionics. 01.2019. Accessed 02.10.2019. http://www.mobiusbionics.com/luke-arm/.

[22] S. Cavanaugh, L. Shin, N. Karamouz, S. Raunch. "Psychiatric and Emotional Sequelae of Surgical Amputation." Psychosomatics. Vol. 47, Issue 6. 04.09.2011. Accessed 02.16.2019. https://www.sciencedirect.com/science/article/pii/S0033318206710921?via%3Dihub.

[23] L. Resnik, F. Acluche, M. Borgia, J. Cancio."Function, quality of life, and community integration of DEKA Arm users after discharge from prosthetic training: Impact of home experience." International Society for Prosthetics and Orthotics. Vol. 42, Issue 6. 10.01.2017. Accessed 02.20.2019. https://journals.sagepub.com/doi/pdf/10.1177/0309364618774054.

ACKNOWLEDGEMENTS

We'd like to thank Dr. Batista for inspiring us to pursue research in brain machine interfaces. And, also thank you to our families for continuing to support our academic endeavors.