TARGETED MUSCLE REINNERVATION: CONTROLLING ARTIFICIAL LIMBS WITH THOUGHT

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Abstract—*While prostheses once had limited functionality, recent prosthetic research has reached a peak with the development of artificial limbs that have the apparent ability to read thought. At the core of this research is targeted muscle reinnervation (TMR), a surgical technique that relocates residual nerve endings formed during amputations to denervated muscle targets that serve as biological amplifiers and isolators of EMG signals sent from the brain. When applied to myoelectric prosthetics, this technique can optimize the speed, accuracy, and ability of an artificial limb to interpret EMG signals. As arms and legs play such an integral role in the flow of daily life, the loss of a limb can be quite devastating. This surgery is vital because it can alleviate the pain of neuromas and allow amputees to have a smoother transition into life with a prosthesis. In addition, it provides patients much more natural control over the movement of an artificial limb. Although intricate tasks are still difficult, this surgery in congruence with myoelectric prosthetics can truly transform the lives of amputees and restore previous abilities. Tiffany Johnson, an arm amputee, and Joe Pleban, a leg amputee, both underwent TMR and prove how it can provide opportunities that were previously not possible for both arm and leg amputees. While TMR is currently helping patients, one of its characteristics is particularly intriguing to researchers: its potential to revolutionize the medical industry. It opens a portal to a whole realm of research, such as its ability to expand from just a motor path to both a motor and a sensory path, allowing amputees to experience tactile sensations in their phantom limbs. In addition, TMR applied to myoelectric prosthetics is a sustainable innovation in that it improves the quality of life both mentally and physically for the current generation and future generations. Its ability to allow amputees to regain control, its implications for future research, and its sustainability make TMR an incredible breakthrough in medical research.*

Key Words—Amputation, Motor Function, Myoelectric Control, Neuroma, EMG signals, Prosthetics, Targeted Muscle Reinnervation

TMR: AN OPPORTUNITY FOR AMPUTEES

Each day, millions of people throughout the world are affected by the impaired functionality that amputations can inflict. They are unable to go about their daily life with the ease, comfort, and independence that many people enjoy. Even simple tasks, like washing dishes or picking something up from the ground can be challenging. On top of this, many amputees experience excruciating neuroma and phantom limb pain that can create the need for further surgeries. The pain is so severe that wearing a prosthesis is incredibly hard or, in some cases, impossible.

However, TMR, or targeted muscle reinnervation, presents an opportunity for amputees like none other before. The severed residual nerve endings that reside near the site of an amputation do not cease to work after an amputation has been performed. These nerves are still active but unable to naturally control other muscles. TMR takes these residual nerve endings and relocates them to "target muscles" in other parts of the body close to the amputation site so that the information can be transferred to these muscles [1]. This way, the useful yet inaccessible information being sent to residual nerves can now facilitate accessible motor function. When utilized in congruence with myoelectric prostheses, this surgical technique allows amputees to control their devices through natural thought rather than device manipulation.

In addition, TMR can serve as a solution to the intensely excruciating neuroma and phantom limb pain that amputees with conventional treatment normally experience. Since it facilitates organized nerve growth, patients who have undergone TMR experience significantly less or even no pain. This surgery clearly has many incredible impacts on the lives of amputees, as illuminated by Tiffany Johnson and Joe Pleban, two amputees who are now reaping the benefits of this surgical technique. TMR can have the sustainable impact of increased quality of life regardless of whether it is paired with myoelectric prosthetics or not.

TMR and myoelectric prostheses have transformed medical research by introducing ideas that were not previously imagined outside the realm of science fiction. Many new prostheses are being developed to provide amputees with unmatched control and functionality, which is significantly improved if the patient has received TMR. Targeted muscle reinnervation has even opened the door for tactile sensation in the phantom limbs of amputees.

HISTORY OF PROSTHETIC RESEARCH AND TMR

A Brief History of Prostheses

Throughout history, many incredible advances in prosthetic research have been made. The ancient Egyptians used artificial limbs for mainly aesthetic purposes and the Romans created heavy metal prosthetics for improving war performance. These empires laid the foundation for prosthetic development that would continue to be improved upon until it reached a peak present-day with TMR and myoelectric prostheses. In between these ancient civilizations and the development of the myoelectric prosthesis and TMR, there were some notable developments that planted the seeds for recent medical breakthroughs. In the 1500s, a prosthetic that could mimic movement through a series of springs and work in conjunction with the user's natural movement was created followed by the invention of the surgical technique to amputate that is quite similar to the one used today. Additionally, research involving using lighter materials such as leather and aluminum over heavy pieces of iron for prostheses was commenced. Prosthetic research greatly expanded in the 1900s as the demand for prostheses increased due to the World War II, when U.S. government made a deal with military companies to focus their efforts into improving prosthetics over weaponry [2]. Although all of these improvements have paved the way for modern medical research, none have even come close to the greatest advancements that were to come in more recent times to transform the lives of amputees.

Myoelectric Prosthetics History

In terms of myoelectric prosthetics, many efforts starting as early as the 1920s had been made to create a limb that utilizes the EMG signals sent from the brain; however, early inventions were quite bulky and required a power source. In 1960, the first significant myoelectric prosthetic was invented by Alexander Kobrinski. Using transistors, he created a prosthetic that was significantly less bulky and much more portable. There were still issues with his prosthesis, though, because its weight made movement difficult. Additionally, the wire connections were likely to inflict damage which compromised the reliability of the arm. Since 1980, however, myoelectric prosthetics have become more popular, and their demand has caused many great advancements. Improvements regarding the materials used for the arm have resulted in lighter, sustainable, and more practical designs. Additionally, the prostheses have since become more aesthetically pleasing and safer to wear [3].

Target Muscle Reinnervation Surgery History

All of these developments throughout history are quite impressive, but the most profound medical advances in history occurred with the invention of TMR. It all began in 1917, when it was discovered that severed nerves can be transferred to new, reinnervated muscles that can respond to neural signals from the transferred nerves. This observation that nerves can be transferred to "target" muscles which can amplify EMG signals intended for a missing limb sparked the idea of TMR [3]. Applied to the use of myoelectric prosthetics, this surgical technique takes all the highlights in historical advances and combines them to construct the perfect amputee-prosthesis interface that combines wide-ranging functionality, comfort, intuitive ability, and natural pain prevention.

The first surgery was performed in 2001 on an individual named Jesse Sullivan. Sullivan had suffered severe damage to his chest and both of his arms because live wires of high voltages electrocuted him; consequently, both of his arms needed to be completely amputated. When the doctors decided his chest needed revision surgery, they realized he was the ideal first candidate for TMR. Once they had cut into his arm muscles to access the nerves, they transferred them down onto his chest to the target muscles. After approximately three months, the nerves started to grow, and after about six months, strong contractions became very visible. Later on, Sullivan could feel sensations from his chest that felt to him as if they were originating from his missing hand [1]. Because the brachial plexus nerves that control hand function were moved to the chest target muscles, his hand sensations were felt in his chest. Essentially, when Sullivan experienced any tactile sensations by the target muscles, it felt as if they were coming from his missing hand.

BETTER CONTROL OF PROSTHETICS: AMPLIFYING NERVE SIGNALS

Targeted muscle reinnervation surgery achieves one very important goal if performed successfully: to produce strong, isolated EMG signals that are easily accessible by a myoelectric prosthesis and clearly transmitted. Essentially, it generates these signals by relocating residual nerve endings that are unused but fully functional to denervated target muscles, where they can grow and thrive.

The Surgical Procedure

The surgical procedure of targeted muscle reinnervation surgery, which is typically performed on only arm amputees involves several nerve transfers from the site of the amputation to a site on the chest or higher up on the arm, depending on the amputation type. To optimize the strength and clarity of EMG signals, it is essential that the brachial plexus nerves be transferred to motor nerve branches that are smaller in diameter to induce “hyperinnervation,” which ensures the smooth recovery of the target muscles [4]. The nerve transfer locations are different depending on which amputation the patient in question has received because this determines how much muscle they have left and the length of their nerves; however, all TMR cases involve the transfer of the brachial plexus nerves, which control the hands and elbows [4]. For example, in an elbow disarticulation or transhumeral amputation, five nerve transfers take place. The median nerve is placed in the medial biceps (allows “hand close” movement), the distal radial nerve is relocated to the lateral triceps (allows “hand open” action), the ulnar nerve is moved to the brachialis, (allows alternate hand/wrist movement), the proximal radial nerve is moved to the long triceps (allows for “elbow extension”), and the musculocutaneous nerve (allows for “elbow flexion”) is relocated to the lateral biceps [4, 5, 6]. The figure below shows the nerve transfers that occur during a transhumeral amputation.

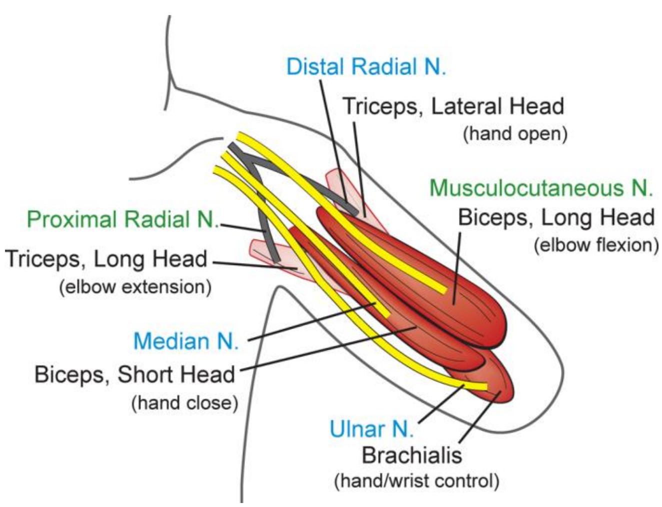

FIGURE 1 [7]
Nerve Transfers that Occur During TMR Surgery in a Patient with a Transhumeral Amputation

The surgical technique of TMR applies the same general method to each amputee it helps; that is, it involves the transfer of residual nerve endings to target muscles. As shown above in Figure 1, patients who have part of their arm remaining have nerve transfers to target muscles higher up in their arm because this is where the prosthesis will be placed and is the optimal location for receiving strong signals; however, for patients with shoulder disarticulations, there are no arm target muscles where the nerves can grow. In this case, they are relocated to target muscles in the chest. Figure 2 below shows the typical nerve transfers that occur in a shoulder disarticulation.

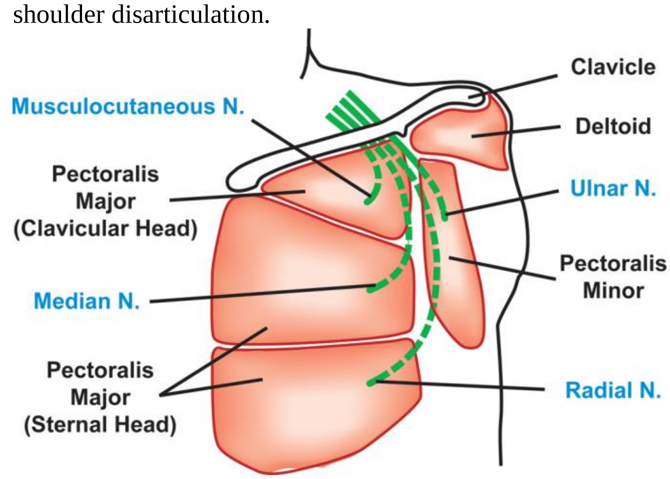

FIGURE 2 [8]
Nerve Transfers that Occur During TMR Surgery in a Patient with a Shoulder Disarticulation

Clearly, the exact surgical procedure for TMR changes for different types of amputations because of factors such as arm length and muscle/nerve availability as seen in Figure 1 and Figure 2; however, TMR has the same concept, same goal, and similar outcome in each patient.

The muscles where these nerves are relocated are called “target muscles,” which are the muscles in which the nerves grow. They are referred to as “biological amplifiers” or “bioamplifiers” of nerve signals because they allow the EMG signals sent from the brain to be magnified and much more transmittable by a myoelectric prosthesis.

Because the goal of TMR is to create strong, isolated EMG signals, several measures must be taken to prepare the target muscles for increased biological amplification. For example, all the fat must be removed from the target muscle because this “allows the prosthesis to record EMG signals from a smaller surface area” and eliminates another barrier between the nerve and the prosthesis, so the signal is much stronger [9, 10]. Another measure that must be taken is to separate the target muscles from each other. If they are not physically apart, some crosstalk may occur between the electrodes and the signals will be mixed; consequently, neither isolated nor clear signals will be available for a myoelectric prosthetic to accurately read [9, 4]. Additionally, the target muscle must be denervated, meaning that it needs to be stripped of its functionality so that the EMG signal is the only information the muscle is receiving [4]. All these treatments are essential to ensure that the myoelectric prosthetic receives the right signals from the brain for natural, intuitive limb operation.

Optimal Time for TMR

Ideally, TMR surgery should happen at the same time as the amputation, as this would reduce the number of surgeries, thereby reducing risks and recovery time. Therefore, the precise optimal time for TMR would be at the same time as the elective amputation; however, this is not a possibility for some people who unexpectedly undergo amputations [6]. In the case of amputees who do not receive their amputation and TMR at the same time, the sooner after the surgery, the more effective it will be. The primary reason for this is that one still has the natural, intuitive knowledge on how to make the elbow contract or the hand move closer to the time of the surgery. As time goes on, it is harder for one to retrieve the information on how to intuitively close the hand. Essentially, training the arm to move is harder as more time has passed since the amputation.

The Ideal Patients

Another factor that affects the success of TMR is the patients upon whom it is performed. Patients must be willing and motivated to undergo a long training process with an occupational therapist and prosthetist. In addition, the patient must be willing to abstain from wearing his/her prosthesis for 3-6 weeks. Also, he/she must have enough muscle and nerve remaining to be able to undergo the surgery; however, if a patient lacks enough muscle, a muscle transplant may be a viable option to make him/her qualified for TMR [4, 5]. Lastly, the patient must not have brachial plexopathy, which can result from a traumatic amputation and "occurs when the brachial plexus is not operating correctly, causing lack of shoulder movement/lack of feelings in arm and shoulder" [11]. This is clearly problematic because this surgery is dependent upon the brachial plexus nerves being fully functional because these nerves are what allows the target muscles to become biological amplifiers.

Neuroma Pain Relief

One of the most significant benefits of TMR, its ability to alleviate the pain caused by neuromas, was one that was not expected when the surgical technique was developed. Neuromas are painful growths that are caused by disorganized nerve growth at an amputation site. These can cause extreme discomfort in amputees, and the pain can be so excruciating that it makes wearing prosthetics extremely uncomfortable. In some cases, the pain becomes so unbearable that patients cannot wear the prosthetic at all. Unfortunately, 71% of amputees report experiencing this kind of agonizing pain; however, TMR can help mitigate this pain by creating more organized growth for the nerve [4]. Because the nerves now have a function and are growing into the target muscles, they have a purpose and do not form these painful growths.

Before TMR, there were various methods that attempted to eliminate this pain, but none was nearly as successful. For instance, a traction neurectomy in which the nerve with the neuroma is relocated to a softer tissue bed can serve as a temporary relief, but this sometimes results in a new neuroma formation in the softer tissue bed and recurring pain [12]. In a clinical study that examined the effects of this technique, 42% of the patients experienced recurring pain around three years after the surgery and 21% ended up receiving additional surgeries [13]. Patients who received TMR, on the other hand, reported that their neuroma pain had been almost or completely resolved up to ten years after the surgery. Other options to reduce neuroma and phantom limb pain include "crushing the distal nerve stump, burying the nerve stump within a cortical window cut into a nearby bone, and sewing two distal nerve stumps directly together into a loop" [12]. These options are all viable and have proven to be helpful in certain cases; however, none of these options have had consistent results. Clearly, TMR is the most effective and long-term solution to neuroma and phantom limb pain, even though this was not its original intended purpose.

COMPLEX CONTROL OF MOTOR FUNCTIONS

Conventional myoelectric prosthetics are able to pick up the amplitude of EMG signals that muscles produce to allow an amputee to control movements. However, these signals with significant strength are difficult to find and must be on specific muscles that do not flex concurrently. Therefore, only two main control sites can be found, and patients are only able to control one part of their prosthesis at a given time. In a transhumeral amputee, these are the bicep and tricep; however, as the level of amputation increases, it is more difficult to find sufficient muscles. Subjects report that without TMR, control is not normal and switching between modes of arm movement is "slow and awkward" [6].

The performance of TMR surgery allows for superior, intuitive control of myoelectric prostheses by increasing the complexity and amplitude of EMG signals present in muscle sites. Surgery results in the creation of four control sites, two that control elbow movement and two that control the hand. This is a significant improvement from the two that conventional myoelectric control presents. Control sites are in muscles that are ordinarily used in the movement of the elbow and hand so that as the user thinks about moving their amputated limb the corresponding movement occurs. When the user tries to flex their elbow the normal heads of the triceps and biceps flex sending EMG signals to the prosthetic to flex the mechanical elbow. In the same way, attempting to close their hand will flex the medial head of the biceps sending signals to perform the task in the prosthetic. Using these coordinated muscle contractions allows the amputee to proficiently perform tasks using myoelectric devices because its control is no different than a real hand. This can be quantitatively demonstrated through the performance of five amputees in the block and clothespin test. In the block test, subjects must move as many blocks from one box to another in an allotted time. Subjects that received TMR moved an average of 323% more blocks than subjects using a myoelectric prosthesis without TMR. Data from a clothespin relocation test also showed that TMR subjects were able to manipulate and move 49% more clothespins [6]. These subjects are able to perform much better because tasks are intuitive with TMR surgery. Without it, subjects are only able to use their biceps and triceps to control either the elbow, wrist, or hand individually. These signals come from any part of the muscles so they are not intuitively linked to the movement of the hand or elbow, causing patients to need much more time and mental effort to perform everyday tasks. Deciding to get TMR surgery can transform a user's ability and view of their own disability. One patient said, "To be able to think 'open your hand' and your hand opens, rather than using your elbow, which is so unnatural- I wouldn't change it for anything" [6].

The signals generated by muscles that have been reinnervated can be used for much more than elbow and hand operation. Detailed studies of these signals have shown that these nerves still send signals to control body parts no longer intact. They have detected signals that can be used for side-to-side movements, flexing of the wrist, and multiple hand grasps. These EMG signals are received from a combination of reinnervated and native muscles to identify muscles throughout the entire arm being activated for a task. In order to obtain this information, a large grid of electrodes can be placed over the arm without having to find specific points of myoelectric control. Therefore, researchers have developed pattern recognition algorithms that detect patterns in signals to determine what motion the user is trying to perform. By using these algorithms, users can perform complex movements such as reaching out to grab a fork by attempting to do so with their missing hand. Without this new algorithm, the user would have to move their elbow into the correct position, then change the angle of their wrist, and then grasp the fork [6]. Therefore, increasing an amputee's ability to perform tasks that they previously could not do provides him/her with a feeling of self-achievement.

INCREASED QUALITY OF LIFE FOR AMPUTEES

Although this surgery is definitely a more recently developed procedure, TMR has been tested on several people and has produced outstanding results. Many recipients have reported having far less or even no neuroma pain. In addition, it has reduced many of the risks associated with amputations by curtailing the amount of surgeries needed, thereby "eliminating recovery time and other risks associated with additional operations" [11]. Two cases in particular, Tiffany Johnson's story and Joe Pleban's story, bring the benefits of this surgery to life, as they can attest that TMR can change lives as it gives amputees another chance to regain the abilities they thought they had lost forever.

Tiffany Johnson: Shark Attack Survivor and Arm Amputee

One woman who can certainly attest to the benefits of TMR is Tiffany Johnson. While snorkeling through the reefs of the Bahamas, she felt a tug on her arm and found herself face-to-face with a tiger shark. Initially, the shark had bitten her arm three inches below her shoulder, but it then attacked a second time, severing her arm right below her elbow. After she managed to escape the tiger shark and make her way back to shore, she was rushed into a five hour long surgery in the Bahamas where she ended up in critical but stable condition. Since the hospitals in the Bahamas could only do so much for her lost arm, she was quickly transferred to a hospital in Charlotte, North Carolina where she underwent a second surgery to debride and clean her arm to reduce the risks of infections [14]. Eventually, she was placed in the care of Dr. Bryan Loeffler and Dr. Glenn Gaston, two doctors known for their work in TMR. They performed targeted muscle reinnervation by taking her residual nerves and relocating them so that any pain from neuromas were lessened and would allow her to function with a prosthetic much faster.

Although it normally takes three months for someone who has not received TMR, Johnson was ready to control a myoelectric prosthetic after only seven weeks [15]. Receiving TMR surgery and pairing it with a myoelectric prosthesis allows her to complete a wide range of actions because of the clear, amplified EMG signals, whereas she "would only be able to use a single-site system with a very limited function if the TMR was not performed," according to her prosthetist Michael Jenks [14].

Johnson's story is one of the many cases where TMR and myoelectric prosthetics improved an individual's life greatly. Commenting on the effect of TMR on her life, she stated, "The benefits of the surgery beyond setting me up for a myoelectric prosthesis was a no-brainer. I was definitely willing to go through an additional surgery not to be in pain for the rest of my life" [14]. Tiffany Johnson is now thriving with the help of TMR and myoelectric prosthetics and is living a relatively pain-free life with her loving husband and three children.

Joe Pleban: Leg Amputee and Paralympic Snowboarder

Another individual who has received TMR surgery is Joe Pleban, who is famously known for his ‘Please Cut Here’ tattoo. From a young age, Pleban was very athletic but suffered constant ankle injuries, which he later learned was due to a rare joint disease called PVNS that caused benign tumors to invade his ankle joints. After six years of undergoing various surgeries, radiation therapy, and pain medication, the doctors informed him he would either have to undergo ankle fusion, which would have enormously hindered his ankle movement, or amputation. Initially believing that after the surgery he would not be able to do everything he loved, he went on a multitude of adventures, including getting his famous ‘Please Cut Here’ tattoo one month before his surgery [16]. However, shortly after undergoing his amputation and two additional surgeries to mitigate excruciating neuroma and phantom limb pain, he received TMR surgery which allowed him to transition back into his normal athletic lifestyle. He is one of the only leg amputees to receive this surgery, as this method was very recently developed. He was so pleased with the surgery that he stated, “For me, TMR has been “an amazing [way] out from chronic pain” [17]. Neuroma pain is one of the most terrible side effects of an amputee because it can even cause a prosthesis to be too uncomfortable to wear. Therefore, Pleban was extremely fortunate to have received TMR because his current lifestyle would not have been possible without it. Enjoying the benefits of a robotic leg because of TMR, Pleban is now “play[ing] rugby on [his] local team, participate[ing] in races with Johnna on [his] ‘running blade’, wake-surf[ing] with [his] family, and, most importantly, snowboard[ing]” [16]. He is now able to snowboard competitively in the Paralympic Olympics, for which he is nationally ranked, and is happily engaged [18].

How Benefits Outweigh Costs

Although TMR seems like the answer to every amputee’s prayer, there are a few drawbacks worth addressing, mainly in the area of cost. Surgery in general can be very expensive, especially in advanced procedures that involve nerve relocation. There are likewise several additional costs that need to be factored in, such as the cost of physical therapy and training to become accustomed to the new prosthesis and to learn how to operate it with the new muscle targets. Additionally, the prices of the new state-of-the-art prostheses are quite costly; for example, a DEKA arm, which has extremely advanced capabilities and can “perform almost as well as a natural arm,” has been estimated to cost around $100,000 depending on the patient’s individual needs. [19, 20]. However, the benefits of receiving targeted muscle reinnervation surgery far outweigh its subsequent costs because receiving it can mean the difference between an excruciatingly painful life and an enjoyable one with much less pain.

A clinical study involving twenty-eight major limb amputees all experiencing chronic neuroma pain shows that that patients who receive TMR experience less residual and phantom limb pain both short and long term than those who do not receive it. In this study, while the average pain score was 5.8 before receiving surgery, the average score was reduced to 2.6 (a 3.2 change) for patients who received the TMR treatment. For those who received standard treatment, the average pain score pre-treatment was 3.9, which increased to 4.1 after one year. This means that their phantom limb pain increased after treatment by .2, which is the exact opposite purpose of the treatment. Clearly, TMR has a dramatic effect on the pain experienced by amputees [21].

In addition, Mike LaForgia, a double amputee who did not receive TMR, explained that the phantom limb pain is the most difficult thing he has ever had to surmount, which clearly indicates that benefits supersede the drawbacks because one cannot put a price on a happy, less painful life [22]. In addition, even though the functionality of myoelectric prosthetics is optimized, an advanced prosthesis is not completely necessary for the surgery; in fact, TMR can increase the comfort and facilitate greater control of a less advanced prosthetic. Also, even without any prosthetics, the alleviation of neuroma and phantom limb pain is invaluable. Therefore, the great cost of a state-of-the-art prosthetic is not necessary to experience the substantial effects of TMR.

To solve the cost issue, there are several efforts being made to reduce the prices of these advanced prosthetics to make them a more realistic dream for amputees. For example, 3-D printing is currently being researched for its use in advanced prosthetics to make artificial limbs less expensive because they require less operation than traditional machinery. While a limb created traditionally would undergo several processes to reach completion to integrate each part together, computer-aided design (CAD) allows prosthetics to be designed in layers and then simply printed out in a shorter period of time [23]. Although this research is in its preliminary stages, there are lots of efforts being made to make the life of an amputee as normal as possible.

THE PROMISING FUTURE OF TMR AND ARTIFICIAL LIMBS

TMR is likewise paving the way for amputees to gain more control of cutting-edge prosthetics, such as the Deka “Luke” Arm, which was developed by Mobius Bionics, funded by DARPA, and granted its name from the arm Luke

Skywalker receives in Star Wars V. Although this arm is quite pricey, it weighs the same amount as an actual arm, which is an incredible achievement considering many prosthetic arms on the forefront of medical research are very heavy due to their advanced hardware [24]. Greatly expanding the array of motor functions available, the arm has 10 degrees of movement and allows amputees to operate a prosthesis that feels just like a real arm. In the trial of the Luke arm, 90% of the participants were able to perform a wide range of tasks that they could not previously perform with their original prostheses. Patients with TMR have much better control over it and have increased intuitive ability to operate it; for example, Amanda Kitts, an amputee and TMR recipient who lost her arm in a car accident, is a research collaborator for TMR and reported that using this arm allowed her to perform more tasks that require fine motor skills than with her original myoelectric prosthesis. She particularly enjoys using this arm because it allows her to clap as she teaches her elementary level children because her arm has a much greater range of motion [1].

In addition, TMR has surprised researchers with an astounding ability to add a sensory component to the motor component that the surgery and myoelectric prostheses possess [25]. Jesse Williams, mentioned above for his improved control of a myoelectric prosthetic, began to "feel" his hands and fingers in his chest, the site of the brachial plexus nerves and the target muscles. According to Todd Kuiken, this means that TMR has opened a "portal, or a way, to potentially give back sensation so he might feel what he touches in his prosthetic" [1]. This is an incredible notion because patients who have received TMR not only have better control of their artificial limbs, but now may be given the opportunity to miraculously feel again, which can infinitely increase the quality of life for an amputee. According to Todd Kuiken, the "brain doesn't know that these nerves are connected to different tissue or muscle"; therefore, if one touches the target muscle containing the reinnervated nerve, a patient experiences the sensation that their limb would normally feel [26]. However, there are a couple challenges currently facing this research; for example, the arm cannot yet transmit sensory information and output motor function simultaneously without the aid of implanted electrodes. In addition, the long-term effect of these electrodes is not known, so researchers are studying ways to make tactile perception among amputees with TMR a permanent reality. They are likewise trying to expand the scope of textures that this sensory perception allows them to detect. Although this research is still clearly in its preliminary stages, it is incredible that TMR, a surgery that was created to increase functionality of prosthetics among amputees, has unleashed a whole new extraordinary field of medical research that was previously unthinkable.

Lots of current research involving prosthetics and TMR involves the improvement of the pattern-recognizing algorithm that dictates the degrees of freedom a certain prosthesis possesses. These algorithms pick up additional, smaller EMG signals sent from the brain and accumulate more information regarding those signals than conventional myoelectric control; consequently, further degrees of freedom are available for prosthetic control and functionality is greatly increased [6]. This topic is a large area of research recently because even with the improvement that TMR provides, the degrees of freedom of normal myoelectric prosthetics (besides the "Luke" Arm and other very advanced limbs) reach a maximum of around two. Without the algorithm, users need to switch from elbow to hand mode when completing an action; however, the use of this algorithm allows the user to simultaneously use both to facilitate cohesive and seamless movement. TMR already has provided a solution to this problem because it allows users to automatically switch modes without thinking about it. Essentially, this algorithm is yet another step provided by TMR towards creating the perfect prosthetic arm.

Clearly, the amount of research TMR has made possible in the prosthetic medical field is unmatched. This surgery alone has been the starting point of several areas of further research that are drastically improving the lives of amputees. A limb controlled by thought was once an inconceivable notion, and now the idea that amputees will be able to feel through their prosthetic limbs is becoming a reality. With all these advances, it is clear that targeted muscle reinnervation surgery is one of the most significant medical breakthroughs in history.

SUSTAINABILITY

Our Definition of Sustainability

One extremely important factor to explore when examining any innovation is its sustainability because it is vital that we are not improving the lives of our own generation and the expense of the future one. In broad terms, sustainability is defined as "the ability to be maintained at a certain rate or level" [27]. Applied to TMR and myoelectric prosthetics, sustainability can be defined as the increased longevity and long-term improvement of the quality of life on both a mental and physical level. It likewise refers to the ability to transfer this improved quality to life to future generations, and it must be attainable by those who need it. This definition expands upon the typical meaning of sustainability and requires a balance of these criteria enclosed within our definition in order to achieve maximum sustainability.

Sustainability in TMR and Myoelectric Prosthetics

The first part of our definition of sustainability regards the improved quality of life and the longevity of an individual physically and mentally after receiving TMR. Physically, it allows amputees to control a prosthetic arm through natural, seamless actions instead of forced mode switches that are awkward and hard to learn. It provides an amputee the luxury of performing daily tasks with more ease, a notion that is not possible without TMR surgery. This surgery helps patients mentally as well because the loss of a limb can be quite traumatic, even when planned in advance. Many amputees experience anxiety because they feel a "loss of the ability to remain independent and support their families," which can give them the false notion that they have no purpose [28]. Anxiety and depression simultaneously affect amputees from different factors such as time since amputation, number of hospital visits, surgeries, and the extent of their pain. The excruciating phantom limb pain can cause "poor adjustment with life, anxiety disorder, substantial decrease in [quality of life], maladjustment with prosthesis and activity restriction" [28]. Clearly, there are several ways that pain can negatively impact an amputee's life. However, TMR tears down several of these barriers by preventing neuroma pain and reducing the number of surgeries required, thereby decreasing the severity of the mental illnesses that affect amputees. In addition, because patients can perform tasks with relative ease, their sense of purpose is less threatened due to increased independence. Clearly, in terms of mental and physical improvement of life and longevity, TMR is an extremely sustainable technique for amputees.

While it has now been established that TMR increases the quality of life for our current generation, it is now important to look at how it is impacting the future generation. Due to this innovative technique generating strong EMG signals, stimulating sensory perception, and preventing neuromas, it has lead to several new areas of research. This means that targeted muscle reinnervation has paved the way for the creation of new techniques and innovations that will allow the transition of amputees back to a normal life even easier in the future. The future generation will see more advanced limbs same motor and sensory pathways that a real arm, less phantom limb pain, and an opportunity for a life that is comparable to that of a non-amputee. Essentially, TMR is sustainable in its ability to increase the quality of life of future generations because it has opened a door for many new developments.

The last aspect of sustainability that must be examined is TMR's ability to be attainable by those who need it. This is the weakest area because, while there are a wide variety of options for amputees, the most advanced developments are increasingly difficult to obtain. For example, as mentioned before, the DEKA Luke Arm can cost up to $100,000 which is a sum of money that people, especially those paying medical bills, do not have to spare. This is where the balancing of different aspects of sustainability becomes important. While it is critical to continue research and create these advanced arms to increase amputee's quality of life, it is also very important to have options that are available to those that need functional artificial limbs but cannot afford one as advanced as the Luke Arm. In order to be fully sustainable, innovations such as the Luke Arm and TMR must create a balance between the ability to improve quality of life and the availability of their product to the majority of amputees. One way to receive this advanced technology is to participate in a research study that will cover the costs of TMR, compensate the participants, and permit them to keep their artificial limb when the study concludes [29]. Studies similar to these contribute to the economic sustainability of TMR. Therefore, there are several opportunities to give to those who do not have the economic means the experience of increased quality of life that TMR provides. With lots of research taking place, TMR is sustainable in the way that it sustains an increased quality of life of current and future generations of amputees.

A TRANSITION BACK TO NORMAL LIFE

For most of history, amputees have faced countless obstacles including painful, slow, and complicated prosthetics that were unable to perform the functions they needed for autonomy. However, TMR surgery revolutionizes the way that amputees go about their daily lives. By optimizing the functionality of myoelectric limbs through biological amplification and the use of target muscles, natural movement allows amputees to learn the controls, move faster, and perform more tasks with a prosthetic than an amputee who has not received TMR. Additionally, the pain associated with neuromas is reduced, giving amputees the ability to use prosthetics with little discomfort. Because the outcome of targeted muscle reinnervation has been almost overwhelmingly positive, there has been an enormous amount of further research on it to return more control to amputees. This confirms that TMR is a sustainable innovation and ensures that the future generation will be graced with the same increased quality of life that amputees in the current generation are experiencing. Essentially, TMR with the use of a myoelectric prosthetic is a sustainable innovation that greatly increases the quality of life of amputees and can help them return to the best possible life.

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