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TARGETED MUSCLE REINNERVATION: A BIONIC RECONNECTION

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Abstract—*Prosthetics have emerged as a staple in the medical industry, becoming the best way for patients who have lost a limb to regain some form of functionality. Their rapid advancement has led to robotic artificial limbs, which are more functional, but most are difficult to use. Targeted muscle reinnervation (TMR), a procedure that reroutes the residual nerves from an amputated body part to a nearby muscle group, allows the brain to communicate with and enhance robotic prosthetics. The procedure allows the patient to control the prosthetic through the natural process of brain signals being sent to the reinnervated nerves. The rerouted nerves send myoelectric signals through the muscles which can then be read by sensors in the prosthetic. The best example of the potential of TMR is the modular prosthetic limb (MPL), which is an advanced robotic arm designed to be as functionable and articulate as a normal human arm. Having been tested in numerous lab trials, the MPL has proven successful with the use of TMR. While there are some potential ethical dilemmas associated with the MPL and TMR, the benefits greatly outweigh them. With the rapid progression of technology and medicine, the potential to utilize targeted muscle reinnervation for other areas such as the legs is immense. The combination of the MPL and TMR helps to normalize the lives of those affected by paralysis, trauma, amputation, and other forms of injury. Targeted muscle reinnervation can revolutionize the fields of medicine and engineering and positively change the lives of people everywhere.*

Key Words—Artificial limbs, Bioengineering, Prosthetics, Robotic prosthetics, Targeted muscle reinnervation

ENGINEERING A NEW TARGET FOR HEALTHCARE

While someone can learn to live without a limb, the lack of a limb can be quite difficult and prevents them from even doing simple tasks that once were second nature, such as putting on clothes. Man's solution to loss of limb was to replace them with artificial ones, known as prosthetics. While prosthetics help, they are still not as versatile and useful as natural limbs. Even robotic artificial limbs, which improve upon simpler prosthetics, are not all user friendly; most rely on reading the signals sent by muscles contractions from remaining limbs or body parts, such as the forearm muscles. Therefore, in order to use such prosthetics, a patient would have to learn to contract muscles they normally do not use in different ways. However, an innovative procedure known as targeted muscle reinnervation (TMR) resolves the issue of prosthetic ease of use. After surgery is performed, TMR allows a person to control a robotic prosthetic with their brain as if it were a natural limb. The best example of how TMR improves robotic limbs is the modular prosthetic limb (MPL), a robotic upper-extremity prosthetic created by engineers at Johns Hopkins University. The MPL is able to function because of TMR and is more than sufficient as a replacement arm. While there are some ethical dilemmas regarding sustainability that arise with targeted muscle reinnervation and the modular prosthetic limb, they mainly revolve around availability and do not outweigh the benefits they provide. With the rapid advancement of techniques and technologies, these dilemmas will eventually no longer be factors. The potential for targeted muscle reinnervation to help people all over the world makes an essential innovation for the fields of healthcare and engineering and can propel prosthetics into the future.

INTRODUCTION TO PROSTHETICS

Prosthetics have actually existed for millennia. The Egyptians were responsible for the most rudimentary developments of prostheses; archaeologists found evidence of the first known prosthetic, an artificial toe which appears to be fully functional. Back then, however, prosthetics were merely worn for a sense of "wholeness." Over the years, artificial limbs have progressed from cumbersome wooden limbs to lightweight, fully functional, metal or plastic limbs. The major shift to the modern model of prosthetics arose during the Civil War, a time when amputations were at an all-time high. The solution to this dilemma was an invention known as the "hanger limb," a prosthetic leg made from barrel staves and metal, that featured hinged joints at the knee and ankle. This was a movement towards total rehabilitation, allowing amputees to have the chance to actually use a limb again. Since the creation of the hanger limb, prosthetics have grown into their own field, with dedicated men and women working constantly towards further improvement. Modern materials like carbon fiber are making prosthetics both lighter and stronger. Advancements like 3D printing and biometrics have enhanced the lives of amputees and will continue to do so. While many advances have been made, there is still room for improving current models, and innovations like TMR could shorten the time needed for further advancement.

PROSTHETICS: A NECESSARY AND BENEFICIAL DEVELOPMENT

In 2005, there were an estimated 1.6 million people who had suffered the loss of a limb in the United States alone. That number is projected to grow to a staggering 3.6 million by the year 2050 [1]. It is also estimated that around 185,000 people have to undergo amputation in the United States each year [2]. There is an obvious need for prosthetics in the United States and across the globe, with a growing demand for functionality and ergonomics. Due to this demand, engineers and researchers are constantly working to improve prosthetics designs, leading to the development of many different designs; some designs are simply upgraded versions of peg legs, while others are more creative, such as those worn by runners which function like springs. Even though these satisfy the basic needs for amputees, there is still room for improvement. This gap was filled with the development of robotic artificial limbs [3]. Robotic artificial limbs represented a massive advancement in prosthetic technology and development.

Quickly becoming the most advanced designs of prosthetics, robotic artificial limbs allow more freedom to their users. While some are simpler than others, such as reactive prosthetics used to help leg-amputees walk, they all provide improvements over conventional designs, such as weighing less, being easier to use, and being more durable. They also prove to be much more versatile than simple prosthetics, giving the user the ability to perform a larger number of tasks, as well as more difficult ones. With technology advancing as quickly as it is, robotic prosthetics might one day completely eradicate the need for simple prosthetics. The more prosthetics are able emulate the body parts they are replacing, the better quality of life amputees will experience, which is a target engineers should always aim to hit.

ISSUES WITH MODERN PROSTHETICS

Though prosthetics are considered a major breakthrough in the fields of medicine and engineering, there are many issues with today's models. Many patients experience extreme discomfort after being fit with a limb, as it can be very difficult to find the right fit for a specific socket. Amputees also often experience phantom limb pain, pain that feels like it's coming from a body part that's no longer there. This can be exacerbated even more by a prosthetic. Another common issue that patients face is the issue of mobility. An amputee might often complain that his or her prosthetic does not fully meet their needs, or that it holds them back. Many prosthetics often connect nerves to lesser used muscles to allow the patient to gain motion of the limb. However, this is a very difficult way of living. Patients must learn to flex less commonly used muscles, such as their pectorals or forearms. Even robotic limbs can be very difficult to maneuver. Probably one of the biggest issues that amputees face with today's prosthetics is that they never feel truly whole again. Even though they now have a replacement to their lost limb, it might never feel the same or rid them of the feeling of being disabled. However, with new technologies arising, there is hope for even more advanced prosthetics. One of the more promising of these innovations in known as targeted muscle reinnervation, which offers a solution to many of the issues cited with current prosthetics.

One of the most pressing issues with modern prosthetics is sustainability. While new materials and technology have improved upon prosthetic sustainability, there are still problems. For example, they must be constantly removed and put back on, leading to more wear over time. Some upper-body prosthetics are not able to withstand the weight that normal arms could, leading to damage and the need for replacement. For an ideal level of sustainability, a prosthetic would need to be as strong as a natural limb and have the ability to be fully integrated to the body.

TARGETED MUSCLE REINNERVATION

Targeted muscle reinnervation is a significant development in the medical industry, providing a way to give amputees the ability to control their prosthetic implant through a natural process. When a limb is amputated, the nerves still receive the signals from the brain; however, because the limb was cut off, the signals have nowhere to go. Targeted muscle reinnervation, a new and innovative surgical procedure, bypasses this issue by redirecting the nerves to other muscles. Therefore, when the brain attempts to send signals to the missing limb, it sends them to the new muscle, which then contracts and sends its own electrical signals. This is similar to the concept of how most modern day robotic prosthetics function, however, TMR utilizes the brain's natural signals to cause the target muscles to contract, while other prosthetics require the user to flex the specific muscle themselves. These signals are then received by electrodes in the prosthetic, allowing it to be controlled just like the original limb. As seen in "Hand," a well-known medical journal, "Residual nerves from the amputated limb are transferred to reinnervate new muscle targets that have otherwise lost their function. These reinnervated muscles then serve as biological amplifiers of the amputated nerve motor signals, allowing for more intuitive control of advanced prosthetic arms," [4]. Not only does this make working the prosthetic more user-friendly, it also greatly improves the patient's quality of life. The procedure also revolutionizes the fields of bioengineering, medicine, and healthcare since it can be applied to various kinds of prosthetics.

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The Procedure

The surgical procedure of TMR is quite extensive. In fact, the entire procedure can last up to or exceeding sixteen hours in total. As mentioned earlier, TMR is meant to permit intuitive control of upper limb prostheses by performing a series of nerve transfers. According to Jennifer E. Cheesborough, M.D., "the goal is to create four independent myoelectric control sites for hand open, hand close, elbow extension, and elbow flexion," [5]. These sites, which are located at another group of muscles, allow the patient to regain control of the remnant of the limb. The new "target muscles" are disconnected from their local nerve input in order to allow the newly transferred nerves to supply them. Per the Seminars in Plastic Surgery Journal, "By transferring multiple nerves, TMR myoelectric signals allow intuitive, simultaneous control of multiple joints in an advanced prosthesis," [4]. In other words, the reassignment of nerves allows the brain to send out electrical signals to the once useless robotic limb, allowing it to control a prosthetic as it were a real arm.

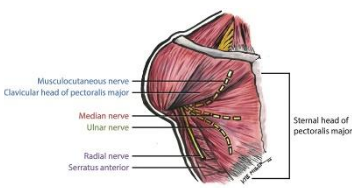

FIGURE 1 [3]
Diagram of surgery plans for shoulder disarticulation targeted muscle reinnervation

Targeted muscle reinnervation can be done at multiple locations within the arm. Figure 1 depicts a basic diagram of targeted muscle reinnervation for a patient who is getting their full arm amputated. The nerves can be seen being transferred to locations in the upper torso, such as the pectoral muscle. This is a common surgical plan for a patient who has lost their entire arm [3]. The surgery allows these target muscles to relay the brain's signals to the prosthetic in the form of myoelectric signals.

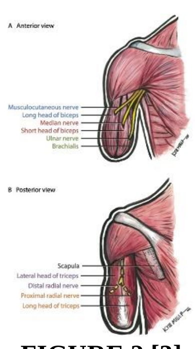

FIGURE 2 [3]
Diagram of surgery plans for transhumeral disarticulation targeted muscle reinnervation

The second figure, Figure 2, shows the surgery plans for a patient with transhumeral disarticulation, or an amputation at the elbow. The reinnervated nerves in this instance are rerouted to locations in the biceps and triceps, making use of the muscles in the remaining half of the arm [3]. Both surgeries are usually done right after the limb has been amputated.

With the nerves reassigned, the brain is able to emit signals to the target sites. Upon their arrival, they cause the muscles to contract and release their own myoelectric signals. Myoelectric refers to the electric properties of muscles. A myoelectric-controlled prosthesis is an externally powered artificial limb that you control with the electrical signals generated naturally by your own muscles. Most traditional forms of myoelectric control~~, however,~~ are quite difficult and awkward to learn. They require the user to learn how to flex typically unused muscles, which can feel unnatural and difficult. Targeted muscle reinnervation, however, offers a new method which allows for more fluid use of prosthetics. Targeted muscle reinnervation utilizes the placement of electrodes in patients' muscles to extract neural control information. It has been discovered by He Huang and other members of the IEEE that using too many electromyography (EMG) electrodes can hinder the use of TMR [6]. Electromyography is defined as a diagnostic procedure to assess the health of muscles and the nerve cells that control them. Consequently, scientists have been looking into using ~~less~~ fewer electrodes and using precise placement to maximize neural control information extracted from the muscles. According to a journal IEEE Transactions on Neural Systems and Rehabilitation Engineering, "Four pairs of bipolar EMG electrodes mounted in the prosthetic socket captured myoelectric signals from the reinnervated muscles for proportional control of hand open/close and elbow extension/flexion," [6]. In addition to these controls, other very intricate movement intents were picked up such as those in the elbow, wrist, individual fingers and thumb [6]. These results are extremely promising, showing that not only is TMR effective, but that it is more efficient than other methods of controlling robotic prostheses.

Targeted Muscle Reinnervation and Revamping Prosthetics

There is no doubt that targeted muscle reinnervation has the ability to truly change the face of medicine. A successful targeted muscle reinnervation procedure allows amputees to have a physiologic conduit to the brain for controlling a prosthetic arm and hand, using their body's own nerves and muscles. Unlike an implanted chip or other device, there is nothing to break down or wear out or which the body might reject as foreign. The surgery involves the transfer of the median nerve, which controls forearm, wrist, and hand movement. It is relocated to the motor point where musculocutaneous nerve, which controls shoulder and elbow movement, originally entered the muscle. However, it is not a simple reconnection. If the surgery is successful, within two to six months the median nerve will grow into the bicep muscle and find endpoints. Then, the muscle is ready to receive signals. The patient must strengthen these signals by exercising and using the muscle frequently. Over time, patients will be able to learn complex movements like wrist rotation, hand grasp, and elbow bending with the MPL. However, it is not difficult to learn. The more the patient uses the arm, the more the machine will adapt and perform even more natural movements. There have even been reports of sensory feelings and feedback received from some patients' modular prosthetic limbs.

Because TMR only needs to be performed once, it could potentially improve the sustainability of the prosthetics used with it [4]. For a prosthetic arm to be sustainable, it would ideally not have to be removed from the patient and could last the entirety of their life. If a prosthetic could be fully integrated, any damage could be treated like a surgery. The limb could therefore be repaired without it being detached from the body. Targeted muscle reinnervation brings healthcare closer to such a reality. Since the residual nerves have been relocated to their new target sites, they are able to remain functionable. With this, a prosthetic could be kept attached the patient with the knowledge that the nerves will remain healthy and will continue to work [4].

MODULAR PROSTHETIC LIMB

Development of the Modular Prosthetic Limb

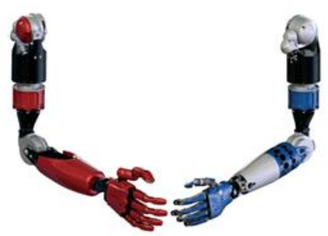

FIGURE 3 [6]
Right and left arm variants of the MPL

While targeted muscle reinnervation is able to improve the functionality of most robotic prosthetics, the best working example of TMR being used is the modular prosthetic limb created by engineers and researchers at the Applied Physics Lab of Johns Hopkins University. The MPL is the result of a project ~~deemed~~ called "Revolutionizing Prosthetics", which began in 2005 when they were contracted to design a fully functioning artificial arm by the Defense Advanced Research Projects Agency (DARPA). The original need for the MPL came from DARPA's desire to help soldiers who had lost limbs regain natural function. However, that need has grown to encompass not only soldiers but all amputees. The project has so far been conducted in three phases, each one building off the other [7]. The goal of the first phase was to create a plan of action and an initial prototype of the MPL. The second phase sought to improve on the prototypes, with the objective of making them neurally integrated. The third phase's main goal was to further refine the designs and make it usable in the aid of patients with spinal cord damage. As each phase reached its completion, the modular prosthetic limb became even more like a natural arm, giving it a greater potential than other prosthetics.

The modular prosthetic limb was designed around neural integration, which is why it relies heavily on targeted muscle reinnervation to operate. Without TMR, the modular prosthetic limb would be little more than a mechanical model of an arm. The complexity of the limb means it is not able to operate without the proper control system. The MPL can be controlled with motion capture sensors as well. However, this is only practical for demonstration purposes, as it would take away the use of the patient's good limb. For this reason, the MPL is most effective when operated by a patient who has undergone targeted muscle reinnervation.

How the Modular Prosthetic Limb Works

The modular prosthetic limb is made of many complex parts that allow it to function like a natural arm. Relatively lightweight, the MPL only weighs about two pounds more than an average human arm, which means it is does not burden the user or operating system. In total, the MPL holds over one hundred different sensors~~,~~— and seventeen motors~~,~~. In addition, the MPL also has twenty-six degrees of freedom, meaning the it can move in twenty-six unique ways. Each sensor monitors a different part of the arm, such as the joint sensors which monitor angle, velocity, and torque. The motors allow the joints to move like their natural counterparts, giving the MPL a similar dexterity to a normal limb. When each of these pieces are combined, they create an almost fully functioning replacement arm, but they still cannot work properly without TMR [8].

The final link for the modular prosthetic limb is the neural integration, which is made possible by targeted muscle reinnervation. After a patient has undergone targeted muscle reinnervation, the MPL is able to be connected; it is usually attached with a special socket and a patient-specific body mount for improved stability and support [8]. The electrode sites in the MPL are then placed over the target sites from the TMR procedure, allowing them to read the myoelectric signals. The modular prosthetic limb's built-in computer analyzes the signals and then activates the proper motors based on which nerve the signals came from. This process is what allows the MPL to operate like a normal arm and is why the joints can operate smoothly and independently of one another. With all aspects of the limb working together and being controlled by the brain, the modular prosthetic limb is able to match the dexterity and functionality of its natural counterpart.

A Synergistic Pair

In the world of nature, symbiotic relationships exist to better improve the lives of the organisms involved. While the relationship between targeted muscle reinnervation and the modular prosthetic limb are not truly symbiotic, as they are not organisms, they do share the characteristic of making each other more efficient. The two create a synergistic pair with the ability to perform tasks that other prosthetics simply cannot. For example, the Applied Physics Laboratory at Johns Hopkins has proved through lab trials that it is possible for a double amputee to control two modular prosthetic limbs independently of one another simultaneously [9]. Les Baugh, a man from Colorado who had to undergo a bilateral shoulder-level amputation due to an electrical accident, was able to learn how to control two separate devices at the same time, with relative ease. After his TMR surgery was completed, he spent time training with virtual reality to gain an idea of what it would be like to use the MPL. After only ten days of training, Baugh was able to successfully complete everyday tasks, such as moving a cup from one shelf to another, with both the right and left variants of the MPL [9]. While the trial may seem relatively simple to the average person, it is a major success for Baugh and for the prosthetic industry.

Another example of the versatility of the modular prosthetic limb and targeted muscle reinnervation is the case of Johnny Matheny, who has voluntarily helped test variants of the MPL in hopes that one day he may have his own [10]. His trials prove that the MPL can successfully be applied to those who had amputations at the elbow rather than losing their full arm. This speaks to not only the versatility of the modular prosthetic limb, but also the adaptability of targeted muscle reinnervation.

With more practice and development being done with targeted muscle reinnervation and the modular prosthetic limb, the quality of both are set to improve greatly over time. The hope of researchers and engineers is that the procedure can one day become commonplace for amputee patients, and eventually each patient that undergoes TMR can leave with their own integrated prosthetic. At the moment this is not possible, with such prosthetics, such as the MPL, being relatively scarce. However, as more research is accomplished, designs are refined, and procedures are improved, both parts of the synergistic pair will become more accessible to those who need them.

THE POTENTIAL OF TARGETED MUSCLE REINNERVATION

The Impact and Benefits of Targeted Muscle Reinnervation

One of the appealing aspects of targeted muscle reinnervation is its wide spectrum of benefits it provides. As discussed, TMR works to give patients with more ease of control in regard to their prosthesis, but it holds greater potential than just improving prosthetic operability. In a growing number of cases, TMR is restoring patients sense of touch. The case of Melissa Loomis represents this breakthrough perfectly. In 2015, she was bitten by a raccoon and, after numerous surgeries within the following weeks, had to have her arm amputated due to a septic infection. One of her surgeries was targeted muscle reinnervation, making her able to utilize the modular prosthetic limb. In lab trials, she became one of the first amputees to be able regain their sense of touch through a prosthetic. During the trial, she was required to pick up a ball and dunk it into a bin. However, when she picked up the ball she was surprised to find out that she could feel it. The sensors distributed throughout the prosthetic are able to provide information on what the prosthetic comes in contact with and can then send that information to the brain [11]. This small ability can have a great impact on people who have lost their sense of touch, allowing them to experience things such as textures and temperatures once again. For example, it could allow a person to feel the warmth and intimacy of holding a significant other’s hand and or the firmness of a handshake with a colleague. It helps bring them closer to living a normal life.

Besides regaining the ability to feel, targeted muscle reinnervation also holds more medical benefits. In certain trauma cases, targeted muscle reinnervation has proven to both help treat and prevent neuroma and pain. Even though some trauma patients are not eligible for TMR as treatment, those who are able to undergo the procedure report lessened or no pain, as well as no development of neuroma, the swelling of nerve endings due to damage to the nerve, in the majority of case [12]. This also helps improve post-traumatic rehabilitation. In addition, the process does not compromise other muscles or body parts, while ~~also~~ at the same time giving the patient the option of having a prosthetic fitted since they would already have the myoelectric control sites [12]. Therefore, in these cases of trauma, patients are able to not only be treated for their pain and neuroma, but they are also then able to opt to have a new prosthetic attached. In essence, they are able to reap multiple benefits from one surgery. Targeted muscle reinnervation can also be used to treat patients for phantom limb pain, a phenomenon that occurs after a body part has been removed. Targeted muscle reinnervation has helped reduce phantom limb pain within three to six months after operation, making use of a prosthesis and general life more tolerable for amputees. [2]. Not only does targeted muscle reinnervation prove to aid in prosthetics, it also is showing its use as a form of medical treatment.

Other Applications with Prosthetics

As of now, targeted muscle reinnervation is only used for upper limb amputations, but the concept of rerouting nerves could potentially be applied to more than just the upper torso or arms. For example, if someone had an amputation at the knee, the nerves that previously controlled the lower leg could potentially be reinnervated to one of the many muscles in the upper leg, such as one of the quadricep muscles or the hamstring; if the entire leg was amputated, the nerves could be rerouted to a muscle such as the oblique or abdominals. This application could allow lower body prosthetics to advance even more. Instead of more complex versions of peg legs or springs, artificial legs could become emulations of their natural versions. The larger platform would also compensate for the need to make them strong enough to bear the weight of the user and could be modified to be patient specific. While applying targeted muscle reinnervation to the lower body may be potentially more difficult, it is worth exploring to provide a more dexterous prosthetic for those who cannot walk. If integrated properly, the leg could also become a permanent part of the body, eliminating the need to constantly remove and put on the prosthetic, which makes the patient's life all the easier.

Fortunately, there are already robotic prosthetic legs in development that are designed to be controlled through a neural interface. These designs are able to move independently from the user's other leg, making them more versatile than passive prosthetics, and are able to distinguish between the user's intended movements. However, these current models require the use of neural interfaces that are generally more invasive than targeted muscle reinnervation. One of the methods used is electromyography, which is what TMR uses to transmit signals, so there is potential to use targeted muscle reinnervation in the current designs, meaning an entirely new model would not have to be created [13]. Using targeted muscle reinnervation would be also be more advantageous because it could be performed right after the initial amputation, making the patient immediately ready to be fitted with a robotic prosthetic. While they might be more complex, robotic legs offer more benefits than simpler models. Not only do they allow users to move faster and lower the amount of effort the hip must put in, which also decreases hip deterioration, they also could be potentially safer. In his article "Robotic advances promise artificial legs that emulate healthy limbs", David Salisbury states, "...amputees using conventional artificial legs experience falls that lead to hospitalization at a higher rate than elderly living in institutions," [13]. Due to their ability to move more like a natural leg, robotic legs would reduce the need for their users to compensate for flaws in movement; they also compensate for factors such as differences in terrain and weight distribution, especially if programmed with active responses to help prevent stumbling [13]. These features would be enhanced with targeted muscle reinnervation since it would allow the brain's natural muscular communication and response systems to control the leg, making the leg safer and more versatile.

Ethics and Sustainability

With a technology as groundbreaking as targeted muscle reinnervation, and its counterpart the modular prosthetic limb, there is much controversy that follows them. One of the major issues with this procedure is cost and availability. TMR is so new and experimental that it is not readily available to just any patient that would like to schedule the surgery. Clinical trials will be going on for years to come. For those that are lucky enough to get treatment, the surgeries can be very costly. According to the American Medical Association Journal of Ethics, "Perhaps the greatest cause of prosthesis- and rehabilitation-related disparities in outcomes for those who have had amputations is cost, and there are also, in some cases, drastic limitations on insurance coverage of the necessary prosthetic devices and services. As many as 20 percent of nonmilitary amputees report an unmet need for rehabilitation services, largely because of inability to pay," [14]. The MPL itself can cost up to $500,000. This is not easy money to come by, and that is just the prosthetic itself. There are many other tests, appointments, and physical therapy that must be paid for overtime. In addition, the MPL is a very rare product at this time. Per Johns Hopkins Applied Physics Laboratory, "There are currently six MPLs being used for neurorehabilitation research across the United States, with four more in development," [15]. The scarcity of the product and technology, as well as its fiscal reputation, calls into question the ethics and sustainability of the MPL and TMR. As long as the MPL costs what it does now, it will be inaccessible to the general public. Even if the cost can be lowered to a point where it is affordable to the general public, it would be pointless if only a handful of them exist. Products and technology that are this difficult to access could be thought unfair and immoral. Not only are they unfair, such products explicitly break most engineering and medical codes of ethics, which call for products to be affordable for all.

In contrast, it could be for these very reasons that the sustainability of the procedure and MPL are improved in due time. For any kind of service to be practical, it must be able to be marketed. In economic terms, a good or service that is so scarce and costs so much will never generate demand from the consumer population, regardless of its potential. A more efficient means of producing the good or service will then need to be developed. For this reason, it is fair to believe that the methods of producing prosthetics such as the MPL will improve to lower the cost and increase the number in production. With cheaper materials and technologies such as 3D-printing being developed, parts could be manufactured at a cheaper and quicker rate, without sacrificing durability or function [16]. Also, as more surgeons perform TMR for longer periods of time, they will become more proficient in the practice, as well as find ways to increase the efficiency of the process. With the natural process of demand leading to the increased quality of goods and services, it is reasonable to assume targeted muscle reinnervation and the modular prosthetic limb will become sufficiently sustainable in the near future.

REROUTING THE PATH OF HEALTH

A procedure that is continuously being perfected and improved upon is quickly becoming one of healthcare's newest revolutions. While it has its drawbacks and is currently not the most accessible option, research and development will surely make such limitations nonfactors in the future. The spectrum of benefits carry significance in the argument for its further development and give but a mere glimpse into the possibilities it holds. A procedure that can give amputees new, life-like limbs, while also treating phantom pain and neuroma, giving back lost senses, bringing back a sense of normalcy, used to be nothing more than a dream. Now thanks to the engineers, researchers, and doctors who work to better the welfare of humanity, such an innovation is a reality. As it continues to improve, only one's imagination could guess where the rerouted path will lead medicine.

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ACKNOWLEDGEMENTS

We would like to thank our co-chair, Grace Bova, and our chair, Uma Balakrishnan, for helping us with our paper and providing support throughout this process. We would also like to acknowledge our parents for always supporting us through our lives and helping shape us into the people we are today. Without them we would not have our desire to have a positive impact on the world and the people living in it.