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ADDING TACTILE SENSE TO PROSTHETICS THROUGH INTRACORTICAL MICROSTIMULATION

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Abstract — The last two hundred years have seen many advancements in prosthetic limb technology, but only minimal improvements in dexterity and grip. This is partially due to the lack of tactile sensation in prostheses. To remedy this problem, researchers are applying brain implant technology called intracortical microstimulation. Intracortical microstimulation of the brain’s somatosensory cortex can be used to induce a sense of feeling in prosthetic limbs vital to the user’s ability to gauge pressure and grip. The integration of intracortical microstimulation with prosthetics is important to the increase of independence for veterans and paraplegics because of its unique ability to provide a sense of touch.

This technology requires two parts: a robotic hand and electrode arrays implanted in the brain. Together, they create a brain-computer interface (BCI), that connects the brain to the robotic hand. The robotic hand is equipped with torque sensors that measure pressure exerted on the hand and send electrical signals to electrode arrays. The torque sensor sends a specific current to the implanted arrays depending on the amount of torque sensed by the robotic hand. When the arrays receive a signal, they release electrical current to stimulate the somatosensory cortex, the area of the brain responsible for the sense of touch. Through this process, users without a tactile sense can use the prosthetic arm and regain a sense of touch.

Key Words—Intracortical microstimulation, Somatosensory cortex, Brain Computer Interface, Electrode Arrays, Torque Sensors, Paraplegic, Cutaneous Feedback

INTRACORTICAL MICROSTIMULATION FOR SENSORY FEEDBACK

The field of prosthetics is very important in biomedical science, as it directly affects the lives of people with very serious injuries. These people range from those who suffered accidents to veterans who were wounded in the line of duty. In an effort to constantly improve prosthetic technology, researchers have been investigating the possibility of creating an artificial sense of touch in the user through the prosthetic arm.

The sense of touch is extremely important both psychologically and physically in human beings [1]. Emotionally, a sense of touch is necessary for interactions with each other. According to Psychology Today, humans provide comfort that is psychologically necessary to the brain through a squeeze of a hand, or a hug [2]. The sense of touch functions in a calming manner, both with humans comforting each other physically and in feeling things with our hands to calm ourselves down. Physically, tactile sense is necessary to provide sensory feedback to the brain, which gives information on what objects are being held, how the hand should be oriented to best hold it, whether the object is slipping and if the hand must readjust grip, as well as sense pressure and textures [3]. Humans can use vision to convey some information to the brain in the absence of sensory feedback. Without tactile sense, however, people will not be able to gauge how much pressure they place on an object, and will not be able to tell when an object is slipping from their grasp, making normal tasks awkward and difficult.

Even with an advanced prosthetic, people who lack cutaneous feedback, such as paraplegics and those with upper limb loss, cannot perform daily tasks without these motions being awkward, slow, or ineffective [3]. Eating a sandwich is difficult when one does not realize their grip strength is ripping holes in the bread. Throwing a ball becomes infinitely more difficult when someone cannot feel the ball to know when to let go of it, or they cannot tell if he/she has dropped it accidentally mid-throw. To solve this problem in prosthetics, researchers have built on increasing knowledge in the field of neurology to artificially create sensory feedback in tetraplegic people and those with limb loss. Intracortical microstimulation sends signals to the brain to provide artificial sensation. When combined with a robotic arm that senses touch, this technology has the capability to provide tetraplegics with a device that can significantly increase their independence.

PROSTHETIC TECHNOLOGY OVER TIME

Breakthroughs and research in prosthetic technology has been pursued since ancient Egyptian times. The first known prosthetic was a toe made from wood and leather found on an Egyptian mummy, which dates to around 900 BC. This
technology was continued throughout Egyptian history, and influenced much of the ancient world, with prosthetics being found as far away as ancient Greece and the Roman Empire. During the middle ages, prosthetic use and technology developed into peg legs and hand hooks for knights. These knights had prosthetics specially created by watchmakers to fit into the stirrups of their horses. This technology was further advanced upon during the Renaissance and all the way to the American Civil War, when prosthetic hands with moving fingers were introduced. The 1970’s saw advances in prosthetics when plastics were used as the foundations for the product, instead of wood and leather [4]. Over time, prosthetic technology has improved in terms of comfort, safety, and usability, but even as recently as the 1970’s, prosthetics were awkward and slow, preventing users from performing many everyday tasks.

**Current Prosthetic Technology**

Current prosthetic technology has significantly improved from the previous rudimentary devices, owing to the advancements made from the 1970’s to the 1990’s in plastics. These plastic prosthetics are lightweight and easier to clean as they do not absorb perspiration as much as wood and leather. Current prosthetics also make use of carbon fiber material to further improve weight and durability [5]. This technology is designed to be more responsive and controllable through electronic interfaces. Operation is mostly controlled by other parts of the body, such as an arm controlled by the opposite arm, or by small contractions of muscles elsewhere in the body [1]. Despite these significant advances which have made prosthetics more durable, wearable, and useable, all of these control schemes are flawed because none give the user direct control or provide tactile feedback. As the next breakthrough in prosthetics, TNP technology revolutionizes the field with its ability to provide both hand functionality and sensory feedback.

**FUNDAMENTAL COMPONENTS OF THE TACTILE PROSTHETIC**

In a normally working body, signals are sent from the hand to the brain whenever the hand touches something. These signals are sent to an area of the brain that uses the information to evoke a sensation in the hand, providing information on where the hand is, what it is touching, as well as an object’s shape, texture, and temperature. In tetraplegic people, there is a disconnect in the nervous system between the brain and the hand, meaning that signals cannot be sent to the brain from the hand, and the person therefore cannot feel. The intracortical microstimulation process attempts to artificially send signals of touch to the brain by mimicking a sensory signal with electrical current sent to the sensory part of the brain. In a recent advancement, intracortical microstimulation has been connected to a bionic hand that senses touch and relays this information to the brain [6]. This technology, referred to as the Tactile Neuro-Prosthetic (TNP), can mimic the hand both in movement and sense of touch to help tetraplegic people perform tasks that would normally be difficult or impossible to achieve without a sense of touch.

TNP technology aims to fix many of the problems with current prosthetic technologies by synthesizing a sense of touch in the user. This sense of touch is imperative to many activities in everyday life; for example, properly adjusting grip to be able to hold objects while moving [3]. The goal of the technology is to allow for not only sensory communication from the bionic arm to the brain, but also for motor control from the brain to the bionic arm.

The TNP technology is made up of two core components, the bionic arm and the electrode arrays. These two components working in tandem function as a Brain Computer Interface (BCI), which converts forces detected by the torque sensors in the bionic arm into signals sent directly to the brain, providing a sense of touch for the user [6].

![FIGURE 1](image_url)

**FIGURE 1 [7]**

This figure depicts the basics of the TNP technology: a bionic arm working in tandem with electrode arrays.

The above image shows a diagram of the TNP technology. The bionic arm, labeled as 1 above, receives physical data recorded by the torque sensors, and sends it to the electrode arrays. This signal is transformed into a signal usable in the brain, and is sent directly to the somatosensory cortex through the electrode arrays, indicated as 2 in the figure.

This synthesized sense of touch was found to provide an almost natural sense of touch in the prosthetic arm. Through this technology, the subject of the human trial was also “able to feel pressure and distinguish intensity to some extent” [8]. This level of natural sense is a major success and shows that the TNP technology is capable of improving the lives of those who depend on prosthetics.

**Human Trial**

The TNP technology is under development by a team at the University of Pittsburgh Medical Center (UPMC). A big
part in the research and development of the TNP was a human trial run conducted in 2016 on an individual who was paralyzed from the upper chest down. During this trial, many aspects were analyzed such as the longevity of the technology as related to long lasting neural connections in the brain, and the quality of the senses being induced in the test subject. This trial was very successful and has set up for even more development of the technology.

**Bionic Arm**

The bionic arm used in TNP is a full prosthetic arm called the Modular Prosthetic Limb (MPL), which was created in the Johns Hopkins Applied Physics Laboratory [6]. This arm was designed to mimic a normal human arm as much as possible by having sensors measure angle, velocity, and torque, in addition to 26 degrees of freedom to give the arm an ability to move in virtually every direction a normal arm can move. It can hold up to 35 pounds, and the joints move quickly, at 120 degrees per second for the wrist and upper arm speed [9].

The MPL is made partially of titanium and carbon fiber, which aid the strength and reduce the weight of the limb, to make it the weight of an average arm [9]. This is important to give the arm durability and make it manageable to wear. However, these materials are environmentally taxing. The creation of titanium requires first strip mining, then the use of the Kroll Method, which involves refining the titanium with chlorine. Chlorine is a toxic chemical and if it is not disposed of correctly, the nearby environment can be severely affected. In addition, the amount of energy required to refine titanium (embodied energy) is exorbitant, almost double the amount of energy of all other commonly used metals [10].

The carbon fiber in the Modular Prosthetic Limb also results in a negative impact for the environment, as Carbon Fiber uses 183-286 MJ/kg of embodied energy, compared to 110-210 MJ/kg for stainless steel or 63-78 MJ/kg for polyester resin [11]. Therefore, the prosthetic limb portion of the TNP is not sustainable in terms of production. However, both Carbon Fiber and Titanium are recyclable, so if these prosthetic limbs are made from recycled Carbon Fiber and Titanium, the environmental impact will be significantly less [12][11].

When the TNP technology is finalized, this specialized bionic arm will allow the user to perform nearly all the tasks as can be done with a healthy arm, with the extensive movement abilities of the MPL aided by the sensory feedback from the TNP and torque sensors. In the human study using TNP, only the torque sensors were used to gauge how much force is put on the bionic hand, as the study was focused on understanding the quality of sense of touch evoked by TNP [6].

The torque sensors are located at the base joint of every finger, at each joint on the thumb, and on the right side of the palm [9]. These sensors detect torque applied to the hand from an external force such as a touch from another person’s hand or holding an object by measuring the deformation of the material inside the torque sensor [6]. The material is deformed when pressure is applied from an outside source, and this deformation creates an electrical current that is proportional to the level of deformation, and therefore torque, that is applied to the hand [13],[6].

This electrical current is then sent to the electrode arrays in the brain via wires connecting the two parts, which provide the current needed to stimulate the brain. These torque sensors are vital to the system as they allow the BCI to vary the amount of force felt by the user and therefore gauge different levels of pressure and grip.

**Electrode Arrays**

The signals transmitted by the bionic arm are received by the electrode arrays implanted in the primary somatosensory cortex of the brain, the area which controls the sense of touch [1]. These arrays allow for electric signals from the bionic arm to stimulate the brain directly. Before the implantation of the arrays, an imaging scan of the brain must be performed to identify the specific parts of the patient’s brain that are responsible for tactile sense. Every individual has slightly different pathways in the brain that correlate to touch. Stimulation of the somatosensory cortex is dependent on the area which receives stimulation. Though the somatosensory cortex is always responsible for touch, and is always located in the same place, the areas of the cortex that are responsible for sensing touch of specific parts of the body is specific to each person and must be determined before surgery occurs [6].

The TNP technology takes advantage of the brain’s organization by stimulating different areas through electrode arrays causing the sense of touch to be felt in corresponding areas of the hand. When a specific torque sensor on the robotic hand is touched, a current is sent through a wire that travels to the corresponding electrode in the brain. This allows a greater level of specificity in the area of the hand that sensation is induced, giving users high quality sensory feedback. After the proper areas are identified two arrays are implanted, which are 2.4mm x 4mm in size, each containing 60, 1.5mm electrodes in a 6x10 grid [6]. Having many small electrodes means that only very specific parts of the brain are stimulated for each torque sensor. Therefore, the user will feel sensation in only the specific area that was touched on the bionic hand.

These electrode arrays are coated in a substance called Parylene-C, which is compatible with the environment of the brain [14]. This means the body will accept the implant and the arrays will not harm the brain tissue or corrode after implantation. In addition to being biocompatible, the material is an environmentally sound product. According to the parylene company ParaTech, there are no volatile organic compounds in Parylene-C, making it easy to dispose of without lasting effects to the environment or causing harmful reactions [15]. The Environmental Protection Agency (EPA)
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has also stated that the process for creating Parylene-C, known as chemical vapor deposition, is dry and pollution free [16]. This means that the electrode arrays used cause minimal environmental impact while also being compatible in the brain.

There also are two arrays implanted in the motor cortex, which are 4mm x 4mm in a 10x10 grid [6]. In future stages of the project, these signals would allow the brain to directly control the arm without the need for complicated mechanisms such as are found in current prosthetics. Together, these two types of arrays would allow a person to move the bionic arm just by thinking about it, and then gain sensory feedback and use the BCI to adjust the robotic arm accordingly. With this setup, all important functionalities of the hand will be taken care of with one prosthetic.

EFFECTIVENESS

TNP technology has not yet been cleared for clinical trials, but research done on implanting this technology in an individual with tetraplegia, as well as multiple animal studies have given significant insight into its effectiveness. Through these trials TNP has been proven to effectively transmit quality signals with accurate specificity and intensity, and has proven its stability and longevity over an extended period of time.

Varying Pressure

One concern about the use of intracortical microstimulation to evoke sensory feeling is that the user may not be able to tell the difference between varying levels of current that respond to varying levels of pressure [6]. However, a study done on Rhesus macaques found that the width, frequency, and duration of the current pulse sent to the brain causes noticeable changes in the detectability of the signal by the macaques [17].

Through this research, scientists discovered that varying currents do change the level of pressure sensed by the user [17]. Increasing the width, frequency, or duration of the current increased the sensitivity of the stimulation, which means that the torque sensors could send an electrical signal based on the amount of torque experienced and the brain would interpret an increased current as a stronger pressure exerted on the hand, leading to a stronger sensation of touch. Through this study, researchers at UPMC found that intracortical microstimulation can cause varied enough sensations that users will be able to adjust grip strength and manipulate objects based on sensory feedback from TNP [6].

Quality of Induced Sensation

The UPMC trial explored other aspects of the effectiveness of this technology, including the quality of sense of touch felt by the user, the stability of TNP, and its longevity. Through a series of trials conducted over six months, the participant reported that the evoked sensations were “possibly natural” for 93% of the trials. The subject described the sensation as “feeling just about every finger… Sometimes it feels electrical and sometimes its pressure, but for the most part, I can tell most of the fingers with definite precision. It feels like my fingers are getting touched or pushed” [6]. This shows that artificial sensations from intracortical microstimulation provide more sensations than just a tingle or electrical current that occurs from direct electrical stimulation of the hand. No completely natural sensations were reported by the participant, which suggests that intracortical microstimulation does not have the same effect as the sensory system of the body. Further research will need to be done to discover whether intracortical microstimulation will be able to provide a fully natural sensation with more precise technology. Senses evoked were described further as originating from both the skin surface and below the skin surface [6]. Ideally, artificial senses from the TNP would feel as though they originate from only the outside skin to relate most closely to a normal hand sensation. Again, further research must be done to limit evoked sensation to only the outside of the hand.

FIGURE 2 [18]
The TNP technology in use in the human trial

The above figure shows the TNP product in the human trial. A researcher stimulates the bionic arm (1) to create a signal. This signal is sent to the electrode arrays (2) to invoke a tactile sensation in the user.

Specificity of Stimulation

Although the quality and identifying location of the induced sense is not yet ideal, the TNP-induced sensation was reported as almost always coming from a specific region of the hand. When blindfolded, the user could correctly identify which finger on the robotic hand was being touched 84.3% of the time. Researchers also would touch more than one finger at once at random times, and the participant could identify that more than one finger was being touched. He was also able to identify at least one of the fingers touched 100% of the time.
when multiple fingers were touched, and could identify both fingers that were touched 53% of the time [6].

While these results are not perfect, the participant accurately identified specific regions being touched most of the time, which shows that intracortical microstimulation of precise regions of the brain is capable of evoking sensations in precise regions of the hand [6]. This precision is necessary for optimal sensory feedback. When holding objects, unavoidable disturbances such as shifting or slipping of the object in the hand will occur, but without tactile feedback a person will not be able to adjust their grip to prevent the object from falling [3]. The ability of users to identify the regions of the hand being touched at the time and how much pressure is being exerted on each region will provide users with enough information to adjust grip and pressure when necessary to achieve more specific tasks that require motor skills.

**Stability of TNP**

The stability of TNP is also an important factor of its effectiveness as a consumer product. Currently this technology is not yet available for consumer use, but throughout the study of TNP with a human participant, all parts of the technology have worked safely. The participant never reported any experience of pain from any of the trials, and the maximum current sent to the brain was carefully controlled. It is possible for intracortical microstimulation to cause damage to the implanted electrodes and/or surrounding tissue; however, this study kept current levels well below potentially dangerous levels [6].

**Longevity of TNP**

Another important aspect to consider when evaluating the effectiveness of this technology is the longevity of this product. Neuronal plasticity, or the ability of the brain to reorganize and change the setup of neural pathways, was a major potential concern in the longevity of neural prosthetics, as the somatosensory cortex of the brain might shift. If this shifting occurs, the area corresponding to different regions of the hand might change over time [19]. However, over the entire six-month UPMC trial, no significant changes in the organization of this area of the brain occurred [6]. This suggests that the user would not have to undergo surgery often to adjust the electrode array position in the brain. In addition, the various electrodes in the arrays did not decrease in efficiency or ability over the course of the trial, and brain activity continued to function normally [6]. This suggests that the implantation and stimulation of the arrays did not affect the arrays or the neurons near the arrays.

**Overall Effectiveness**

Overall this technology has been effective at providing a person with a sense of touch realistic enough to distinguish different pressures and allow the user to adjust grip accordingly. There are many areas of the technology that must be improved, including the quality, the precise location, and the origination of the artificial sensation. Since there has been only one human trial of this technology to date, more trials must also be done to confirm the results of this trial, and more research must be done to make the technology viable for production and consumer use.

**OUR TECHNOLOGY AND THE FUTURE**

The future of the TNP technology is the addition of motor control technology to form a two-way brain computer interface [6]. This will allow for the technology to both send tactile signals to the brain and for the brain to send motor signals to the arm, effectively controlling it. This would allow for the users to feel the objects they are touching, and also adjust grip accordingly to greatly improve independence of paralyzed persons.

Another improvement to be made to the technology is portability and maneuverability. The TNP currently can only be used in a lab setting because the bionic arm must be connected to computers to operate successfully [6]. In the future, the technology will be made portable so that users can move about freely and use their prosthetic in all situations in everyday life.

The University of Pittsburgh Medical Center (UPMC) stated in a research article on the human trial that some goals for this technology include implanting more electrode arrays, and implementing modulated or biomimetically inspired patterning of stimulus trains [6]. Adding more electrode arrays would allow for the user to feel sensations on more parts of the hand, making the sensation feel more natural. Changing the stimulus patterns would improve the realism of the sensations being felt by the user, mimicking real signals found in normal sensory functions.

**Motor Cortex**

Though the TNP technology does not currently support direct control from the motor cortex, this improvement is under development. In preparation for this, during the initial surgery for the human trial electrode arrays were implanted in the motor cortex in addition to the somatosensory cortex. Receiving signals from the motor cortex and transmitting them to outside receivers has been very successful in the past, but it has never been accomplished while receiving sensory input from the prosthetic. This two-way transmission of signals is the ultimate goal of the technology.
As shown in the figure above, the brain (A) sends motor signals to the arm. These signals are recorded and decoded (B) then sent to the robot arm (C) to cause motion. Sensory information is read and converted (D) to usable signals for the brain, which is then electrically stimulated (E). This full two-way neural prosthetic would allow for a much higher degree of independence for the user.

**ETHICAL PROBLEMS AND DOWNFALLS**

As prosthetics become increasingly more advanced and connected to the body, ethical dilemmas and hazards increase. Potential problems that may arise from this prosthetic include health, economic, and future ethical issues.

**Health Concerns**

Advanced prosthetics such as TNP come with many health concerns that must be considered before manufacturing this product. First, TNP requires an implant of electrode arrays into the brain, a potentially dangerous and invasive surgery. Possible side effects from brain surgery include seizures, permanent and temporary neurological deficits, and infections [21]. Users must be willing to accept the risks of brain surgery before they can use this product, which may turn away many potential consumers.

Electrical arrays in the brain are also a health risk, as a degraded wire could cause a short circuit that could be very dangerous for the area of the brain where the electrodes are implanted. The product would have to be regulated, and users would need regular checkups to ensure that the technology remains in excellent working condition. Finally, this product has not yet been used in a full clinical trial, and therefore the full long term effects of this technology on the brain are still unknown. Over the course of the six-month human trial, the participant did not experience any adverse effects from the implantation or use of the brain computer interface. However, more trials on more people need to be conducted in order to fully understand the long-term risks and side effects the use of this technology may cause. Because many of the health concerns are unknown, surgery and use of this technology could severely affect the medical conditions of trial participants. To prevent health problems from the electrode arrays, researchers limited current sent through the wires to a maximum of 100 mA [6]. As research continues, additional precautionary safety measures need to be enforced to ensure minimal adverse effects.

**Economic Sustainability**

The research and development of TNP is a very costly process. In addition to the costs of research and development, the costs of physical production of the technology also factor into the overall price of production. Because of this, the cost of the TNP will most likely be unpayable for the average consumer. A similar smart prosthetic, DARPA’s Luke prosthetic arm, has a cost to the user of about $100,000 [22]. The current cost of these advanced prosthetics is therefore unsustainable if it is marketed for the public, as many people will opt for more affordable traditional prosthetics. However, veterans may be able to purchase this product with government funding, and further research of this technology could reduce its price [23]. While traditional prosthetics will not be as useful, for many their relatively inexpensive price tag will make them a more viable option. TNP will also have costs associated with the installation of the product in the brain.

Installation of the TNP will be costly as every individual would need separate brain mappings and specially ordered arrays to be implanted in different areas. Surgeons must know what areas of the brain to implant arrays in for each individual, which would require special training with the technology. The actual brain surgery itself would also be expensive.

Though the procedure would be expensive, the neurotechnology industry has made efforts to reduce the cost of neurosurgery. One specific technological improvement that was used in the UPMC human trial is the ElektaNeuromag magnetoencephalography (MEG) system. This imaging technology is used before implantation of the electrode arrays to identify the areas of the somatosensory cortex that specifically relate to tactile sense in the hand [6]. MEG technologies require liquid Helium when in use, and in most MEG systems the liquid Helium has to be replaced often. Technological improvements require liquid Helium when in use, and in most MEG systems the liquid Helium has to be replaced often. However, ElektaNeuromag has implemented a Helium recycling system that can save up to 1,300 gallons of Helium per year per machine. Recently many helium reserves have been depleting, making lab ready liquid helium rise 250% from 2009-2015 [24]. Eliminating the cost of buying more liquid helium makes the ElektaNeuromag MEG much more cost effective than other MEGs. Surgery costs will be reduced
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significantly, and therefore the overall cost of TNP will be reduced [25].

Even with the reduced surgery price, the combination of research, production, and installation costs will not be easily affordable to most potential customers. Insurance coverage is not expected to help consumers with costs either, as most insurance companies would not be able to or willing to cover the TNP installation [22]. Because of this, some believe that the TNP would only be available to the wealthiest in America, or wounded veterans receiving support from the government.

Ethics in Prosthetic Research

A final ethical concern with advanced prosthetic research overall is the potential for overly advanced prosthetic limbs. As research into prosthetics continues and devices become better and better at mimicking the human body, there is a likelihood that eventually prosthetics will be made that give their users more abilities than a normal human. Prosthetics will be more powerful than their human counterparts, which could turn prosthetics into an advantageous tool rather than a medical device. Research into BCIs and advanced prosthetics moves technology closer to becoming ‘superhuman’ [26]. This concern does not cancel out the importance of this technology and continuing research for those who need it; however, it is important to address possible ethical concerns with any research to prevent such problems from occurring.

SOCIETAL RELEVANCE

With the many issues that come with TNP and smarter prosthetics research, it can be difficult to conclude that prosthetic research is worth continuing. However, thousands of people, including veterans, are affected severely by tetraplegia or limb loss. For these disabled veterans and tetraplegics, daily tasks are impossible without prosthetics.

Current prosthetics allow users to perform many tasks that would otherwise be impossible, but many prosthetic users have expressed that there are many limitations in the functionality of certain aspects of traditional and even new prosthetics. According to a study on the needs of people with prosthetics, a survey of prosthetic users revealed that the most common dissatisfaction with prosthetics is their inability to grasp objects and lack of dexterity [27]. Both problems can be fixed with sensory feedback from TNP, making TNP the best solution for those with prosthetics. With sensory feedback, users will be able to hold objects, use tools, open doors, and much more without relying on vision.

In addition, further research into this technology will benefit the field of neurology. This research will provide more insight into how the brain encodes stimulus information. This will be helpful in research on devices for other diseases such as Parkinson’s Disease, as well as to improve the general understanding of the brain [1]. A deeper understanding of the brain and application to problems outside of the scope of prosthetics makes this product a great benefit to the entire field of bioengineering.

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