Methods of nervous system stimulation to provide sensation for amputees in a prosthetic device

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Abstract

Prosthetic limbs are more advanced than ever before due to modern technology. There are two paths that need to be properly established for a prosthetic to feel natural: the ability to control the limb and its fingers, and the ability to feel through the prosthetic. The first part, the movement, has been established for the most part. The myoelectric prosthesis registers signals from the user's muscles and allows them to move the limb easily and in a natural manner. However, the second part, the sensory feedback, is the area of research that is currently being investigated. There are three different methods of stimulating the nervous system which can achieve that sensory feedback. Stimulation of the primary somatosensory cortex, the cervical spinal cord, and the arm's peripheral nerves are being investigated. Research on peripheral nerve stimulation is the most extensive of these three methods. Within that method, temporal and qualitative properties of the artificial somatosensory experience are investigated. So far, sensation has been proven to be felt, but it is generally unnatural feeling. Further, this field of research is limited due to invasiveness, small sample sizes, and accessibility. With modern technology, scientists are making it possible to restore the sense of touch in an area that no longer exists.

Introduction

Background on Prosthetics

Prosthetic limbs can generate an image of a futuristic human cyborg, but prosthetics have a deep history, dating back much farther than one may think. An ancient Egyptian mummy from the fifteenth century BC, was found to have had one of his big toes amputated and fitted with a prosthesis made of leather and wood[13]. In 484 BC, a Persian prisoner was reported to have escaped prison by amputating his leg, and later replacing it with a wooden prosthesis. Essentially, humans have always found ways to replace their lost limbs. Doing it as practically as possible given their circumstances.

While lower limbs provide the ability to walk, upper limbs allow one to control their environment, and more easily interact with the world around them. Part of the reason arms and hands are so useful is because they are intricate, and thus can perform intricate tasks. This is the reason that complex upper limb prosthetics came only after the invention of certain manufacturing practices. In this context, a complex upper limb prosthetic is one that attempts to mimic the intricacies of the hand, in terms of shape and useability. The first complex upper limb prosthetic recorded belonged to a German knight named Götz von Berlichingen in the early 1500s[14]. Later, in 1575, a French artist drew an example of a prosthetic arm which was designed to restore knights be able to engage in battle.

A few hundred years later, conflict still influences the field of prosthetics. In 1917, after World War I, the Association of Limb Manufacturers was established in the United States to help provide prosthetics for the over 4000 amputees from the war. World War II spurred the invention of the body powered prosthesis. These prosthetic devices used the amputees' own body-movements to move the 'hand' which was typically a two-pronged hook. Movements of the shoulder and upper arm pulled and released a cable that opened and closed the hook. This model is called the Bowden cable body powered prosthesis.

A myoelectric prosthesis is one that uses electrical power to move joints in the prosthetic. It detects electric nerve signals in the stump of the amputee, then translates them into the desired movement. The first myoelectric prosthesis, called the 'Russian Hand' had many drawbacks: it was slow, and heavy, and therefore not very comfortable to use.

As humans have more easily accessible, lighter, and better functioning technology, the goal of a prosthetic embodiment: the feeling that the prosthetic is part of their body. To achieve embodiment, prosthetic engineers need to implement a somatosensory feedback loop which includes two essential paths. First, the ability to easily and naturally move the arm and fingers of the prosthetic. This is the most important aspect. The second path is the ability to process and convey sensory information to the brain, or in other words: the ability to feel. While this is not vital to amputee's ability to generally interact with their surroundings, it is essential to embodiment. Sensory feedback lets the user engage in fine motor tasks and feel the world around them with the part of their body that is best for that skill: their hands.

Nervous System Stimulation

Many amputees experience something called phantom limb pain. During this phenomenon, the amputee feels a painful sensation where their amputated limb would be. They are, of course, not feeling an actual sensation in their limb because it has been amputated. The idea that amputees are still able to "feel" in their limb opens up the idea that scientists can manipulate the nervous system in a way in which amputees can "feel" their surroundings again via electric stimulation.

The nervous system is composed of two parts: the central nervous system (CNS), which includes the brain and the spinal cord, and the peripheral nervous system (PNS), which includes the nerves throughout the body. The CNS is split into two parts: the brain, and the spinal cord. There are three areas in the nervous system that have been shown to evoke sensation for amputees: the brain, the spinal cord, and the peripheral nerves. This paper will describe the stimulation of these three parts of the nervous system in amputees.

Types of Stimulation

Brain

Humans feel the objects they interact with through electric signals. These signals start at the place of contact, the hand for example, then travel through the peripheral nerves in the arm, through the spinal cord, and finally to the brain. There are multiple points along this path that can be stimulated to imitate this process. One place to stimulate, is the ultimate destination of the electric signals: the brain.

The cortex of the brain is responsible for the high-level processing of senses. Different regions in the brain are responsible for different senses. The region that controls the sense of touch is the primary somatosensory cortex (S1) (Figure 1). Within the S1, specific regions are responsible for receiving sensory information from different parts of the body. For example, processing of sensory input from the mouth happens in a different place in the S1 from processing of sensory input from the hands.

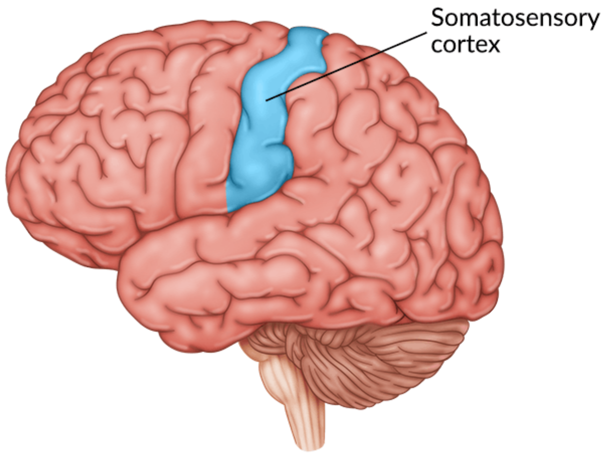

Figure 1[6]

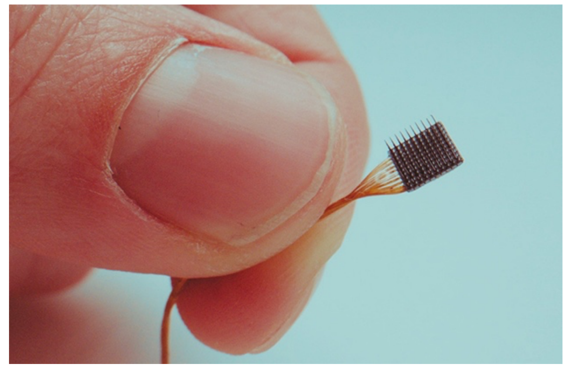

Figure 2[11]

Prior research on non-human primates confirmed that electric stimulation of the S1 resulted in the subjects feeling sensations that were similar to mechanical stimulation of the hand. In 2016, researchers placed two multielectrode arrays (Figure 2) on the S1 through surgical implantation (Flesher). This study included one participant, a male with tetraplegia. The study concluded that the participant felt natural sensation in his hand. Further, it was discovered that the participant was able to feel six separate degrees of intensity of the stimulation when the parameters of the stimulation were changed. These parameters will be further discussed in the Peripheral Nerve section.

Spinal Cord

Before reaching the brain, the sensory signals travel up the spinal cord. In most cases, studies stimulate the cervical part of the spinal cord (Figure 2), which lies in the neck. This is because the cervical spinal cord is connected to the nerves in the arms.

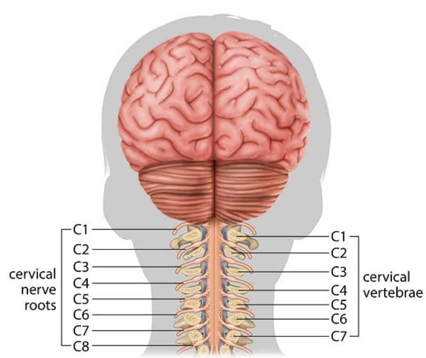

Figure 3[5]

Figure 4[1]

In the context of treating chronic pain, SCS is a very common treatment, thus the implantation of these leads (Figure 4) is also common, with around 50,000 SCS devices implanted annually[10]. Due to this procedure's normalcy, researchers conducted and published a study in 2020 where they stimulated the cervical spinal cord of four participants to see where and what kind of sensations would occur[2]. All four participants consistently perceived sensation in the missing limb, specifically the "fingers, palm, and forearm". Most of the time, the elicited sensation was parasthetic. Parasthetic sensations are tingly and prickly sensations similar to the feeling of pins and needles. However, there were times when the perceived sensation was natural and not parasthetic.

Peripheral Nerve

Before arriving at the spinal cord, electric impulses from the hand and lower arm travel up the nerves of the arm. These nerves are part of the PNS. Stimulation of the PNS has been explored and proven to cause sensation in the phantom limb for amputees. There are three main nerves in the arm that are stimulated during PNS stimulation: ulnar, median, and radial nerves (Figure 5). A study in 2013 implanted flat interface nerve electrodes (FINEs) (Figure 6) on the ulnar, median and radial nerves of two participants. One of which had a wrist disarticulation, and the other had a below the elbow amputation[12]. Because this type of stimulation is not novel anymore, recent studies have focused on how to make the artificial sensations closer to those of a natural hand.

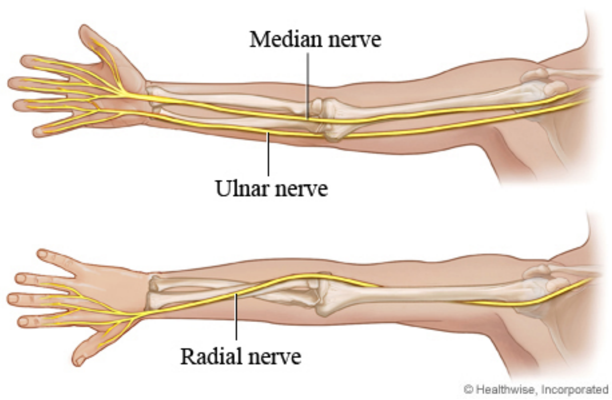

Figure 5[8]

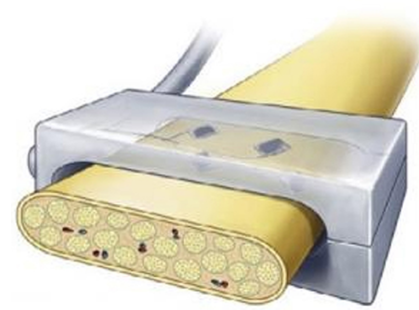

Figure 6[9]

One aspect of sensation that is being researched is the quality and type of sensation. For example, picking up a glass feels very different from petting a dog. The nerves in one's hand send different types of signals to one's brain depending on what is it they are touching. In order to elicit different kinds of sensations, researchers altered the electric stimulation parameters such as pulse frequency (PF), amplitude, and pulse width (PW)[7]. This study also used implanted FINEs in four upper-limb amputees and three lower-limb amputees. While variations of these parameters did evoke sensation with noticeable differences, the participants did not experience sensations they would feel in an everyday scenario. For example, they did not report feeling a specific kind of surface, like a glass or a dog's fur. Instead, choosing from a list of 30 descriptors, they reported sensations described as "tingling", "pressure", or "electric" often. This is due to the fact that the intricacies of the neuronal responses to specific objects are hard to artificially recreate.

Another property which contributes to making artificial sensation feel more natural is the temporal property. To explain, if a peripheral nerve stimulator is implemented into a prosthetic, the amputee may not feel the artificial stimulation at the same time as when they see the interaction happening. For example, if an amputee touches a table in one moment, and their visual perception does not occur at the same time as their sensory perception, the prosthetic feels less like it is part of the user's body. A group of researchers conducted a study to determine if the temporal properties of PNS mimic those of the visual sense[3]. Figure 7 displays that the temporal properties of a natural visual cue and an artificial sensory cue, via the FINEs, are similar. The natural stimulation is represented in orange, while the artificial stimulation is represented in teal. Their overlapping shows that they are perceived very similarly by the participants.

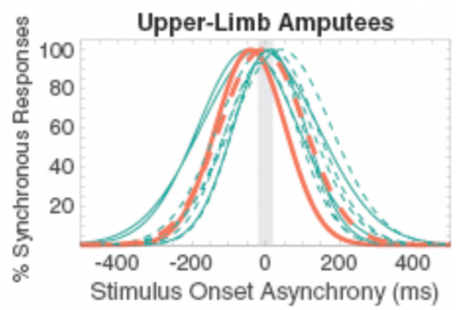

Figure 7[3]

Conclusion

Stimulation of the nervous system in these three ways has proven to elicit sensation in a place that is no longer existent in the human body. However, most of these artificial sensations are noticeably artificial. The way researchers believe they can achieve sensory feedback is that the prosthetic will interact with an object, sensors on the prosthetic will register this object and subsequently send a signal to an electrode in the nervous system, and the electrode will shock the part of the nerve that corresponds to the area that the object touched. One main issue with this idea is that the nervous system is quite intricate, and extensive programming and testing is required in order for prosthetic users to be able to feel all different types of sensations.

Other limitations of this research include invasiveness, sample size, and accessibility. All three methods require surgically implanted devices. Every surgery comes with risks which may deter participants away from these studies. Due to the specific nature of these studies, the sample sizes are quite small. The studies mentioned in this paper range from as little as one participant to only seven participants. Further, if applied in clinical settings, these approaches would be expensive because they require surgical operations, a considerable amount of hardware and software, and rehabilitation.

In conclusion, these different methods of stimulation of the nervous system are representative of the current state of technology in medicine. Throughout history, prosthetics have been used in ways that were hard to control, and did not provide any sensory feedback. Now humans are able to move their prostheses and now humans The idea that amputees will be able to easily feel through an artificial device highlights both the intricacies of the nervous system, and the progression of technology used in medicine.

Citations

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