A review on the current state of neuroprosthetics

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Introduction

Neuroprosthetics are devices that use electrical signals from the brain to mimic the function of another body part. Frequently, these devices are used as a replacement for individuals with amputations or tetraplegia, the inability to move the upper or lower limbs of the body. While the current market has commercially available prosthetics that are an adequate replacement for a limb, the purpose of a neuroprosthetic is to provide full or near full functionality. On a day to day basis, an individual needs to be able to position the hand in space, rotate the hand, and grasp an object. By adding tactile feedback, as well as increasing the degrees in which the arm can move, a patient suffering from loss of limb can have a much more immersive experience. In this paper, we will review the current state of the field of neuroprosthetics, including how they work and how recent advances such as tactile feedback and increasing degrees of freedom can improve them.

Background (Leuthardt et al., 2006)

A healthily functioning brain operates by sending small electric signals called action potentials down nerves to cause movement by creating a muscle contraction. Multiple brain cells work in tandem by sending multiple action potentials to contract and relax multiple muscles and move a limb.

Neuroprosthetics work by “decoding” action potentials and using the signal to control an external device, such as a prosthetic arm. Decoding simply means to detect the action potentials in the brain and turn them into a language that is usable by human-made machines.

Electroencephalography (EEG) is a brain recording method in which electrodes are positioned on a cap that sits on the outside of the skull with no surgical invasion, and can read brain waves that are then processed by a Brain Computer Interface (BCI) controlling a prosthetic. Another method would be electrocorticography (ECOG), which is an invasive method of reading brain signals for a BCI. ECOG involves an array of electrodes surgically implanted beneath the skull. These electrodes can get a better reading of signals from brain cells because they need not travel through layers of bone and skin to be recorded, as is the case with EEG. ECOG requires a permanent attachment to a patient because of surgical implantation, while EEG electrodes can simply be placed on the surface. EEG also reads signals from a larger area (3-5 cm), while ECOG reads from a much smaller region (.5-1 cm). This integration area comes with a significant tradeoff, because the resolution of the neural signal is impaired. An alternate method of brain signal reading is single unit recording, which can measure the electrical response of a single neuron using an electrode array. These 3 methods of recording fall on a spectrum of scope and detail. While EEG can record a large number of cells at a time, they lack the amount of detail provided by a single cell recording. However, a single cell recording reads signals from far fewer cells, and struggles to put together a cohesive signal. ECOG lay in the middle of these 2 methods, being able to read an assortment of cell signals, without sacrificing too much on detail.

A brain-computer interface that evokes tactile sensations improves robotic arm control (Flesher et al., 2021)

The purpose of this paper is to test the effect of intracortical microstimulation (ICMS) feedback on the reaction time and accuracy of patients with neuroprosthetic implants. In the use of a normal limb, tactile feedback is important because it allows humans to exert an appropriate amount of force to grip an object. ICMS feedback involves a bidirectional BCI between the extremity and the brain. One direction sends signals from the motor cortex to the arm, while the other sends signals from the arm to the somatosensory cortex. The returning channel sends signals based on the torque (grip strength) the prosthetic is using to grasp an object, and this triggers an electrode array to stimulate the sensation of tactile feedback in the patient's parietal lobe.

In this study, a patient was set up to do a modified Action Research Arm Test (ARAT) test in order to test their mobility with the prosthetic arm. They were positioned in front of a table with several geometrical objects on the left side. Their task was to use the prosthetic arm to pick up the object and move it to the right side of the table. When ICMS feedback was turned on, patients had a much higher percentage of successful trials, as well as a faster time, with the average time decreasing by around ten seconds, showing that the feedback improved the overall performance of the device. The ability for a patient to experience tactile feedback through an artificial limb is revolutionary because it offers a more immersive experience for the user, and helps replicate a real limb. Future iterations of this project might include more sensors to relay sensations such as temperature, pain, and proprioception.

An Implantable Neuroprosthesis for Restoring Bladder and Bowel Control to Patients With Spinal Cord Injuries: A Multicenter Trial (Creasey et al., 2001)

The study outlined in this paper evaluates the safety and efficiency of a neuroprosthetic designed to manage the bowel and bladder functions of patients with spinal cord injuries(SCI). Some cases of SCI result in loss of bowel control because the sacral nerves in the lower back and pelvic area are no longer receiving signals from the brain. As a volume of urine builds up in the bladder, the patient doesn’t receive the sensation of pressure from the bladder, so they do not know that they need to empty it. When excessive pressure starts to press on the sphincter, it leaks.

The hypothesis is that a neuroprosthetic can help patients relieve themselves while minimizing postvoid residual waste. The neuroprosthetic system used in this study has an internal stimulator that is controlled by an external device operated by the patient. The stimulator includes electrodes implanted onto the sacral nerves, and is wired to a receiver under the skin. The receiver does not require batteries, because it is powered and operated by radio waves from the external device. The patient can then select a program which will deliver the stimulation to the sacral nerves.

All of the patients selected had suprasacral SCI’s and were unable to void waste independently. With 3 months of implantation, 91% of the patients were able to void a minimum of 200mL of urine with the assistance of the device. The prosthetic also helped with control when turned off, as no patient voided more that 200mL of urine when they were not supposed to. Although counterintuitive, this could be due to the prosthetic helping the patient empty themselves more completely, leaving far less residual matter than if the patient were to do it without the device. Since there is less urine in the bladder, there is a longer window of time before the patient risks overfilling their bladder again. Interestingly, this study doesn’t include any interaction between the prosthetic system and the brain. A future direction of this research might include a pressure sensor on the urinary sphincter which signals the brain when pressure reaches a predetermined threshold. The brain would then send a tactile sensation to the bladder via a prosthetic, which would alert the user that they need to void their bladder. This system would also benefit users with tetraplegia, as they don't need to physically activate an external device.

Conclusion

The current state of neuroprosthetics is a hotbed of innovation. This field of research is of great importance because it can significantly improve the standard of living for individuals with tetraplegia, SCI, or other movement-impairing conditions. Future prosthetics will only get faster, more accurate, more portable, and more economical from here. While most prosthetics in the current field do an adequate job of restoring basic function to a limb, the challenge now is to make that limb mimic a natural extremity as closely as possible. This can be done by adding more degrees of freedom, and more sensors for other feedback, such as temperature, pain, and proprioception.

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