“A New Dawn in Neuroprosthetics”:
Scientists create novel systems that cover traditionally science fiction topics: prosthetics and “mind reading”

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In the popular film series *Star Wars,* a character can lose a limb and replace it with a prosthetic device that perfectly emulates the original limb. Similarly, in thousands of science fiction films and television series, people use devices to enhance their brain functions and enjoy superhuman powers. These technologies seem futuristic and fantastic. Now, however, neuroscientists, medical and electrical engineers, and computer scientists around the world are taking gigantic steps towards turning perfect prosthetic limbs and “mind reading” from science fiction to reality.

Scientists across the world are developing new devices that mark the dawn of the field of neurotechnology. Technology known as the brain computer interface (BCI) has shown great potential in restoring mobility to disabled persons, just as the field of prosthetic technology has advanced enough to allow an amputee to regain control of their lives.

Anatomy of the Nervous system

The nervous system has two main parts: the central nervous system and the peripheral nerves. The central nervous system comprises of the brain and the nerves of the spinal cord, while the peripheral nerves are the nerves in the limbs.

The central nervous system is in a perpetual G_0 phase. The G_0 phase of the cell cycle is the period when the cell cannot divide. In most cases, such as in the fibroblasts, cells that help build the structure of animal tissue by generating the extracellular matrix, the cells stay in temporary G_0, but may divide when necessary. The fibroblasts can enter the cell cycle in order to heal damaged tissue. However, the neurons in the central nervous do not replicate without outside physical or chemical influences.

Since the neurons do not divide and replace destroyed or injured cells, researchers have tried other means to restore motility and cure potentially harmful diseases. One of the cures is to repair the output system of the neuron, also known as the axon. The axon is a long fiber-like extension of a neuron that connects to other neurons to communicate action potentials. Neurons communicate in action potentials, which are voltages generated by the neurons. The frequency of action potentials determines the movement or action in the receiving cells. For instance, a greater firing rate contracts the extensor carpi radialis longus, a muscle that helps bring the hand in a clenching motion.

An injury to an axon destroys the extension up to the next neuron. However, if the neuron itself is unharmed, certain stimulatory chemicals can force the neuron to create the axon extension. The technology of brain computer interfaces (BCIs) aims to measure signals in the brain and function as a computer axon to communicate action potentials to the peripheral nerves.

Brain Computer Interface (BCI)

As early as the 1950s and 60s, it was possible to implant electrodes into animals' brains to record and analyze their brain signals. Recent advances in neurotechnology and neuroscience have enabled scientists to create Brain Computer Interfaces (BCIs), computer systems that use electrodes to interpret brain signals and use them to control remote devices. This technology may one day restore motility completely to disabled individuals.

BCIs can be invasive or non-invasive. Non-invasive BCIs use a technology called electroencephalography (EEG), which utilizes electrodes to measure the potentials from the individual's scalp. EEGs measure field potentials, changes in voltage for a large group of neurons, rather than the potential of individual neurons. It can measure these changes at millisecond resolution. This technique has many advantages over other non-invasive techniques, but EEG technology in prosthetics is limited to relatively simple tasks such as moving a cursor on a screen. It also requires extensive user training. In addition, EEG output is susceptible to artifacts, or anomalies inherent in the design and noise in the signal.

In recent years, research has been limited to non-invasive BCIs with EEG technology, but scientists are now experimenting with invasive BCIs. These devices require electrode grids, containing tiny silicon chips with 100 electrodes each, to be implanted directly on the surface of the cortical regions of the brain. This technique is known as electrocorticography (ECoG). Since the grid is mounted directly on the surface of the brain, it is less susceptible to artifacts or other such interference. While neither EEG nor ECoG measure the potentials generated by individual neurons, ECoG has a greater range for accuracy since it measures the field potentials of smaller and more specific fields.

In a study published in the Journal of Neural Engineering in June 2004, researchers showed that the advantages of using ECoG technology for invasive BCIs outweighed the advantages of using EEG technology. The study showed that electrocorticography has greater accuracy, wider frequency range, and requires less user training.

However, invasive BCIs do have their disadvantages. Invasive BCIs have a certain potential for harm to the patient's brain, because of the location of the electrode grid. It can cause harm to the surface of the cerebral cortex, and allows for a possibility for infection, which could happen if the grid is detached from the scalp.

Invasive BCI technology was developed with monkeys, due to the risks inherent in the surgery. In 2000, researchers from Duke University and Massachusetts Institute of Technology used ECoG on an owl monkey to manipulate a robotic arm over the Internet. Duke University researchers trained the monkey to move a cursor to touch a "button" on the screen. The invasive BCI recorded and analyzed the potentials generated in the brain and transmitted them to MIT's Laboratory for Human and Machine Haptics, or the Touch Lab. The signals controlled a robotic arm that used a joystick to touch the "button." The study showed that the brain "could prove extraordinarily adept at using feedback to adapt to such an artificial appendage," (MIT press release) according to Dr. Miguel Nicolelis, an associate professor of neurobiology at Duke University.

In addition to proving the functionality and usefulness of the BCI system, the scientists uncovered important facts about brain structure. According to Dr. Nicolelis, "the brain signals denoting hand trajectory show up simultaneously in all the cortical areas we measured. This finding has important implications for the theory of brain coding, which holds that information about trajectory is distributed really over large territories in each of these areas even though the information is slightly different in each area" (MIT press release). The information derived from this experiment provides a basis for future BCI research.

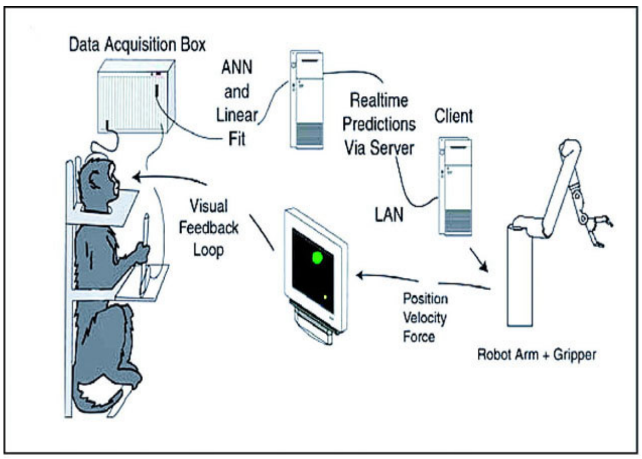


Diagram of monkey experiment, where Data Acquisition Box and other servers are part of BCI

Further implications of this project include the fact that the brain of the monkey "accepted" the robotic arm, in the sense that the robot moved according to the signals. According to Dr. Mandayam Srinivasan, director of MIT's Touch Lab, "once you establish a closed loop that is very consistent, you're basically telling the brain that the external device is part of the body representation" (MIT press release). A closed loop system, also called servo-system, utilizes feedback to come to a decision. The programming of the robotic arm in this experiment creates "a haptic interface – a device that is part of a multisensory virtual-reality system […] that enables us to touch, feel and manipulate virtual objects created solely through computer programs," says Dr. Srinivasan (MIT press release). The virtual world allows the arm to return feedback to the program. The BCI system allows the brain to accept the existence of the robotic arm. Since the signals were in perfect sync with the movement of the arm 600 miles away, it seems a BCI can make sure that the prosthetic arm moves in harmony with the individual's thoughts. In contrast, an open loop functions without feedback. Current prosthetics systems are mainly open loop.

While most invasive BCI technology breakthroughs have used primates as subjects, in 2004, researchers at Washington University in St. Louis used the popular two-dimensional game Space Invaders to test the bounds of invasive BCI function in humans. Dr. Eric Leuthardt, an assistant professor of neurosurgery, and Daniel Moran, an assistant professor in biomedical engineering, devised an interface that allowed a 14-year-old epilepsy patient to play Space Invaders by thought. In Space Invaders, a player controls a movable laser cannon to shoot down rows of aliens that advance down the screen and attack. The researchers found that the patient could master two levels using only his thoughts to control the cannon. This remarkable achievement illustrates the power of invasive BCIs.

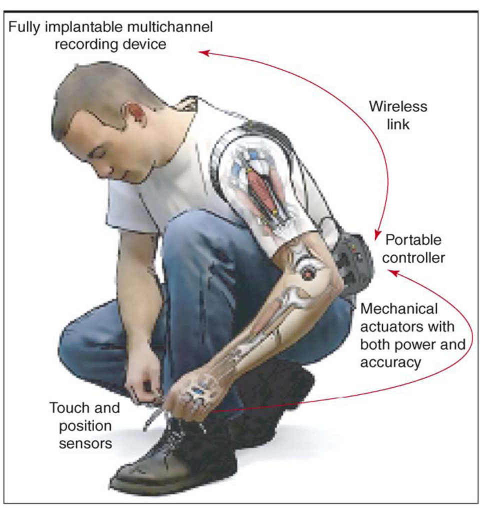


Diagram of BCI and prosthetic link

The diagram shows a futuristic hypothesis as published by Dr. Nicolelis and Dr. Mikhail Lebedev, a senior research scientist at the Center of Neuroengineering at Duke University. Note that the touch and position sensors on the prosthetic arm create the so-called virtual world for the BCI. The system gets feedback from the sensors so that it can allow the brain to come to a decision. This is similar to a human hand because the nerve endings of the hand return feedback to the brain.

In November 2006, Dr. Eberhard Fetz, professor of physiology and biophysics, Dr. Andrew Jackson, senior research fellow of the same, and Dr. Jaideep Mavoori, a PhD in electrical engineering at the University of Washington conducted research on BCIs to develop the Neurochip. This device is an invasive BCI, which recorded potentials communicated by the neurons on the motor cortex. On November 14, 2006, the journal Nature published their 21-page paper titled "Long-term motor plasticity induced by an electronic neural implant." Their device both recorded potentials and induced movements with voltages transmitted over the neurochip. Their study not only suggests the feasibility of such a device, but also demonstrates that motor cortex could adapt to the device. This is a phenomenon known as plasticity. In prosthetic technology, it is almost vital for the motor cortex to adapt the device.

In 2003, a biotechnology company named Cyberkinetics Neurotechnology Systems Inc. built, in conjunction with the Department of Neuroscience at Brown University, the first commercialized BCI known as BrainGate, which helps people with amyotrophic lateral sclerosis (ALS) or spinal cord injury. ALS, also known as Lou Gehrig's disease, is a progressive, fatal neurodegenerative disease that causes the degeneration of motor neurons. It is currently in pilot clinical trials in the United States.

Prosthetic Technology

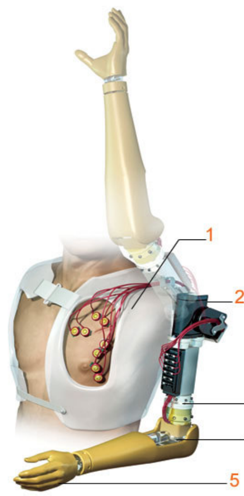
Prosthetic technology is currently the most controversial type of medical technology in the world today. The debate over prosthetics rages over several issues, from societal norms to the very technology. Ideally, a prosthetic device must meet three requirements: it must be easy to learn to use, it must be easy to control, and it must seem within societal norms. Researchers are making improvements on all three frontiers.

Current prosthetics, which use EEGs or no BCI, are relatively clumsy, since they neither move in response to brain signals, nor provide direct sensory feedback to the brain. In the past, prosthetic technology did not incorporate important sensory feedback necessary to emulate human limbs. This works for some prostheses, but not for others. For example, in contrast to foot prostheses, which are easy to use, hand prostheses are complicated to control, especially since they do not yet directly incorporate signals from the brain. Foot prostheses are also generally easier to control than hands, because the human foot naturally needs fewer sensors to function. Hand prostheses are often uncomfortable and may cause frustration to the user.

A prosthetic device should not attract negative attention. Foot prostheses generally do not incorporate toes. However, this is unimportant since foot prostheses are not visible in public. However, hand prostheses cannot fit in societal norms if they do not have a natural shape. The user must not feel segregated from society because of the device. Thus, an artificial hand's design must be aesthetically pleasing, meaning it must have working fingers – a difficult demand. These points demonstrate the different obstacles in designing different limbs, and the difficulty of producing what would be the masterpiece of prosthetics: a fully functioning hand. However, the cosmetic appearance is of less importance than the functionality of the device. The moral justification for downgrading of cosmetic appearance is that the usability of the device is far more important than its appearance.

Finally, the device must provide ease of control to the user. Most hand prostheses are uncomfortable and do not function very well. Invasive BCI technology shows promise in this field. The monkey experiment proved that the technology could accurately move the robotic arm at Massachusetts Institute of Technology from Duke University.

The prosthetic field, coupled with BCI technology, may not have any substantial leaps forward, but in 2002, a $6 million prosthetic device, known as the “Bionic Arm” showed the feasibility of developing high-tech prostheses with the same concepts as a BCI. Jesse Sullivan was a 54-year old lineman when he made contact with a high-powered extension cable that transferred 7,200 volts into his arms, which incidentally is enough to power homes for 9,000 to 10,000 customers. He received third-degree burns and had to have both his arms amputated. He received two standard prosthetic devices. To move the levers controlling his arms, Mr. Sullivan had to press tabs placed under his chin. However, Jesse Sullivan soon became the world’s first “Bionic Man” when Dr. Todd Kuiken, the Rehabilitation Institute of Chicago’s (R.I.C.) director of Amputee programs and Associate Dean of Northwestern Feinberg School of Medicine, and his team at R.I.C.’s Neural Engineering Center of Artificial Limbs (NECAL), used nerve muscle grafts to connect Mr. Sullivan’s arm nerves to his chest muscle. Now, due to the amazing plasticity of the brain, Mr. Sullivan can treat his novel robotic arm just like his original. The device displays a new approach: it uses a 64-bit computer placed inside the device to process signals. It also contains the world’s first motorized shoulder, which is made of aluminum and carbon fiber and runs on a 14.8-volt lithium-ion battery. It has a humeral motorized joint that enables the user to perform tasks around the midline, simulating the signals. Finally, the device contains the world’s first hand that features a motorized wrist. To achieve this goal, surgeons reconnected the peripheral nerves in his arm to his chest muscle. His brain soon recognized the device as its own and controlled the arm with the chest muscle.



Schematic of Bionic arm where 1 – nerve grafts, 2 – shoulder, 3 – humeral rotator, 4 – computer, and 5 – hand

Future of Prosthetics and BCI

As of now, prosthetic and BCI technology are still in trial stage. Jesse Sullivan's bionic arm is far from perfect, though researchers say they will make complete use of the $6 million grant provided to them by the U.S. government.

Likewise, BCI technology is only in its infancy. According to Dr. Steve Perlmutter, assistant professor of biophysics and neurobiology, "the motions and time taken by the [device] are still slow."

Current funding for both BCI and prosthetic technology comes from various private and public sponsors, most notably Defense Advanced Research Projects Agency (DARPA) of the United States Department of Defense. The US Department of Defense also plans to explore the possible use of brain computer interfaces for their fighter pilots.

However, prosthetic technology has advanced considerably. Pressure sensors now provide advanced feedback to the system and the user can achieve some independence.

It is true that the two fields have not advanced to point where amputee could receive a robotic arm that functions and looks like the original. It is also true that epileptics, paraplegics, etc. have not yet earned motility through the brain computer interface. Yet, the advancements in both technologies mean that people with epilepsy, ALS, and other disorders or injuries can hope for a future where their various disabilities no longer matter.

Annotated Bibliography

1. Fetz, Eberhard, Andrew Jackson, Jaideep Mavoori. “Long-term plasticity induced by electronic neural implant.” Nature 444(2006): 56-60.

Dr. Eberhard Fetz, Dr. Andrew Jackson, and Dr. Jaideep Mavoori are professor, research fellow, and student respectively at the University of Washington Institute of Physiology and Biophysics. None of the authors has a financial interest in this topic and therefore the paper has credible data. This paper describes a BCI named Neurochip, which both records and excites potentials in the cerebral cortex. This demonstrated the long-term plasticity of the brain.

2. Leuthardt, Eric, Jonathan Wolpaw, Jeffrey Ojemann, Gerwin Schalk, Daniel Moran. “A brain-computer interface using electrocorticographic signals in humans.” Journal of Neural Engineering 1(2004): 63-71.

Dr. Leuthardt and Dr. Wolpaw participated in the experiment that allowed the epileptic patient to play the game Space Invaders with his mind. While this paper is supplemented by the video of the patient, the paper as published in Journal of Neural Engineering gives technical and background information on the topic. It is credible since both professors work at the Washington University of St. Louis School of Medicine and have no financial interests in this topic.

3. Shenoy, Krishna, Stephen Ryu, Byron Yu, Afsheen Afshar, Gopal Santhanam. "A high-performance brain-computer interface." Nature 442(2006): 195-198.

This resource, published in the journal Nature, describes a project done by researchers at Stanford University School of Medicine. It is credible since these researchers are highly praised and trusted by medical professionals. While most of them are medical students or professors, Dr. Ryu and Afsheen Afshar are engineering professor and student respectively. It simplifies and betters the BrainGate system of collecting data, which uses direct implantation of electrodes on the cerebral cortex.

4. Thomson, Elizabeth. “Monkey controls robotic arm using brain signals sent over Internet.” 06 Dec 2000. Massachusetts Institute of Technology. 28 Dec 2006. <http://web.mit.edu/newsoffice/2000/monkeys-1206.html>.

This resource gave me information on a novel approach to BCIs. The researchers in MIT, working in conjunction with Duke University researchers, constructed a device that moved a robotic arm flawlessly to the field potentials generated by a rhesus monkey. This resource comes from credible source, since it is from an MIT press release. The paper related to the press release was published in the journal Nature in December of 2000. This MIT press release was similar to that of Duke University.

5. Fitzpatrick, Tony. “Teenager moves video icons just by imagination.” Washington University of St. Louis School of Medicine. 09 Oct 2006. Washington University of St. Louis. 11 Dec 2006 <http://mednews.wustl.edu/news/page/normal/7800.html>.

This resource also came from a university, specifically the Washington University of St. Louis School of Medicine. It is of a highly credible source, which is proven by the fact that it is a university press release and contains information that is also available in the Journal of Neural Engineering. This resource gave information on how researchers at the university created an invasive BCI that employed a technique called electrocorticography to attain data to allow an epileptic patient to play the computer Space Invaders without using his hands.

6. Dyer, Nicole. "A Toast to the Bionic Man." Popular Science. Sept 2006. Popular Science. 21 Jan 2007 <http://www.popsci.com/popsci/medicine/6123dc8a25076010vgnvcm1000004eecbccdrcrd.html>.

This resource was published in the technology magazine Popular Science and describes the structure of a device known as the bionic arm. This source is credible since it is supported by government-sponsored Rehabilitation Institute of Chicago, who developed the device in the first place. This article describes the novel techniques employed by the researchers who developed this device. It gives information on the structure and advantages of the new arm prosthetic.

Use of Resources

For this project, I interviewed Professor Steve Perlmutter and Eberhard Fetz of the University of Washington Institute of Physiology and Biophysics. Dr. Perlmutter is an assistant professor that researches and teaches neural motor systems. He gave a dearth of information on the properties and anatomy of the human nervous system. He also talked about the research conducted at the University of Washington and described the advancements made in the neuroprosthetic fields. Dr. Eberhard Fetz is a professor, who is currently researching brain computer interfaces and their uses for prosthetics and/or orthotics. Orthotics is the field of neuroprosthetics where the device supports the weak limb instead of replacing it. He discussed the development of a brain computer interface known as the Neurochip, which is being developed by Dr. Fetz and two other scientists at the university.

I devoted much time to researching in journals such as Nature, Scientific American, and the Journal of Neural Engineering. Knowledgeable researchers that have made major breakthroughs in the field of neural engineering have written the articles in each of these prestigious journals.

I have also worked with an Expo Advisor named Robin Harris. She is a graduate student at the University of Washington that is majoring in biotechnology, neurobiology, genetics, biomedicine, and bioethics. She helped me by editing my papers and sending me information on papers that were inaccessible to me. She is a helpful mentor, who, although we never met in person, seems to share my passion for biomedicine and neurobiology. We communicated via email on Oct. 16, Oct. 26, Oct. 29, Nov. 27, Dec. 5, Dec. 16, Dec. 18, Jan. 3, Jan. 11, Jan. 14, Jan. 16, and Jan. 18.