The development of Neuro-prosthetic Devices

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1 Abstract
While we still know very little of the brain, (despite the many discoveries and advancements over the last decades) neuroscience (and related fields) show promising applications for humans. In this article we will discuss the latest developments regarding prosthetic devices that use brain signals as input. With some historical and theoretical background I hope to give you some insight in the exciting development of neuro-prosthetic devices. I will focus mainly on the recent development of neuro-controlled arms, but I will discuss cochlear implants and Deep Brain Stimulators as well.

Keywords: neuroprosthetic, cochlear, deka-arm, John Hopkins APL, EEG, ECoG, LFP, Single-unit recordings

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3 Introduction

For as long as humankind existed, we have used tools to overcome problems. We use sharp objects to cut, long objects to extend our reach and small objects to improve our precision. These objects have become increasingly complex and varied in their application.

When a person is injured, ill or hurt, our medical knowledge and applications will help to restore the damage that has been caused by these diseases and injuries. In the case of the patient losing a limb or suffering any type of nerve damage, the damage cannot be fully repaired. For centuries, the medical world could offer nothing more than crude solutions, in the forms of wheelchairs, wooden legs and hooks. While these solutions have been refined and improved to provide a better replacement for the bodily functions that have been lost, a real remedy for these types of injuries was yet to be found. In recent years however, mankind is close to developing (and, in some cases, already have developed[16]) real applications to give these patients a vastly improved quality of life. In this paper, I will focus on the development of neuroprosthetic limbs, and the devices used to read signals directly from the brain.

The biggest challenge of developing neuroprosthetic devices can be nicely condensed into a haiku by Rahul Sonnad in 1998:

There is a chasm
of carbon and silicon
the software can't bridge

The Brain machine interface, the communication between brain and machine, is where nearly every aspect of neuroprosthetic devices is centered around. Whether it is recording signals, interpretation of signals, or sensory feedback and adaptation, all of those aspects require and desire clear communication between brain and machine.

First, I will discuss the place of the subject within the field of Cognitive Artificial Intelligence. I will then examine the complexity of the brain, and put the subject in perspective. After that, I will discuss current BMI applications. Next, I will dive into the technical details by first discussing the fundamental components of a brain machine interface neuroprosthetic device.

After I have discussed the technical components needed to make neuroprosthetic devices, I will discuss why a simulation where the sensory input is directly put into the sensory cortexes, is at this point in time, still far from reality. After this I will talk about some of the most recent developments, the DEKA arm, as well as looking into an artificial neural network based-technique for neural prostheses.

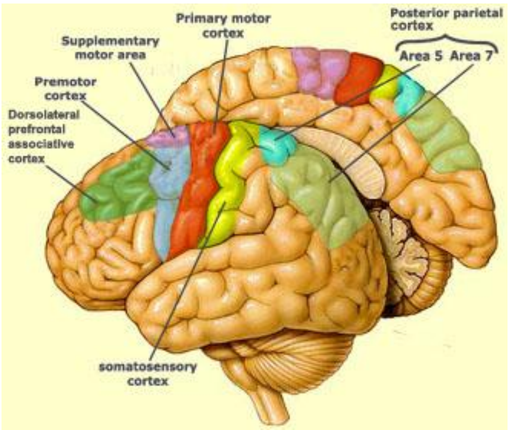
Nearing the end of the paper, I would like to discuss what might be developed in the near future, as well as what could happen beyond that. After that, I will ask the question: “When we have this technology, What are the ethical repercussions?” Finally I will end this paper with a conclusion.

4 Place within the Field of Cognitive Artificial Intelligence

In order for us to make Intelligent systems, Artificial Intelligence scientists often look to the brain for inspiration. In order to make Intelligent systems that operate similar to the brain, we need to know more about the inner workings of the brain. The more we know about the inner workings of the brain, the more the field of medicine can develop solutions and applications that will help patients with all kinds of ailments. Because of these ailments, the medical world has an interest in studying the brain to search for solutions. Neuro-prosthetic devices are part of those solutions. The research that is done by this field of science can in turn be beneficial to the field of AI. Conversely, Research that has been done on the brain in the field of AI can be used to develop medical applications. The cooperation between the world of Medicine and the world of AI can be a wonderful symbiosis.

5 Brain

The human brain is the most complicated biological structure known. Even after decades of research, scientists have yet to figure out just how exactly the brain processes information. "It's a bit like saying after a hundred years of researching the body, 'Do you know if testes produce urine or sperm?'" says neuroscientist V. S. Ramachandran of the University of California at San Diego[16]. "Our notions are still very primitive." However, we do know what region of the brain is associated with what function. We are also able to “read” the brain by looking at the electric discharges. By observing these discharges at specific locations in the brain at specific times during specific circumstances, we are able to make sense of the brain’s activity. The big problem is that whatever findings a new study might have, they are too *specific.* Each individual brain differs a great deal to the next (as one would suspect when we observe the differences in personality, memories and convictions) Not only does the size of each region vary, but the connections between them, (1 quadrillion or 10^{15} synaptic connections) are variable as well. On a low level, we know exactly how individual neurons exchange information. We know that electrical discharge is fired, travels through its connections to other neurons, and if a neuron reaches a certain accumulative action-potential, it fires as well, spreading the signal around. On a higher level however, many processes still remain a mystery.



Areas of the brain associated with motion of the body.

6 BMI neuroprosthetic applications

What a BMI neuroprosthetic device does, is functionally replace the biological signal modality with a technological one.[15] For example, a patient that fails to communicate between the brain and an arm due to spinal cord injury can be outfitted with a BMI neuroprosthetic device. This device will read signals from the motor cortex, use these signals to control the motors in a prosthetic arm, and provide feedback signals to the sensory cortex to allow for a closed-loop control of a robotic arm. Ideally, This BMI neuroprosthetic device would allow for a seamless translation of thoughts into action, with no artifacts or signal distruption, and no invasive maintenance needed. Controlling a robotic arm should be done on a subconscious level, like moving a natural limb. A subconscious way of moving the arm makes the user feel that controlling the arm feels natural and transparent.

Conceptually, any function that the brain or nervous system serves could be implemented by a neuroprosthetic device, provided that it could harness the appropriate signals and direct them accordingly.

With the current knowledge of the field, the following applications lie within the realm of possibility: cochlear stimulation for hearing restoration, spinal cord stimulation for pain relief, and visual system stimulation for blindness. The conceptual underpinnings of these applications is that they directly stimulate sensory pathways to emulate natural signals.

6.1 Cochlear Implants

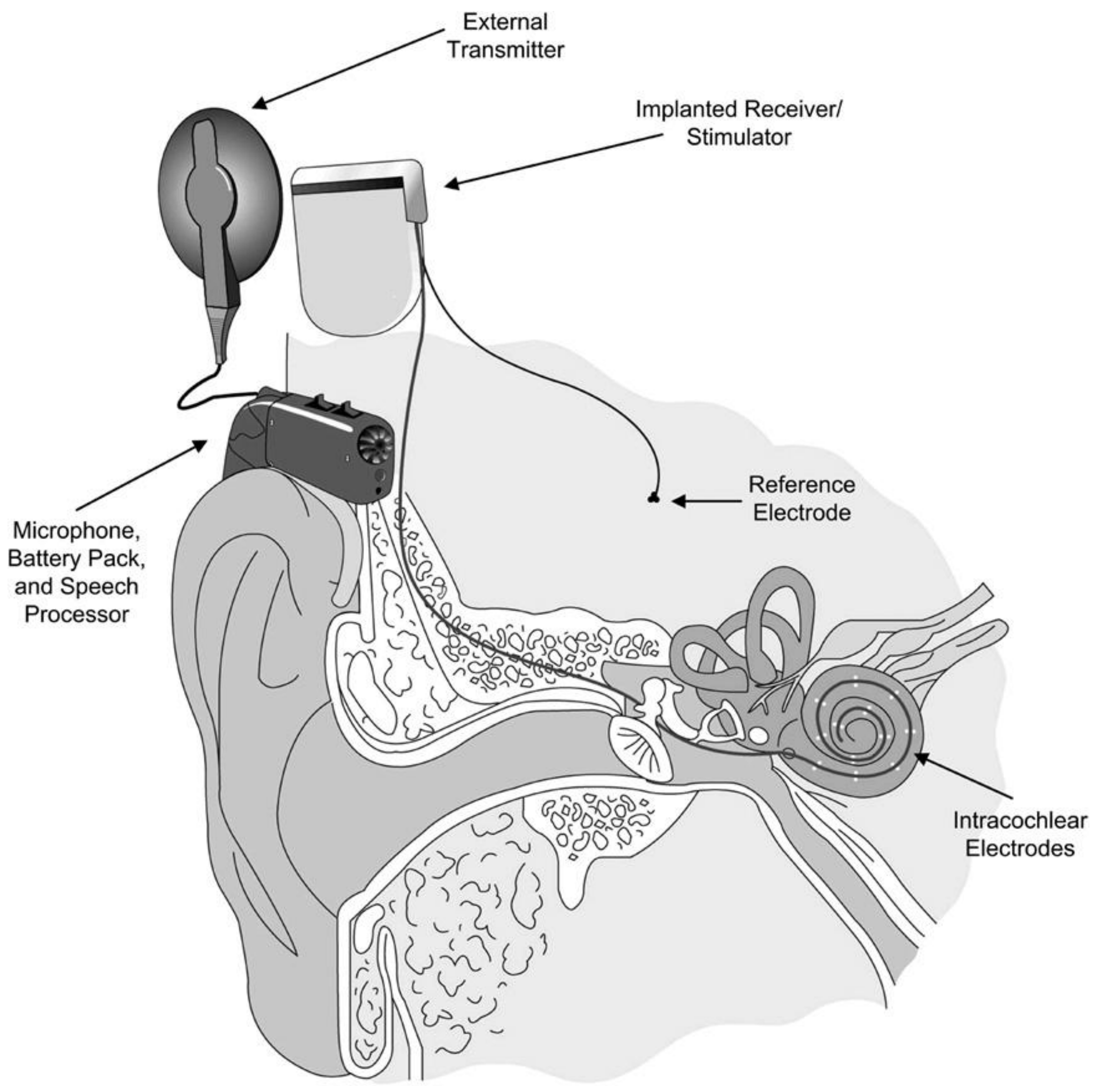
The discovery that electrical Cochlear stimulation could produce the sensation of sound was as early at 1790, when Allesandro Volta (the man who developed the electric battery) placed metal rods and connected them to a 50-volt circuit, experiencing a jolt and hearing a noise “like a thick boiling soup”15.

The first implant of a device for electrical stimulation of the auditory nerve was performed by Djourno and Eyriès in Paris in 1957. An Induction coil was used, with one end placed on the stub of the auditory nerve or adjacent brainstem and the other end within the temporalis muscle (the patient had had bilateral cholesteatomas which had been removed in prior operations, taking the cochleas and peripheral parts of the auditory nerves with them.) While the patient could not understand speech, he could discriminate between (I) large changes in frequenties of stimulation below about 1000 hz, and (II) speech sounds in small closet sets (e.g. three words per set) most likely on the basis of rhythmic cues. As the technology improved, so did the discrimination of different stimuli. Modern cochlear implants are capable of scoring 100% standard sentence material, and asked for more difficult tests. Here is an overview of the development of cochlear implants :

Person(s) or event	Year	Comment or outcome
Merle Lawrence	1964	“Direct stimulation of the auditory nerve fibers with resultant perception of speech is not feasible.”
Blair Simmons	1966	Rated the chances that electrical stimulation of the auditory nerve might ever provide “uniquely useful communication” at about 5 percent.
Harold Schuknecht	1974	“I have the utmost admiration for the courage of those surgeons who have implanted humans, and I will admit that we need a new operation in otology, but I am afraid this is not it.”
Bilger et al.	1977	“Although the subjects could not understand speech through their prostheses, they did score significantly higher on tests of lipreading and recognition of environmental sounds with their prostheses activated than without them.” (This was a NIH-funded study of all 13 implant patients in the United States at the time.)
First NIH Consensus Statement	1988	Suggested that multichannel implants were more likely to be effective than single-channel implants, and indicated that about 1 in 20 patients could carry out a normal conversation without lipreading. (The world population of implant recipients was about 3000 in 1988.)
Second NIH Consensus Statement	1995	“A majority of those individuals with the latest speech processors for their implants will score above 80 percent correct on high-context sentences, even without visual cues.” (The number of implant recipients approximated 12,000 in 1995.)
Gifford et al.	2008	Reported that over a quarter of CI patients achieve 100% scores on standard sentence material and called for more difficult material to assess patient performance. (The cumulative number of implant recipients now exceeds 120,000.)

The modern cochlear implant has the following components:

- Microphone, batterypack and speech processor are fitted on the earshell, as sound is recorded, it is processed and sent to the external transmitter.
- The external transmitter sends the signals through the skull into the implanted receiver. This prevents the need for a physical wire, which would result in a permanent head wound, and as such is very susceptible to infections.
- The implanted receiver/stimulator receives the signals from the external transmitter and generates the current between the intracochlear electrodes and the reference electrode. The reference electrode is placed sufficiently far from the intracochlear electrodes, usually in the temporalis muscle or on the outside of the case for the receiver/stimulator. This is called *monopolar stimulation*. In *bipolar Stimulation* the reference electrode is placed close to the intracochlear electrodes. All current cochlear implants use monopolar stimulation, because it performs as good as bipolar stimulation but it requires significantly less current and thus battery power. A further improvement is that differences in threshold for individual neurons is significantly lower in monopolar stimulation, and therefore it is easier to implement.



The cochlear implant is one of the most successful neuroprosthetic devices in the world today. However, there are still problems with people with compromised auditory brain. Patients who have been deaf their whole lives, for example, have heightened vision and smell because they use the auditive brain cells for smell and vision processing. The person cannot think with sounds because there is simply no sound available. When a modern CI is fitted into these patients, they experience the sounds they hear as noise, and for example cannot distinguish background noises from speech. These people may need a radical new approach to receive signals that are appropriate for their brains. However, with sufficient brain plasticity, patients who are born deaf can still "reprogram" their brain to deal with sound.

6.2 Deep Brain Stimulators

After decades of development, Deep Brain Stimulators (DBS) for movement disorders (i.e., tremor, Parkinson's disease, and dystonia) are in widespread clinical use because of their simple engineering design and ease of implantation. Although Deep Brain Stimulators can relieve a patient of a lot of problems, it can also create new ones. Of the most common cognitive an psychic problems is a decline in word fluency and verbal memory, depression, increased suicide tendency, anxiety, emotional hyperreactivity, and hypomania[below]. There are even cases where the use of a DBS changed their personality completely, for example from a modest gentleman to a gambling womanizer[15]. It is not yet known exactly why these problems occur, and how to avoid that these problems occur. This shows that even with a very successful and widely used application, many mysteries remain to be solved.

7 Components of a BMI neuroprosthetic device

In order for a BMI neuroprosthetic device to work, it functionally needs to translate thoughts into actions. First, it needs to detect a signal that is intended for a certain movement. This detection of signals has to be done in real time, because we want a fluid and natural response from the device, capable of handling any and all movement signals.

This device will need to extract information from the available data, and be able to deal with noise. With this information, a signal must be transmitted to either an internal or an external actuator, so the movement will happen as intended.

7.1 Signal detection

The initial stage is signal detection. A sensor measures changes in a physiological variable at a timescale relevant to the task to be performed. The flow of information in the brain may be observed through diverse physiological changes. Any of these changes may drive a Neuroprosthetic device. At present time, the available sensors work best at processing the electrical fields produced as a result of action-potential neuronal discharges. Electrical signals in the brain may be detected at the level of individual units (single-unit recordings), small populations of neurons (Multi-unit recordings and local field potentials) or large populations of neurons over several square centimeters of cortex (electrocorticography and electroencephalography) I will elaborate on these different types of sensors in the next paragraph.

Detecting electrical signals on a small scale will provide specific detail of the brain's intent. On the other hand, the larger picture of the brain's intent may be lost. If only high level signals are decoded, then the larger picture may be clear, but vital specific information may be missing. In order to construct a control signal in enough detail, both low level and high level signals are needed.

7.2 Information extraction

Once a signal has been detected, It must be interpreted to determine its information content. The information contained within a signal depends on the location of the sensor, the time of recording with respect to an action, and the nature of the signal itself. Because of these factors, the information contained within the same signaling modality can be highly variable. For example, signals that are recorded in a specific brain region and with respect to the task of making a fist may reflect the following: several potential planned movements under consideration by the subject, coordination of the multiple muscle contractions of a single movement, proprioceptive information, or unrelated neural activity constituting background noise. Understanding the identity and nature of signals associated with motor activity is still being researched. In some cases, the recorded signals may only be indirectly related to the actual signals. Particularly if the specific generator of the needed control signal is damaged and only an associated brain region is suitable for recording. In this scenario, learning at the brain or device level may be required to approximate the desired but unavailable signal and to infer intent.

7.3 Neuroprosthetic actuators

With the information interpreted from the sensors, command signals can be sent to the nerves or muscles. In the case of an amputee, the signals can also drive a computer interface. Depending on how sophisticated the robotic arm is, the rate of information needed to make the arm function increases. For example, an arm with 4 degrees of freedom can function with less information than an arm with 25 degrees of freedom.

Now, even with a command signal with a high bit rate of information, this signal still originates only from the motor cortex. Natural movements are not only shaped by the motor cortex. Additional circuits in the basal ganglia, cerebellum and spinal cord shape a natural movement as well. The neuroprosthetic command signals may require additional interpretation and modulation at the actuator, depending on the granularity of the available signal and the actual device intelligence.

7.4 Feedback and adaptation

In any motor control system, errors in measurement, in interpretation, and in execution may be introduced at any stage of the signaling and output process. For a robust and accurate performance, feedback compensation of errors is vital. When the signal is in any way missing or unclear, extrapolation techniques may be used to approximate the actual signal. Feedback may come in the form of a generated signal going to sensory inputs. However, other feedback signals that rely on other forms of stimulus have proven to be effective. For example, the measure of force used on gripping an object with the DEKA-arm is communicated via vibrating motors in the user’s residual limb. With extensive training, the user can properly guess how big the force of the grip is, adapting the grip when needed. Feedback and adaptation may also be applied at the machine level itself. A computer compares the actions of the actuator with the intent signal and adjusts the actions to the intent signal as close as possible.

8 Methods of recording

There are many methods of recording signals, each with its own strengths and weaknesses. I will compare the information content, the scope of the measurement, the level of noise, and invasiveness. I will list and discuss the ones considered for use in neuroprosthetic devices here.

The four main methods are:

Single unit or multi neuron recordings,

Local field potentials

Electrocorticography (or ECoG)

And *Electroencephalography (or EEG)*

It should be noted that without methods of recording that are acceptable in terms of clearness, accuracy and invasiveness, the neuroprosthetic device will fail in its entirety. Simply put, if the people don't want to use it, it doesn't matter how well it functions if they do. Designing good measuring equipment relies more on Nano-technology and related fields rather than knowledge of the brain. It is the foundation on which the other components can build upon, since whatever they might do, They rely on the input provided by these devices. It is the reason why a lot of the research in neuroprosthetic devices is about recording methods.

8.1 Single Unit Recordings

We can measure neurons by the action potential discharge they release everytime a neuron "fires" To record a single unit, a small probe needs to be inserted into the brain at the location of interest. Preferably this is done inside a neuron cell instead of the smaller axon cells, because the neuron cells can fit a probe more easily. The flow of current into the neuronal soma or axon with each action potential has a return path through the conductive extracellular fluid. This produces a current dipole that produces an extracellular electrical field potential. The magnitude of the potential depends on the amount of current flow, the conductance of the extracellular space, the distance of the recording electrode to the dipole, and the orientation of the dipole with respect to the electrode.

A single Probe may record potentials of several hundreds of microvolts from multiple Nearby Neurons. Single-unit recording electrodes (ranging in size from submicron up to 30 to 50 μm) may record potentials of several hundred microvolts from variably sized cortical neurons, and depending on proximity, from multiple neurons simultaneously.

Single unit recordings have the benefit of providing very precise information, since the recording is zoomed in on a single neuron. The drawback of this, however, is that no process in the brain ever takes place in a single neuron, so just recording one neuron will not provide the "full picture".

Furthermore, because a probe has to be placed physically within an area of very delicate tissue, the brain might suffer damage during this procedure. Another big problem with single-unit recordings is the survivability of the signal. Both the probe itself as the neuron can shift, thereby the probe no longer receives accurate information. The neuron itself can be damaged as well. If the recorded neuron no longer produces a signal, recording the signal of that neuron becomes useless.

8.2 Multi-Unit Recordings

To record from multiple neurons in a single region simultaneously, recording electrodes can be organized into multi-electrode spatial arrays. When electrodes are placed within a spatial array, it might be the case that multiple independent neurons contribute to the output of a single recording electrode. To determine which signal came from where, the signals can be differentiated on the basis of action-potential waveforms. Signal processing software has been developed for doing exactly this.

There are many different kinds of materials under consideration in order to make a stable multi-electrode spatial array. Some consider the array to be flexible, if the brain shifts, the array can move accordingly, thus maintaining a stable connection with the desired recording area. Currently, there are few options for a stable, long term recording array that uses bio-compatible materials, therefore human testing has been severely limited.

The benefits of using multi-unit recordings is that the scope of measurement is larger than single-unit recordings, without sacrificing exactness of the signal. Long term, stable recordings have been achieved in non-human primates, but for this to become the norm in human recording, it needs to be a lot safer.

8.3 Local field potentials

A signal is recorded using a low impenance extracellular microelectrode, placed sufficiently far from individual neurons to prevent any particular cell from dominating the electrophysiological signal. This signal is then low-pass filtered, cut off at approximately 300 Hz, to obtain the local field potential (LFP). The low-pass filter removes the spike component of the signal and passes the lower frequency signal. The recording can be functionally described as median recording. The low impedance and positioning of the electrode allows the activity of a large number of neurons to contribute to the signal. The unfiltered signal reflects the sum of action potentials from cells within approximately 50-350 µm from the tip of the electrode and slower ionic events from within 0.5-3 mm from the tip of the electrode. These electrodes may be the same as the ones used with single and multi unit recordings. One thing to note is that the multiple signals of this field may cancel each other out, leaving a net activity of approximately 0. This method is particularly useful for detecting coordinated activity among a small region of the brain, as this yields a high activity in the recorded LFP signal.

The advantage of this method over single and multi unit recordings is that It considerers a whole area of neurons instead of a single or a small group of neurons. However, due to the fact that it is a median recording, information is lost, and therefore it is less precise than the previous two methods.

8.4 Electrocorticography (ECoG)

Local Field Potentials sample the activity a group of neurons within millimeters of the recording electrode. Electrocorticography records the activity of a much larger area, because it is recorded at the cortical surface. An ECoG is much further removed from neurons than the microelectrodes used in LFP single- and multi-unit recordings. As a result, the amplitude of the signal is much lower, and these recordings display much less time-specific resolution. Commercially available ECoG electrodes were designed to monitor epileptic activity over a large area of the brain, instead of focused monitoring of a specific area of interest. The ECoG electrodes can be optimized for this task by using smaller electrodes, preferably 1 mm in size, spaced 1 to 2 mm apart, in a tight array. This setup can be used to monitor a single Gyrus(a ridge on the cerebral cortex).

LFPs, ECoG, and EEG (which I will discuss in the next paragraph) require progressively larger populations of synchronously active neurons to generate a signal, resulting in several advantages and disadvantages for this modality of recording. Neurons are highly stochastic in nature, meaning that in a population, the loss of individual neurons may be frequent. As a result of this, these field potential methods are likely more robust than single-unit recordings (as I discussed on page 10). Likewise, since microscopic motion is less important, and since electrodes on the surface avoid any inherent local brain damage, the neuronal responses of these larger field potential electrodes are more stable over time. Another advantage is that the electronics are simpler due to lower bandwidth requirements, which is another bottleneck when designing individual recording electrodes. The mayor drawback to field potential methods is that because of the integration of may neurons, the spatial resolution is considerably lower, and it is likely that the information content is more limited than single unit recordings.

ECoG, local field potential, single-unit and multi-unit recordings are all very invasive methods. It may take quite some time before they are safe and ergonomic enough to be widely used by humans. However, other, less invasive methods of recording exist as well, two of which we will discuss next.

8.5 Electroencephalography (EEG)

EEG measures brain activity using electrodes on the scalp. It measures the field potential of a great number of cells, and is therefore the most robust method of recording. As with LFP and ECoG, the field potential will be highest when coordinated activation occurs in the recorded population. Because the electrodes are further removed from the neurons it tries to record, as well as skin and the skull blocking the signal even further, the amplitude is even lower than the previously discussed methods. Additionally, because its special resolution is quite low, the information content is likely to be lower. Furthermore, signals from areas of the brain that do not lie within the area of interest are picked up as well. This means that EEG has a lot more noise to deal with. On the other hand, because the signals are integrated over larger brain regions, the electrode design may be less invasive, and the electronics are simpler due to lowered bandwidth requirements. The low invasiveness of this method is a very desirable quality. If the drawbacks of using this method can be reduced, this method has great potential to be used in a BMI neuroprosthetic device.

Several categories of field-potential signals have proven useful in neuroprosthetic applications. These include sensorimotor rhythms, slow cortical potentials, and P300 evoked potentials.

Sensorimotor rhythms between 8 to 12 Hz (μ-rhythm) and 18 to 26 Hz (β-rhythm) are believed to arise from thalamocortical loops, and they are reduced in activity during real and imagined movements. The thalamocortical loop is the functional loop between the thalamus and the cerebral cortex. It is relatively much larger than other mammals.

Slow cortical potentials are EEG oscillations at frequencies below 1 Hz. Movement and other forms of cortical activation result in negative slow cortical potentials, whereas reduced activity is associated with positive cortical potentials.

P300 evoked potentials are positive deflections in voltage that occur in the parietal cortex some 300 ms after presentation of a significant stimulus. The evoked potential does not occur in response to routine stimuli. Subjects have been able to control these fieldpotential signals with training. However, with direct cortical surface recording, much higher frequency responses (up to 500 Hz) can be used to infer brain activity, allowing both a faster response time as well as more direct linkage to ongoing neuronal responses.

8.6 Myoelectric recording

This recording method is for recording motor signals from nerves directly, instead of signals from within the brain. It is widely used in arms where the elbow is still intact, and the residual muscles in the arm still remain. When a person moves his or her hand, the muscles In the arm either flex or stretch, and thus show electrical activity that can be recorded by an electrode placed on the skin. By measuring the activity of multiple muscle groups, it is possible to work out what the intended movement was. Therefore, in the case of an amputation, a mechanical hand can mimic these instructions and perform like the natural hand. This technique has some serious speed and reliability issues[i8]. For instance, a man with a myoelectric arm fitted was stuck on the bus because after grabbing the bar over his head, his arm would not open again. Because of the low invasiveness, this technique is widely used, but it can only be used on patients with sufficient residual muscles and intact nerve endings to the arm. Patients with a spinal cord injury have no use for devices that use myoelectric recording. Other recording methods need to be applied, such as methods discussed earlier.

9 Information Extraction

As I mentioned in chapter 8, the signal detection modality, be it single-unit recordings, Local Field Potentials, ECoG or EEG, is the only medium for information about the task of interest and the brain's actual intent. Therefore it is vital that this medium has a high information content. Bandwidth is of lesser importance, since a pristine signal with low or uninterpretable information content is not useful for a neuroprosthetic application. Each of the different recording methods has a different information content, but because the information extracted is highly disparate, it is difficult to quantify. Although it is difficult to put a theoretical grade on the information content, it is useful but not vital to know exactly how much information comes from the signal. As long as applications can work with the signal to create results, the question what kind of information is stored in the signal becomes of lesser importance. Fortunately, there have been studies and experiments where the results are very promising.

The results of experiments performed by Georgopoulos and his colleagues in the 1980s showed that detailed movement information could be easily recognized in the activity patterns of motor cortical neurons, thus paving the way for the current generation of BCIs. Unlike previous experiments studying single joints, this work, carried out with monkeys trained to make arm movements in different directions, found that the intensity of recorded activity was related to movement direction in a simple, direct, and robust manner. Linear regression in two (Georgopoulos et al., 1982) and three (Schwartz et al., 1988) dimensions showed that these cells were cosine tuned to movement direction, and that this tuning function had a single —preferred direction where the cell fires at a maximal rate. These preferred directions tend to be distributed uniformly. By representing each unit with a vector in its preferred direction, weighting the vector by each cell's firing rate, and summing these contributions vectorially, the direction of upcoming arm movement can be extracted from the population (Georgopoulos et al., 1983). When this is done in small time intervals (10–40 ms), the resulting population vectors correspond to the upcoming velocity of the moving arm (Georgopoulos et al., 1986). This principle—simple linear extraction of movement kinematics—is the basis for almost all current real-time extraction algorithms. Enhancements using linear and nonlinear filters and pattern recognition algorithms are being developed and promise to be more efficient (better prediction with fewer units) than current algorithms. Most of the power from these techniques will likely come from the use of a more elaborate state space model of movement. For instance, most movements are smooth, with minimal jerk, and faster movements tend to be straight. Modeling this information will limit the range of possible predictions made by the extraction algorithm. The combination of these algorithms with new insights into how subjects learn to modify their neural activity when using these devices (see below) is a current research thrust that will become increasingly important as these devices are used for more demanding movements including those of the hand and finger.

New techniques for deriving movement-control signals from populations of recorded cortical activity are being developed rapidly (Brown et al., 2004 and Kass et al., 2005). Extraction algorithms can be categorized broadly into inferential methods and classifiers (Schwartz et al., 2001 and Schwartz, 2004). Empirically derived models are the basis for inferential methods and include the population vector (see above), optimal estimators (Salinas and Abbott, 1994), and linear (Paninski et al., 2004, Wu et al., 2004 and Wu et al., 2006) and nonlinear (Brockwell et al., 2004 and Rojas et al., 2005) filters. Classifiers require no basic understanding of the relation between neural activity and behavior, relying instead on consistent patterns within and between variables (Fetz, 1999) and include self-organizing feature maps (Lin et al., 1997), back-propagation (Wessberg et al., 2000), and maximum-likelihood methods (Pouget et al., 1998, Schwartz et al., 2001 and Kemere et al., 2004). Filter techniques take into account the current and historic state of the ongoing movement, using motor variables that vary in a regular and predictable way. During the time-varying process underlying a motor act, this state model is combined with instantaneous neural activity to update the predicted (intended) movement. Development of more sophisticated state space models will likely enhance cortical prosthetic control (see above). Another important factor in the success of any extraction method is how well the subject can learn to use the algorithm. It may turn out that a simple approach, using, for instance, the population vector algorithm, may be just as, or more, powerful than more elaborate approaches. The demonstrated learning that takes place with these algorithms in closed-loop algorithms is responsible for an increased performance with fewer recorded units (Taylor et al., 2002, Lebedev et al., 2005 and Kim et al., 2006).

Learning, manifest as feedback-dependent changes in neural activity, serves an important role in achieving high performance with brain-controlled interfaces. So far, the feedback signal has only been visual—for instance, a monkey may watch a computer display or robot arm and make online corrections to the movement or improve the cosine fit of the neural activity recorded with the chronic electrodes. However, for natural control, somatosensory input will play a more and more important role.

10 Revolutionizing Prosthetics

The main problem with research in Neuroprosthetics (in fact any research field for that matter) is funding. Developing microscopic recording equipment, extraction algorithms, researching the motor cortex find more accurate recording areas, etc. all requires a vast amount of resources.

In 2005, DARPA started the Revolutionizing Prosthetics 2009 program[]. The goal of this program is to drastically improve the technology of prosthetics. The goal is to give American veterans who have lost a limb during combat a much better prosthetic than what is being given today. DARPA Invested over a 100.000.000 dollars into two main research projects: DEKA’s Luke and the Modular Prosthetic Limb by John Hopkins laboratory. I will discuss these projects in the next paragraph. Otto Brock healthcare, a company based in Germany, has been working on neuroprosthetic arms as well, showing promising results.

10.1 Luke-Arm

The arm is developed by Deka, a company founded by Dean Kamen, best known as the inventor of the segway scooter. Dean named the arm “Luke” presumable after Luke Skywalker, who had a prosthetic arm in the original Star Wars Trilogy. In 2005, at the start of the project, The DARPA representatives gave Dean Kamen a goal: Make a prosthetic device that enables an amputee to pick up a grape or a raisin, and, without looking, be able to tell the difference.

The arm had to satisfy other demands as well. The arm must weigh approximately the same weight as its biological counterpart. Heavy arms can cause such a strain on the patient both physically and mentally, that the user would only be able to wear it for mere hours, not a whole day. The size of the arm had to be similar to a natural arm as well.

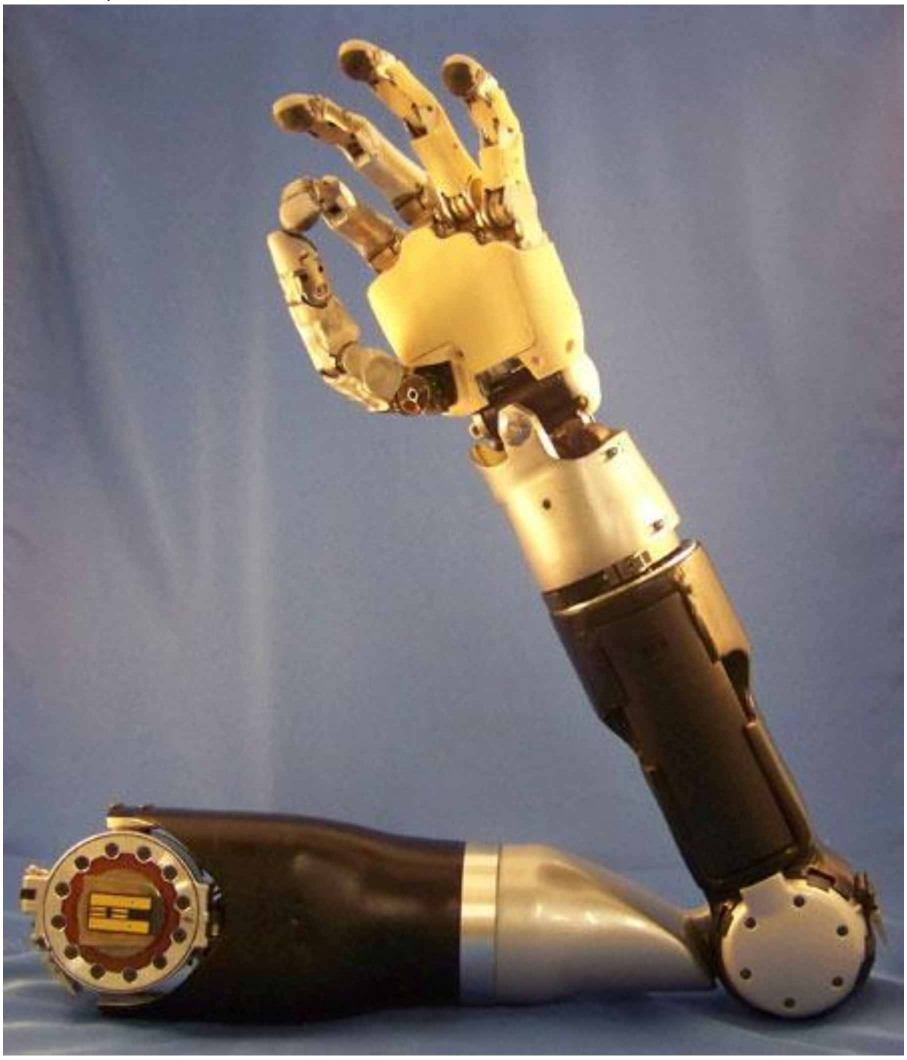
The first prototype of the luke arm was controlled using the remaining muscles on the user’s amputated arm, as well as buttons fitted into the user’s shoes. Later versions are fully controlled by thought alone, needing no additional buttons to use. Myoelectric recording was still used, because of the low invasiveness of the technique. However, myoelectric recordings have some speed, reliability and compatibility issues, as discussed in 8.6. Therefore, the developers are now trying with different recording techniques, for example EEG.

Man wearing the latest myoelectric deka arm, drinking water.

10.2 Modular Prosthetic Limb

Developed by John Hopkins Applied Physics Laboratory[i3,i4], the Modular Prosthetic Limb has 22 degrees of freedom. Each finger can move independently of each other, and has about the same weight as a natural limb. The team will develop micro-arrays of single unit electrodes that record the motor cortex and stimulate sensory cortex of the brain. Awaiting human trials, the team promises restoration of touch sensation, and proprioceptive information, which is the ability to know where you limb is relative to the rest of your body, without the need for visual confirmation. Unlike the DEKA-Arm, the MPL can be used with quadriplegics, people who have lost control and sensation of both their arms and legs(either amputated or nerve damaged). Over the next two years, that is 2011 and 2012, the team hopes to conduct tests with the system on 5 patients.

John Hopkins APL will try to deliver an arm that has a function almost identical to a natural limb in terms of motor control and dexterity, sensory feedback, weight and environmental resilience. This arm has the potential to be the best prosthetic limb in terms of responsiveness and sensitivity. However, we will have to see it to believe it.



The modular prosthetic limb, waiting human trials.

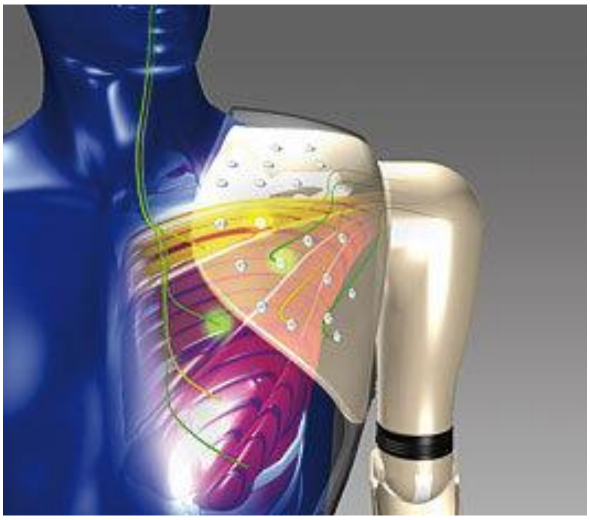
10.3 German Prosthetic Arm

Otto Brock Healthcare, based in Germany, have also developed a mind-controlled prosthetic arm. They claim that it is the first project of its kind in Europe. It uses a technique called Targeted Muscle Reinnervation. TMR is a surgical operation where the nerves that used to control the arm are transplanted to the chest muscles (see the illustration below). When the patient tries to move its ghost arm, the signals will be amplified by the chest muscles, allowing electrodes on the skin to pick up these signals. A powerful micro computer within the prosthesis performs 500 million calculations per second to analyze the signals and determine the movement the patient is imagining. Almost at the same time, the control signals are calculated for the motors, triggering the movement in the prosthesis in less than 80 milliseconds. This lag is still noticeable, but not so bad that patients are unable to use it.

The arm has 3 degrees of freedom. The hand can open and close, the wrist can turn inwards and outward, and the elbow can extend or flex. The batteries are charged every night, and the batteries last the whole day.

The company is already working on an improved model, with 7 joints, and they will use Sensory fibers in the TMR operation as well as the motor fibers they are currently using. This means that the user can have some sense of touch restored, which can greatly improve the somatosensory ability of the user (meaning it can know where the position of the arm is without looking at it) and can for instance feel when the hand hits the table without the need for visual feedback. The sensory project will cost about 3 million euros, and another 30 million euros will be spent on further developing the arm. It will be partly funded from Austrian and American Funding institutions, but the vast majority is funded by the company itself. The first model will be available to the public in late 2010, but it will cost millions of euros. For now, this kind of prosthetic arm will only be available to the rich.

Christian Kandlbauer, the first european with a mind controlled prosthetic arm, picking raspberries without squishing them.



A Schematic rendering of Targeted Muscle Reinnervation.

10.4 Problems with the Neuroprosthetic arm

To use a neuroprosthetic arm, user needs to train with the device. This can be a long, tedious process. There is room for improvement when it comes to training programs. Another problem with the neuroprosthetic arms, especially in the myoelectric arms, is the response time. The natural arm is capable of rapid, fluid movements, with a response time so low that it feels instantaneous to humans (naturally, you don't feel like you need to wait for your hand to move, you just move it). Of course, there is a threshold where the responsiveness becomes acceptable (which depends on the patient's patience) and a threshold where the response is identical to that of a natural arm. The first threshold is absolutely necessary to cross, as there are some patients [16] who prefer a non-electric prosthesis instead of a myoelectric one. The second threshold may be even impossible to cross, only time will tell.

11 Future Work

Although the neuroprosthetic applications that exist today are very impressive, many improvements and optimizations have yet to be made, as well as fundamental research for problems that are currently not solvable by the knowledge available today. First of all, there are a number of developments that focus on the acquisition of signals:

- development of electrodes high bandwidth, capable of large data transfer, as the complexity and number of degrees of freedom of the neuroprosthetic actuator increases, so does the flow of information needed to predict the intended movement.
- Development electrodes that are less invasive.
- Research on the brain as to where to measure to ensure high information content for the task at hand.
- Improved designs of electrodes to ensure low power usage,
- Improved batteries, to ensure a longer survivability of the electrodes
- New designs or placements of electrode arrays, to bring the electrodes in closer proximity to neural targets.
- Detection of peripheral processes, using psychophysical or electrophysiological measures, and selective activation of the processes when present and if possible, to reduce the distance between electrodes and their neural targets.
- Continued efforts to promote the growth of neurites toward implants, to bring the target toward the electrodes.
- Continued development of surgical techniques and adjunctive drug therapies for better preservation of the recording neurons.

While work on the acquisition of signals is important, the information extracted from those signals is important as well. There can be work done in better extraction techniques, such as:

- Work on faster extraction techniques, to facilitate a faster response time, allowing for more fluent and natural movement of Neuroprosthetic actuators.
- Development extraction techniques that are better equipped to deal with signal noise.
- When working with field potential signals, a part of that signal might not be relevant to the task at hand, and developing filtering techniques to ignore these signals can be of great value.
- Development of extraction techniques that can deal with more input, both quantitative (more electrodes as qualitative (more information content per electrode)
- Development of better feedback techniques to ensure an optimal user experience.

On the actuator side of neuroprosthetic devices, a lot of work can be done as well. Areas of interest include:

- Development of fluent movements and expand the degrees of freedom. More degrees of freedom means that even more motors need to be implemented within the same space, while control of more degrees of freedom requires even better information extraction and thus more powerful computing technology.
- Development of a more ergonomic design of the sockets of these arms. If the arms perform excellent, but a user can only wear the arm for short periods of time, the intended improvement of the quality of life is reduced. The ergonomics of the arm has direct effect on the time that patients can use them. Therefore, this area of research is important.
- Batteries and the use of power is also important, as a short battery life directly affects the amount of time the patient can use the arm, no matter how well the arm performs.

All these suggestions might improve the existing design of neuroprosthetic arms we know today. The suggestions regarding the signal acquisition might improve performance of cochlear implants or Deep Brain Stimulators as well. However, the arm of the future might need radical new ideas, ideas that don't build on existing paradigms, but rearranges the playing field, as it were. So far, all the recording techniques focus on the electrical discharge of neurons. However, there many other events that affect the way that the brain processes information, such as the release of hormones and other chemicals. Sensors might also take in consideration the blood flow to certain areas, Furthermore, Magnetic Resonance Imaging (MRI) can look at the brain from a different perspective as well, although no portable ways of MRI exist yet. The Neuroprosthetic arm of the future may use all these techniques at once.

12 Further into the future

So far we have discusses existing technology and the technology on the horizon, as well as where to look on that horizon. However, if we extrapolate from the current technology, we arrive in the uncertain but exciting world of the possible future. One of the techniques that sounds very futuristic is DARPA silent talk16. Currently still in its investigative stage, It tries to map pre-speech signals to specific words. If this is successful, the words can then be transmitted to a teammember, thereby enabling synthetic telepathy. A use for this would a squad of soldiers that try to ambush a certain target, could communicate with each other without speaking, and thus avoiding the risk that the enemy might hear them, thus compromising their position.

As we learn more and more about the brain, we might be able to read minds, Thus eliminating the need for "advanced interrogation techniques" such as waterboarding to get information from the interrogated. Currently, it is possible to use MRI scans and EEG to measure the brain activity of the interrogated when asked questions like "do you know mister X?" or being shown pictures of possible locations of a bomb, for example. Ethical objections can be raised with mind reading, however it is still a much more humane solution than torture.

In the popular science fiction movie *The Matrix(1999)* by the Wachowski brothers, The entire human population are unknowingly living in a artificial dreamworld called the Matrix. People are plugged into this world via a plug that directly inserts into the brain itself. In this dreamworld, touch, smell, vision, sound and heat senses are fooled to believe that the dream world is real. How far is this simulated dreamworld from reality? While recording methods we've discussed so far have uses for a specific task like moving one's arm, to record the *entire* brain at once and process all that information seems highly improbable to be possible in the near future. If not for the basic hardware and bandwidth problems, We still have a lot to learn about the brain before we have extraction techniques capable of interpreting *everything* that goes on in the brain. Furthermore, computing the appropriate input signals to fool the brain it is physically in the dreamworld seems live a daunting task. Although the success of Cochlear implants are an advocate of simulated perception through electrical stimulation, electrical stimulation for simulating vision is still in its very early stages, and is the most important sense to convey the idea of being present in this dream world.

While the difficulties in dealing with both input and output for *one* particular brain is hard enough, imagine the difficulty of doing this for *billions* of people simultaneously, all occupying and manipulating the same space. Furthermore, each brain is different from the next, introducing an extra dimension of challenge. Extrapolating from the current knowledge and expected development, It is realistic to say that it will take many decades before we even come close to develop a dream like simulation as portrayed in *The Matrix.*

If we reach this milestone in technology, however, the possibilities are endless. Within this dream world, just like a modern computer simulation, the parameters can be determined in however the user desires. The imagination of the human mind will be the only limit on the possible simulations of experiences the user can experience. Some users might prefer to reside in this dream world permanently, for example someone who is locked-in in the real world, can move freely in the simulation, therefore escaping the reality of the real world. This technology is so powerful that it can change societies completely. The biggest impact on society would be the shattering of effort vs. reward; why work hard to be smart, charming and successful, if the reward for doing these things can be achieved going into the dream world? This new technology is a lot to think about, but thankfully we will have many decades and many science fiction writers before this becomes close to reality.

13 Ethics

While the neuroprosthetic arms has the potential to improve the quality of life of many amputees and quadriplegics, the arms are still very expensive. This means that in order to acquire such an arm one must have the means to pay it him- or herself or have a large institution (i.e. the U.S. army) pay it for them. The result of this high cost is that people with an average income (and have not served the U.S. Military) will have no access to this wondrous piece of technology. One could argue that children in Africa deserve vaccines to measles just as much as children living in first world countries. The same could be said for a neuroprosthetic arm. After all, it is a device that makes their lives vastly more independent. They would be able to do things that couldn't be done with conventional prosthetics. Is it right then, to only have the rich patients enjoy such privileges?

Another point is more general and can be applied to any neuro-prosthetic device. With continued development of neuroprosthetic-devices, the devices eventually reach a point where they out-perform a normal human being. Let's take the arms for example. Neuroprosthetic arms could become stronger and more agile, and gain prismatic degrees of freedom as well (effectively allowing for variable arm length). These improvements can become of such great importance, that having a neuroprosthetic arm is actually *preferable* to having a natural arm. This creates a dangerous scenario: People with enhancements will have an advantage, and can outperform anyone without enhancements. This can create a group of elite with better jobs, more money and thus more power.

Ambitious people will feel *obligated* to get neuroprosthetic enhancements to compete with the elite, as they too desire power and wealth. In response, the already enhanced elite will enhance themselves even further, thus creating a downward spiral where people are putting so much technology into themselves, that they barely resemble humans anymore.

Another danger lies with performance enhancing Deep Brain Stimulators. If a device were developed that improved the memory, focus and cognitive ability of one using it, to such a degree that a student falls behind in class without the use of one. Richer students become smarter and more successful, poorer students are left behind and can never attain the level that the richer students enjoy.

These new technologies can be dangerous. Applying these new devices should be done carefully and under heavy regulation.

Here are some quotes about the dangers of technology:

The production of too many useful things results in too many useless people. ~Karl Marx

Soon silence will have passed into legend. Man has turned his back on silence. Day after day he invents machines and devices that increase noise and distract humanity from the essence of life, contemplation, meditation...tooting, howling, screeching, booming, crashing, whistling, grinding, and trilling bolster his ego. His anxiety subsides. His inhuman void spreads monstrously like a gray vegetation. ~Jean Arp

If it keeps up, man will atrophy all his limbs but the push-button finger. ~Frank Lloyd Wright

It has become appallingly obvious that our technology has exceeded our humanity. ~Albert Einstein

While these quotes are directed at technology in general, in particular the non-essential technology, it is my personal opinion that medical technologies like the prosthetic arm are a good development. As long as we use these technologies to restore the body, but not enhance it, The use of it is morally just.

14 Conclusion

BMI neuroprosthetic technology will likely change considerably during its evolution from preclinical to clinical studies. The eventual goal is to develop a BMI neuroprosthetic device that will allow seamless translation of thoughts into actions in a manner completely natural and transparent to the user. There are many mountains which have yet to be climbed before this goal is realized however. The understanding of the neural codes underlying intention and action is still in its infant years. The development of a biocompatible electrode with the ability to deliver long lasting, low-noise signals from relevant regions of the brain may take a while to perfect. The same can be said about the operative techniques used to implant them. These techniques can be improved upon so that implanting a device is done reliable and safely. The neuroprosthetic arms that are being developed today are a milestone of human achievement. While there is still a lot of work to do and research to be done, a functioning mind-controlled robotic arm has moved from the realm of science-fiction to the realm of science-fact. As development continues, we will be better equipped to control what happens with our brain. The question remains if there is enough commercial interest in developing these devices. When this is the case, we as human beings must not only look at the question of what is achievable, but what we actually want to achieve.

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