Incorporating External Bodies into the Internal Representation of the Human Body via Brain-Machine Interfaces

Manuel Perez (mperez37@gatech.edu)
Graham Wright (gwright31@gatech.edu)
Kamron Pobst (kgrp@gatech.edu)
Sarah Alsmiller (salsmiller3@gatech.edu)
Chris Shaw (cshaw33@gatech.edu)
CS 3790, Georgia Institute of Technology, North Ave NW, Atlanta, GA 30332

Abstract

One of the most exciting fields of research in biomedical engineering is the development of prosthetics that can be controlled as, and feel like, human limbs. Brain-machine interfaces facilitate communication between the brain and an external device, such as a prosthetic, by monitoring the user's brain activity and controlling the prosthetic according to user's intentions (Tankus, Fried, and Shoham 2014). The internal representation of the body is a schema that allows the mind to transform tactile sensory inputs, such as temperature, vibration, and pressure, into an understanding of the location and current movement of our bodies. In this way, the internal representation allows us to control different parts of our bodies and interpret the sensory inputs we receive from them. Therefore, learning how to use a brain-machine interface to control a prosthetic requires adding the prosthetic in question to the mind's internal representation of its body through either incorporation to, or extension of, the body representation (Preester and Tsakiris 2009). Recent research shows that the mind has the ability to even incorporate bodies that do not resemble the human form into its internal representation. The following paper documents the state of the art in the addition of external bodies that do not resemble the human form into the human mind in a range of applications, from tool use (Cardinalli and Frassinetti 2009) to children's games (O'Hara, Sellen, and Harper 2011), presents examples involving primates (Shokur et al., 2013), and analyzes current challenges that must yet be overcome in this field.

Keywords: Brain-Machine Interfaces (BMI), body schema, incorporation, extension, prosthetics, virtual avatars

Introduction and Background

It was not very long ago that the idea of devices that allow communication between a human brain and a machine seemed like something out of science fiction. This idea is becoming a reality. These devices, for which the first experimental demonstration was in 1999, are called Brain-Machine Interfaces (BMIs, or when interacting solely through a virtual medium, Brain-Computer Interfaces, or BCIs) (Lebedev & Nicolelis, 2006). Fundamentally, BMIs are devices that can translate the brain's neural signals into actions that match the brain's intention (Tankus, Fried, and Shoham, 2014). BMIs were originally envisioned as being a means by which to help restore motor functions in paralyzed patients that suffer from ALS, spinal cord injury, or stroke, to name a few (Lebedev & Nicolelis, 2006). It was also hoped that BMIs could provide assistance to amputees. One of the key characteristics desired in BMIs is the addition of the device into the individual's internal representation of their body, allowing the mind to feel as though the interface is a natural part of the body that can be used with little conscious effort.

Figure 1: The device fully incorporated into the patient's internal body schema

BMI Functionality

There are 2 categories of BMIs: invasive and non-invasive. Non-invasive BMIs involve using primarily electroencephalographic (EEG) to measure a patient's neurological activity. Invasive BMIs involve physically implanting electrodes into the brain in either a single recording site or multiple sites. The single recording site implementation views the brain as more modular while the multi-site recording implementation views the brain as more of a distributed network. In both cases, the electrical activity of the patient's brain is measured and then an attempt is made to interpret the signals as a desire to perform a particular action (Lebedev & Nicolelis, 2006).

More recently, BMI functionality has been extended to speech reconstruction aids, direct object control, and decoding internal mental processes (Tankus et al., 2014). Speech BMIs can include either communication through writing or direct decoding of speech intentions (Tankus et al., 2014). Direct object control involves moving objects without making an associated movement of one's limbs. Decoding internal processes refers to the decoding of sensory perceptions such as vision and the decoding of user decision-making processes which is useful because it helps the BMI to learn the patient's neural feedback patterns and thus be better able to accurately interpret patient neural activity.

Looking Forward

The long-term vision for BMIs is for them to act and feel as though they are a part or extension of the patient's body (Lebedev & Nicolelis, 2006). The accomplishment of this level of machine-body synthesis has not yet been realized. Recent research, however, indicates that the use of experience-dependent plasticity may be able to incorporate a BMI, such as a prosthetic limb, directly into the internal body schema of a patient's brain (Lebedev & Nicolelis, 2006). This does not necessarily need to be a prosthetic. Non-invasive BMIs and invasive BMI implants both need to also be integrated into the patient's body schema.

As far as prostheses are concerned, integration into the body schema means that the prosthesis feels and operates exactly like a human limb (e.g. arm or leg). For other types of BMIs, however, the meaning is more subtle. For example, an implant in an ALS patient that assists in regaining and maintaining motor control should produce movement and create a sense of command over the patient's body that is consistent with normal bodily function. Some of the other key challenges currently facing the development of BMIs includes gaining a better understanding of long-term electrical activity in the brain by obtaining stable, long term recordings of neurons and the development of more efficient algorithms that are capable of controlling more sophisticated BMIs (Lebedev & Nicolelis, 2006).

Higher Level Processes A particular facet of some of the most recent research involves expanding what is typically thought to be the boundary of the field of BMIs to include higher-level cognitive processes (Tankus et al., 2014). This includes things such as working memory, attention, and mental processing networks (Tankus et al., 2014). The trouble with this approach, however, is that it cannot be applied to non-humans as it involves attributes that non-humans are not thought to possess (Tankus et al., 2014). This challenge is related to the previously mentioned extension of BMI functionality into areas such as speech reconstruction. In performing these studies, the intracortical electrical activity of individual cells and larger cell groups is observed in humans that are awake (Tankus et al., 2014). The hope is to understand the big-picture of patterns of activation in the brain while it is undergoing high-level cognitive processes, especially processes that do not include motor output (Tankus et al., 2014).

Measuring Brain Activity

Figuring out an adequate way to implement a BMI is a major issue. Namely, it is important to know how the machinery actually is going to be integrated into the body. You could design a system in which electrodes implanted into the brain directly measure neural activity, but such a design is invasive and poses significant risks. Alternatively, you could place electrodes on the scalp and measure brain activity using electroencephalographic (EEG) signals (Ubeda & Iañez & Azorin & Perez-Vida 2013). As noted earlier, this is the difference between invasive, and non-invasive BMIs.

Non-invasive techniques are further categorized into endogenous and exogenous. Exogenous techniques rely on the fact that the brain reacts differently to different external stimuli. The BMI is controlled by prompting the brain via stimulus (Ubeda & Iañez & Azorin & Perez-Vida 2013). Alternatively, endogenous techniques focus on internal mental stimulation, or the imagination. Similarly to the way the brain reacts in distinguishable ways to external stimuli, different regions of the brain will activate when the brain imagines different actions or stimuli (Ubeda & Iañez & Azorin & Perez-Vida 2013).

Feasibility In order to test the feasibility of the endogenous technique, researchers had participants imagine circular movement of first the left arm, then the right arm. The EEG activity in each patient during these mental activities was recorded and plotted using Matlab. When a new trial was recorded, it was compared against previous EEG mappings (Ubeda & Iañez & Azorin & Perez-Vida 2013). Participants then were asked to perform sessions in which they were required to move a cursor on a screen using the left and right mental activity recorded earlier. They were required to hit a left and a right target using this technique. While the participants were generally able to hit the right target, they struggled to reach the left target (Ubeda & Iañez & Azorin & Perez-Vida 2013). These results suggest that there is a bias towards the left side of the brain in BMI's, however this study only had 4 participants and should not be considered statistically representative.

Notably, the endogenous technique was not accurate enough to give participants the exact trajectory they were envisioning in their minds (Ubeda & Iañez & Azorin & Perez-Vida 2013). However, their experiment was enough of a proof of concept to know that perhaps someday BMI’s will have a simple plug-and-play set up.

Incorporation vs. Extension

The internal representation of the body is a schema that allows humans and other animals to interpret somatosensory inputs such as temperature, pressure, pain, and vibration that originate in different parts of the body (Cardinalli et al.). Without the schema, the mind could not understand what part of the body is exposed to the stimuli it is receiving, and thus would be unable to react appropriately (e.g. not knowing where an injury is inflicted). Another, equally vital, function of the body schema is to allow the mind to understand the position and movement of all parts of the body. Both functions are vital when it comes to receiving feedback from, and sending commands through Brain Machine Interfaces.

Body Schema and Plasticity

The mind can only learn to use the BMI due to the plasticity of the body schema, meaning that it is able to change as the body itself grows and changes, and that it is also able to add new bodies. In a survey of research in this field, Preester and Tsakiris (2009) classify this process as either body incorporation or body extension. They conclude that the human mind seems to have a hard-coded body schema that constrains the amount of objects that make the body "complete". They state that an object can only be incorporated if it enforces the "completeness" of the body schema, such how a prosthesis can replace a limb. It is important to note that there is no proof that the prosthesis has to function like the limb it replaces in order to be incorporated, but simply satisfy some general requirements. Preester and Tsakiris (2009) extend this argument to people with BIID (body integrity identity disorder), who sometimes do not feel a "complete" body until after an amputation of one of their limbs, saying that these people may have a different body schema (one leg instead of two, for example). In general, incorporation implies that the mind is not constantly conscious of the existence of the object, which is what is usually considered the holy grail of BMI's.

Body extension, on the other hand, is an addition to the body schema that only temporarily changes the somatosensory representation of the body, and is additional to the natural, "complete" body.

Extending Body Schema

While body incorporation is used for prosthetics, which are replacing missing body parts and filling empty slots in the body’s schema, other types of BMIs act as an extension of the body. However, there may be some degree of temporary incorporation whenever body extension is reinforced even for a short amount of time, as shown in a 2009 study on the effects of tool use on the body’s schema (Cardinali et al 2009). As a part of this study, blindfolded participants were asked to locate the midpoint between two points relative to their own arm, both before the experiment using a mechanical grabber and after. Results consistently showed that participants located their perceived midpoint further away from their elbow after the experiment was over, indicating that there was some degree of incorporation of the mechanical grabber into the schema of the participant’s arm. This connection exists as a necessary link to the extension of the schema by which the brain understands how to use the mechanical grabber, and allows for mastery over time by creating memory of how to use the tool. The use of this mechanical grabber can be classified overall as an extension rather than an incorporation because there is not a part of the body’s schema designated to the use of the tool. While BMIs attempt to shorten the distance across neural pathways to allow a brain to control an external machine, non-prosthetic BMIs are still classified as extensions rather than incorporations, because there is no slot in the brain’s schema for the BMI.

Dual Purpose The fact that BMIs can act as either an extension or an incorporated prosthetic has several implications. In the same way humans are able to learn new abilities using tools with their hands or feet, new abilities could be learned by brains to operate in new ways, possibly thinking an equation and getting a solution from a BMI or performing visual image searches or facial recognition on memories. It may even be possible to have extended prosthetics, where the normal abilities of a missing limb are incorporated with new abilities in addition, perhaps a watch that only displays the time on a prosthetic arm when the owner wonders what time it is. Outside of prosthetics, incorporated BMIs could include robotic or virtual avatars that imitate the movements, or intended movements, of an individual.

Brain machine interfaces show great potential to revolutionize the way prosthetics work in humans and the ways in which we might extend the body with external tools that do not resemble human body parts.

Computerized Avatars

Another very interesting concept, made possible by brain machine interfaces is the control of an external avatar by using just the mind. This idea introduces a wide range of applications from video games to virtual experimentation. Research on this novel concept has primarily focused on monkeys and their interactions with virtual avatar arms. One such experiment is depicted in Figure 2 (Lebedev and Nicolelis 542).

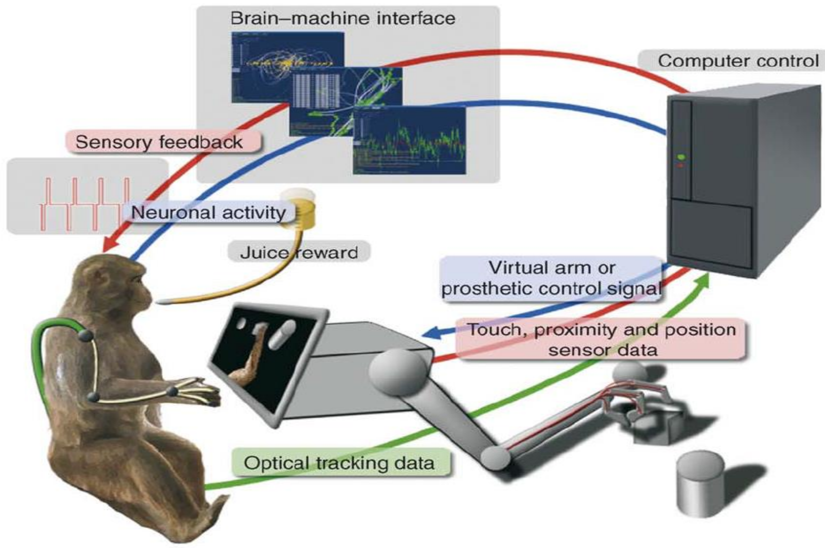

Figure 2: A BMI diagram developed at the Duke University Center for Neuroengineering

BMIs and Primates

First, Lebedev and Nicolelis identify the neuronal activity associated with limb movement in the monkey, allowing researchers to map the activity of these neurons to specific movements in the virtual limb world. This activity is analyzed with the actual movements of the monkey's limbs to train the computer to make an accurate classification of limb movement from neuronal activity. Some type of sensory feedback is then given to the monkey for any situation that the virtual avatar arm encounters a stimulus (such as touching something). This feedback could be a physical touch or direct stimulation of the appropriate areas of the brain. The idea behind this model is that the monkey will begin to include the virtual avatar arm in its body schema, eventually leading to its ability to control the virtual avatar arm without moving its own physical arm.

Feeling Virtually One experiment (Shokur et al. 15121-15126) set out to show that this concept was possible, based on the rubber hand illusion. In this illusion, people start to perceive the hand of a mannequin as their own when their out of sight hand is stimulated at the same time as the mannequin's hand. Results found that this was indeed possible with monkeys. After synchronous physical and virtual touches, neurons from the appropriate somatosensory and motor neurons in the cortex fired from just the touch of the virtual arm, suggesting the addition of the avatar arm into the money's body schema through the plasticity of the brain. Results also found that simply watching the virtual avatar being touched without physical stimulation did not lead to sensations of "feeling" the virtual arm. This procedure of synchronizing physical and virtual touches shows one effective way of encouraging the inclusion of the virtual arm in the monkey's body schema: pairing the touch of an avatar arm with a physical tactile sensation. Utilizing this procedure could prove useful in a wide range of BMIs, as this initial body schema addition is needed to familiarize the user with how to control the body, whether it is a prosthetic, virtual avatar, or external tool.

Mind Game

Brain machine interfaces have shown great potential in the lab, but how does addition of the foreign body to an individual's body schema work in less structured situations such as playing a game that utilizes a brain machine interface?

Figure 3 "Mindflex," a commercially available brain machine interfacing game

BMIs in a Social Setting

One study (O'Hara, Sellen, and Harper, 353-362) explores the techniques that various human participants try in order to assert control over the brain machine interfaced object. In this study, participating groups of people played "Mindflex," a commercially available brain machine interfacing game. A wireless headset placed on the head of the player records the electrical signals (by EEG) from the brain to measure the level of concentration of the player. One player "wills" the ball to rise, while the other provides an opposing input which raises or lowers a floating ball, with a higher concentration leading to an increase in the ball's height. Unlike sophisticated brain machine interfaces, this measure of concentration simply focuses on gross brain activity, but this is to be expected for a relatively cheap consumer toy. While not as precise as brain machine interfaces tested in labs, Mindflex provides a medium through which social interactions can be observed in naturalistic environments. Finally, the player can move the ball through the obstacle course with a control knob.

Emerging Techniques From videos of the participants playing, researchers noticed many different techniques emerge. To concentrate, some participants clenched and unclenched their hands and others gestured to the ball by raising their hands and body to show their intentions and hopefully translate this to the ball. To lower concentration, people tended to look away from the ball. Multiple participants acted as if they were trying to pass "energy" to the ball to get it to rise in height. In the absence of a type of conditioning to integrate the Mindflex ball into the body schema of individuals, people attempt to connect with the ball using body gestures, variable attention, and intentionality. Similarly, primates were moving their arms while controlling the virtual avatar until they had fully integrated the virtual avatar arms into their body schemas. Perhaps focused training with the Mindflex toy could produce accurate control of the ball without a need to gesture, but this is a topic for further study.

Incorporating New Senses

The body schema can be extended to, or incorporate, new objects, but what about new senses? Experiments suggest that it is possible to interpret new inputs from the environment in the same way that temperature, pressure, vibration, and pain already are. Thomson, Carra, and Nicolelis (2013) equipped mice with a head-mounted infrared sensor that stimulated their somatosensory cortex via intracortical stimulation, and they observed the mice rapidly learn employ this new form of stimulus to explore a maze and distinguish between different sources of infrared light. The infrared sensor is an instance of a sensory neuroprosthesis, which are a type of BMI receiving increasing focus as a way to restore lost senses in the blind and deaf.

However, as with the mice, the availability of additional senses to human beings could have significant applications. Currently, computers process sensory information, such as with cameras, at much slower rates than human beings. Due to massive parallelism in the brain, humans are able to quickly draw out useful information from stimuli. Use of these BMI's could allow us to thus replace computers with human brains in situations where it is necessary to sense electromagnetic fields or waves outside of normal vision.

Conclusion

Brain-Machine Interfaces hold the potential to extend human functionality by allowing us to control prosthetics, computer avatars, and even obtain new senses. Potential applications would be those that demand responsiveness, flexibility, and complex movement, such as with robot-assisted surgery, remote repair of satellites, and operation of remote oil rigs, along with other tasks requiring a specific skillset, similarly to the way drones are flown by pilots on the ground. Advances have been made in non-invasively recording the gross activity of the human brain through EEG's, which allow BMI's to be used with relative ease. Primates have been trained to control virtual avatars by obtaining feedback in the form of stimulation to their brains, showing that their body schemas have extended to include the non-physical avatars. Humans have also ventured into using BMI's by controlling external bodies that are dissimilar to their own, and mice have even acquired new senses by receiving stimulation from sensors. This is evidence that suggests that further prostheses of arbitrary forms can be successfully included into the human body schema. However, we have yet to reach the holy grail of prosthetics, a prosthetic that feels completely natural to the human mind.

Extensive research will be required to further the development of BMIs, especially focusing on the precise neural responses induced by intentional control of an external body. Additional research will most likely focus on determining the feasibility of hypothesized devices and how they might be adopted outside of a laboratory environment and thus monitored training. As seen in the game Mindflex, a key weakness of primitive BMIs is the lack of precision in controlling the target external body. Improving this precision requires an upgrade to the brain measuring and machine interfacing techniques so that only the relevant brain activity is recorded. This is a serious challenge to cognitive science and neuroscience and will certainly be a topic of study in the future.

Furthermore, it will be necessary to draw a clearer line between the extension and incorporation when adding new objects to the body schema, as only limited research has been done in this area. Current studies suggest that the form of an object is irrelevant in deciding which of the two phenomena occur, but more research is necessary to confirm this (e.g. using prostheses that resemble or are different from the human body). For practical application, the quality of control and feedback in each case must be measured and compared, as well as the effect of training on this performance.

Supplementary Material

Brain Machine Interfaces Video:
https://www.youtube.com/watch?v=pzW5ZV7Kpis

References

Cardinali, L. and Frassinetti, F. "Tool-use induces morphological updating of the body schema," Current Biology, vol. 19, no. 12, 2009.

De Preester, H. and Tsakiris, M. "Body-extension versus body-incorporation: Is there a need for a body-model?," Phenomenology and the Cognitive Sciences, vol. 8, no. 3, 2009.

Lebedev, M. A., and Nicolelis, M. A., "Brain-machine interfaces: past, present and future," Trends in Neurosciences, vol. 29, no. 9, 2006.

O'Hara, K., Sellen, A. and Harper, R. "Embodiment in Brain-Computer Interaction," in ACM CHI Conference on Human Factors in Computing System, Vancouver, 2011.

Shokur, S., O'Doherty, J. E., Winans, J. A., Bleuler, H Lebedev, M. A. and Nicolelis, M. A. "Expanding the primate body schema in sensorimotor cortex by virtual touches of an avatar," in National Academy of Sciences of the United States of America, Mexico City, D.F., 2013.

Tankus, A., Fried, I. and Shoham, S. "Cognitive-motor brain-machine interfaces," Journal of Physiology - Paris, vol. 108, no. 1, 2014.

Thomson, E. E., Carra, R. and Nicolelis, M. A. "Perceiving invisible light through a somatosensory cortical prosthesis," Nature Communications, vol. 4, 2013

Ubeda, A., Iañez, E., Azorin, J. M. and Perez-Vidal, C. "Endogenous brain-machine interface based on the correlation of EEG maps," Computer Methods and Programs in Biomedicine, vol. 112, 2013.