Spring 2017

# Pain as Feedback for Bionic Limbs

Gordon Sachtjen
gsachtjen@yahoo.com

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Gordon Sachtjen
Murray State University

BIS 437 - Bachelor of Integrated Studies

Field of Study in the Social Sciences

May 3, 2017

**Abstract**

This paper looks at advancements made in the area of thought controlled mechanical prosthesis that are being developed for amputees in order for them to regain mobility. It focuses on the brain-machine interface which is hardware and software that is used to control mechanical prosthesis or bionic limbs by sending and receiving signals between the prosthetic and the users mind. There is signaling feedback from the prosthesis to the user that indicates how much pressure is being applied to an object that is being grasped for instance. This paper explores the notion of the value of pain as a warning in the form of artificial feedback to help prevent damage and death to people and posits that pain should be included in the feedback loop so that when, for example, an artificial hand is in imminent danger of being burned the wearer is alerted.

## Introduction

Solutions for amputees and paralyzed people are explored which include new technological advances in thought controlled artificial limbs. A focus on pain is included and considered is the idea of its value and the notion that it should be included in feedback from a prosthetic for the safety of both the prosthetic and the user as part of a more complete integration of the system. The bionic technology also has great promise for helping others besides amputees to regain mobility such as the elderly, the weak and perhaps even paralyzed as shall be discussed further.

The idea of pain is discussed for the reasons of both its natural unfavorable relationship with people as well as its usefulness as a mechanism that reduces damage. Also discussed is a new understanding of a specific type of pain: phantom pain which is pain felt in a limb that is no longer present and really is of an opposing concept to the thought that artificially induced pain should be inflicted even if for a valuable reason. Different aspects of pain are considered including both its very unfavorable aspect to people as well as its value. There is a very strong link between pain and the mind and the body for a reason and the control of pain is of much interest in people's response to pain (Sachtjen, 2016d).

This paper shows the progress that has been made in the field of thought controlled artificial limbs and relates the latest technological advances as well as historical advances leading up to now that utilize brain-machine interfaces (BMI) that can interpret electronic signals generated by the brain and allow the user to cause a robotic or "bionic" limb to actuate. The history of technological advances in the field is reviewed. Integration of thought controlled artificial limbs is of great interest to many people and scientists have thought about this concept for many years. Also discussed is computer software that acts to interpret neural activity of the brain and control the prosthetics as well as to send feedback from the prosthetic to the brain (Sachtjen, 2016d).

An in depth study is made on a number of experimental research projects that are moving toward perfecting the mind controlled bionic limb systems. Included are the notion of less invasive methods of communicating with and recording electronic signals of neural activity in the brain through brain-machine interfaces (BMI). The software that handles the data is reported on here and the feedback from the artificial limb to the user as well. The research presented in this paper will examine research on thought and otherwise controlled robotic limbs, feedback from those limbs to the brain and even the sensation of pain will be presented in this paper and the relationships shall be examined. There are also military applications also that may be considered.

## Thesis

Pain and or fear should be utilized in feedback from artificial limbs to the user in order to ensure that the limbs are not damaged unnecessarily. Considering that an organic limb will be withdrawn from a damage producing experience because the limb's owner desires to end the pain associated with the experience (such as withdrawing ones hand from a hot stovetop to stop the pain will also stop the damaging effect of the heat) but there is a medical ethics question to consider also which asks if ever intentionally artificially inflict pain. When thinking of pain as a two sided coin one realizes that people all obviously want to avoid pain and this is what contributes to its value, as a means of alerting us to the fact that one is being damaged (Sachtjen, 2016d).

## Amputees Issues

In the past a person who had lost a limb, be it any combination of arm to hand or leg to foot were faced with a disability that they would need to deal with for the rest of their life. Scientific advances have been able to reduce the limitations of such disabilities over the years and will continue to do so. Perhaps the science that promotes more mobility for amputees will provide a favorable unintended consequence that might relieve phantom pain as well. Medical advances have come a very long way from peg legs and hooks.

**Brain-machine interface primer**

Lebedev and Nicolelis (2006) discussed the science in their article entitled "Brain-machine Interfaces: Past, Present and Future." They looked at interfaces between the brain and machines as it pertained to artificial limbs via the mind or thought. This article discusses how people can control robotic prosthetics with their thoughts. The authors report on past achievements in the field and detail the current situation and consider bottlenecks that must be overcome in order to have much success in the future. An exploration of the idea that perhaps pain and/or fear may need to be included in the feedback from a thought controlled or bionic artificial limb is appropriate because of the benefit gained in favor of safety of the limb and the user. The title of the article illustrates that BMIs are a work in progress. The authors reported of past research and proposed future areas of study. They intend to encourage further research in order to clear up issues that continue to thwart success while emphasizing that great breakthroughs are not "just around the corner" (Lebedev & Nicolelis, 2006, p. 537). They refer to the brain-machine interface as a BMI and discuss different types of BMIs. The authors detail the principles behind BMI and explain their operational aspects as well as the hoped for future dream of completely functional BMIs. Lebedev and Nicolelis have a vision that they hope will come about in the next couple of decades where many disabled people will be able to “regain their mobility” (Lebedev & Nicolelis, 2006, p. 543; Sachtjen, 2016d).

**Considering Phantom Pain**

Amputees quite often face the very adverse phenomenon of phantom pain. On top of the fact that their limb is missing and the disadvantage that they face while dealing with life they often also feel pain originating from the limb that is gone.

Sherman, Ernst, Barja, and Bruno (1988) show how in the past phantom pain was thought by most doctors to be all in the mind but it has been found out to actually be real. Phantom pain is pain felt by an amputee in the body part or limb that is no longer present. One would automatically assume that the pain is all in the head since there is no limb but that is not to say that the pain is not real and felt as if it was occurring in the missing limb. The title of the article, “Phantom Pain: A Lesson in the Necessity for Careful Clinical Research on Chronic Pain Problems”, emphasizes the fact that more critical clinical research would need to be completed on the subject to help alleviate the long term suffering of patients. The article shows how doctors would encourage their patients into not reporting their phantom pain. The purpose of the article clearly is emphasized as they encourage more research on the subject as the current (1988) state of affairs was hostile and caused patients to suffer. The authors reported on past research, much of which was conducted by Sherman and other associates, providing proof of their concepts through extensive surveys and literature review. The authors compared the “myth” that phantom pain; that it is rare and all in the mind, to the “reality” that over 80% of over 11,000 amputees surveyed reported phantom pain (Sherman, Ernst, Barja, & Bruno, 1988, p. vii). They also report that phantom pain is caused by very real physiological reasons according to experimental evidence. They state that they analyzed the literature and that after adjusting for effects of chronic pain on all patients that there is no evidence that indicates that sufferers of phantom pain are any more abnormal psychologically than the general population (Sachtjen, 2016d).

Sherman et al. (1988) cite the research that they reviewed as they state that there are very few rigorous studies of the efficacy of the various treatments that are used for those who suffer from chronic phantom pain. Treatment techniques have therefore been used that have little or no chance of improving the patient’s condition. A clinician might try out a new treatment based on a guess as to what the problem is and often will publish the treatment method without even waiting for follow-up feedback from the patient as to whether they were relieved of the pain or not on a longer term basis. Clinicians do this based on an initial belief that the pain is reduced but do not learn if the pain reduction continues or not and, as discovered by the authors previously conducted extensive surveys, they find that the pain reduction does not continue for the most part. The authors look forward to clinical reviews that demonstrate efficacy and research that unlocks the secrets of the physical mechanisms that cause phantom pain. Sherman et al. (1988) implore scholarly medical journals to indicate the dearth of articles containing research on the subject that is rigorous and have little follow-up data as doctors who rely on these short studies to treat their patients do not really do a service to those who suffer from chronic phantom pain. Underemphasized however, indeed totally absent in this discussion was any mention of narcotics prescribed as treatment for chronic phantom pain and any resulting addiction issues. One would be very much surprised if no doctor ever prescribed any opiates for treatment of phantom pain. One would wonder if such treatments would have been included in the “treatment does not work” category for the reason of the adverse side-effects associated with addiction (Sachtjen, 2016d).

**Possible paralysis reversal**

At the risk of providing false hope to people suffering from paralysis that they may regain mobility in their lifetime a team of scientists show some movement in that direction. Beginning with the small step of controlling a computer with thoughts in their mind they wrote “We have previously shown that people with long-standing tetraplegia can use a neural interface system to move and click a computer cursor and to control physical devices” (Hochberg et al., 2012, p. 372). This is especially impressive considering the fact that they were not working with a minor case of partial paralysis. “Paralysis following spinal cord injury, brainstem stroke, amyotrophic lateral sclerosis and other disorders can disconnect the brain from the body, eliminating the ability to perform volitional movements” (Hochberg et al., 2012, p. 372).

The article, entitled “Reach and Grasp by People with Tetraplegia Using a Neurally Controlled Robotic Arm” Hochberg et al. (2012) reported that the patients were wired with a 96 channel microelectrode array to their motor cortex. This was done so they could allow the brain to communicate movement signals outside of their body. They described a patient who drank coffee from a bottle using their bionic/robotic arm. A focus again is on whether that robotic arm should continue to grasp a bottle of hot coffee if the heat might destroy the robotic arm. The robotic arm should transmit pain to the user in such cases so that they will move the robotic hand away from the bottle. This exiting development is well related to previous work described by Lebedev and Nicolelis (2006) as they looked at interfaces between the brain and machines as it pertained to artificial limbs via the mind or thought (Sachtjen, 2016d).

Also working in this field and reported in an article entitled "Electrocorticographic Control of a Prosthetic Hand in Paralyzed Patients." Yanagisawa et al. (2014) recorded electrocorticography (ECoG) signals from 12 people during a study. The electrodes were placed on the sensorimotor cortices of each and the subjects were instructed to move or attempt to move their hands and elbows in a number of motions. Some of the subjects had difficulty in producing signals due to amputation or issues with their central nervous system. The data was rigorously analyzed and used successfully by some of the subjects to control a prosthetic arm (Sachtjen, 2016a). They are not sure, however, if the chronically paralyzed volunteers that they studied were able to provide sufficient recordable signal data that would be able to drive a bionic prosthetic partially because "Sensorimotor function was severely impaired in 3 patients due to peripheral nervous system lesion or amputation…" (Yanagisawa et al., 2014, p. 95).

Sachtjen (2016a) writes that the authors find that this methodology is promising to many but not necessarily promising to those with injured sensorimotor cortex of the brain: "…modulations during different movement types were significantly less in patients with severely impaired motor function. In the impaired patients, cortical representations tended to overlap each other" (Yanagisawa et al., 2014, p. 95). Despite the lack of success noted here there was a positive note however, as the researchers report on one patient who was only moderately impaired (and three patients with no paralysis) were able to control a prosthetic arm (Yanagisawa et al., 2014).

**Summary**

Artificial limbs in the past have been very primitive when you consider a peg leg or a hook. BMI prosthetics have improved significantly where most are very human like and are almost indistinguishable from actual human limbs. Many of those in the past were simply appliances shaped like the limbs but not able to be moved. Now there are a wide variety of limbs that can move and be more functional. One example is the blades that some people who don't have lower legs or feet will have a spring like blade attached to each leg and although they don't look very much like regular feet they are extremely functional for running and other athletic endeavors. Another example is an artificial hand and forearm attached to the remaining limb that has moving parts that can function in a number of ways. Myoelectric prosthesis can be manipulated by the wearer utilizing the electrical signals in the wearer's muscles. Sensors on the prosthesis will pick up electrical signals from the muscles under the wearer's skin and will activate such actions as opening and closing fingers turning their wrist and so on. This is a good method for providing the amputee with an opportunity to regain lost mobility and independence. In other cases however, where a person is unable to manipulate the muscles in order to indirectly control the prosthesis other solutions are being sought and will be discussed in further detail in the next section of this paper.

## Brain Machine Interface: Controlling Bionic Limbs by Thought

The solution discussed here is utilizing the hardware and software installed inside the brain and body to enable the sensory motor related parts of the brain's cortex that are usually active in directing the bodies parts to communicate with an artificial limb with robotic controls instead when the natural limb is no longer present. The basic idea behind this is a brain-machine interface or BMI. The difficulty is getting the brain to communicate with the machine and the researchers have been working on this problem. They have been able to open up the skull and insert electronic leads or electrodes on important parts of the brain where the motor functions are or previously were active in controlling motion or movement in the person's limbs. These electrodes and or other hardware and software work as follows: before any attempt to use them to move an artificial limb is made the electrodes will record the motor activity in the brain section that is associated with moving limbs. For example, an electrode placed in a specific spot on the motor cortex will record the electrical impulses that occur when the subject is thinking about extending their pinky finger. It will, of course, also record the electrical impulses it picks up in that area when the person is thinking about retracting their pinky finger. It will continue recording this electrical activity until it has the patterns detailed. Of course it'll do this with the motions of the other fingers and as well as wrist motions and so on. After this recording is completed the brain-machine interface is ready to be connected to the bionic prosthesis. Then the person can again think about making a fist and the information instead of being recorded is actually transmitted from the brain to the electrode and then to the BMI hardware and software that directs the electronic signals to articulate the mechanisms in the bionic prosthesis to move about for functionality as the wearer directs. Whether the prosthesis be a thought controlled one through a BMI biotic limb Myoelectric limb controlled via the signals the user sends to their stump it may be useful to consider the feedback from the limb to the brain. Scientists have been thinking about this feedback and working on enabling the fingertips for example of an artificial hand to tell the brain how much pressure they are applying to anything that they are touching. This is so the artificial limb "not knowing its own strength" does not inadvertently crush something that it is grasping. The exquisite detail that some of today's technology is capable of achieving enables precision to such a degree that autonomously controlled robotic surgeons hold promise of the ability to do surgery better than human doctors in some cases soon and perhaps in all cases in the future as described in and article by Kassahun et al. (2015) entitled “Surgical Robotics Beyond Enhanced Dexterity Instrumentation: a Survey of Machine Learning Techniques and Their Role in Intelligent and Autonomous Surgical Actions.” appearing in the *International Journal of Computer Assisted Radiology and Surgery*.

**Powering the Machinery**

While providing the electrical power needed by the bionic prosthesis may have its issues a whole other set of challenges arises in regards to powering the hardware installed inside the brain when one is opting for less invasive methods of utilizing BMI technology considering that the process historically included removing parts of the skull in order to lay electrode wiring directly onto select areas of the cortex. In their article "Wireless Power Transfer to Deep-tissue Microimplants." Ho et al. (2014) describe a method to wirelessly power miniaturized medical devices implanted in the body. They plan on this method to be used in order to avoid surgical implantation of larger medical devices. Though they are concerned with powering pacemakers and other surgically implanted medical devices this may also be useful for any array installed within the brain to power the recording, transmitting and reception of feedback data hardware.

“We use the method to realize a tiny electrostimulator that is orders of magnitude smaller than conventional pacemakers” (Ho et al., 2014, p. 7974). The authors here describe body implanted electrostimulators that are smaller than pacemakers by orders of magnitude that are capable of being powered wirelessly as they basically take electromagnetic energy from the tissue that it is near. The performance exceeded the needed energy for functionality of a number of implanted devices. They discuss semiconductor implants as well as some challenges as energy transfer works best nearer the surface of the skin (Sachtjen, 2016a).

Their work is to overcome the wireless powering limitations faced when medical devices are deep inside the body (powering them closer to the surface of the skin has not faced such challenges) because of the relatively large size of the mechanisms. They intend to perfect this task utilizing “…a method, termed midfield powering, to create a high-energy density region deep in tissue inside of which the power-harvesting structure can be made extremely small” (Ho et al., 2014, p. 7974).

Ho et al. (2014) continue to work to solve the issues with high-energy devices to harvest energy that can be deeper implanted. This research begins to solve a number of problems in implanted devices for brain-machine interfacing. Preferred would be a totally wireless electrode that would be not only able to be powered wirelessly but to also be able to communicate wirelessly such as a blue tooth device does. This again is with the aim of providing relief for the burden faced by amputees and the paralyzed (Sachtjen, 2016a).

**Effects of anesthesia and historical perspective**

Rampil (1998) discusses in his article titled "A Primer for EEG Signal Processing in Anesthesia." and published in the journal *Anesthesiology* Rampil (1998) discusses in depth the monitoring of EEG while patients are under anesthesia and states the importance of it. In fact, Rampil notes that EEG of sorts was observed in 1875. He shows that EEG is highly susceptible to anesthesia and should be monitored partially in order to be able to gage how deep a sleep a patient is under anesthesia. This article is important in order to learn more of the historical aspect of EEG and some of what can affect EEG signals (Sachtjen, 2016a). Furthermore Rampil (1998) writes:

> “[1] The EEG was first described in 1875 by Richard Caton, [2] a physician in Liverpool, who noted electrical oscillations on the exposed cortical surface of animals. In 1929, Hans Berger, a psychiatrist in Jena, began a series of reports [3] that are commonly accepted as the first systematic description of human EEG. [4] Within 10 years Gibbs and Gibbs noted that the EEG was sensitive to presence of anesthetic agents. [5] The next 50 years brought significant improvement in the equipment that transduces, amplifies, and displays EEG.” (p. 980)

**ECoG and CAM**

In another research experiment Henle et al. (2010) describe a new method to manufacture electrocotricography (ECoG) microelectrodes which has been developed utilizing computer aided manufacturing (CAM) and by 2010 the authors began to apply these new products to study the brain waves for a variety of reasons including monitoring for seizures before surgery as well as future brain-computer interfacing soon for paralyzed patients (Sachtjen, 2016a). The article that they published "First Long Term in Vivo Study on Subdurally Implanted Micro-ECoG Electrodes, Manufactured with a Novel Laser Technology." appeared in the journal *Biomedical Microdevices Biomed Microdevices* and it shows how the researchers continue to test the durability of the electrodes in vivo or as they are used with living subjects over a period of 25 weeks. They found some inflammation of brain tissue but overall the authors were pleased with results that indicated further advances in the future. This is another alternative method of facilitation two way communications between a brain and a machine that promises success in the field (Henle et al. 2010; Sachtjen, 2016a). They also wrote, "…we plan to target clinical applications, such as…brain-computer interface control in paralyzed patients, in the near future" (Henle et al., 2010, p. 59). Using 8-channel electrode arrays on rats for a 25 weeks period they tested the stability of the electrodes. There was a period of less than stable electrical resistance within the first week but after that and until the end of the testing period there was stability (Henle et al. 2010).

"Overall, these findings suggest that the concept of the presented ECoG-electrodes is promising for use in long-term implantations" (Henle et al., 2010, p. 59).

**Similar work**

As mentioned briefly earlier in this paper some success has been had in facilitating the ability for people to regain motive power in their life and presented now is more detail on such advances beginning with work done by Hochberg et al. in 2006 and more by Hochberg et al. in 2012.

In “Neuronal Ensemble Control of Prosthetic Devices by a Human with Tetraplegia” published in *Nature* Hochberg et al. (2006) describes NMPs or Neuromotor Prostheses that propose to replace lost limbs with prostheses that can be controlled by thought via a 96 microelectrode array. They got positive results with a patient who had a spinal cord injury three years previous. They did this “by routing movement-related signals from the brain, around damaged parts of the nervous system, to external effectors” (Hochberg et al., 2006, p. 164) This is yet more evidence of the fact that successful research is happening and producing results that lead to ultimate mobility for paralyzed and amputated people. This is done while still considering the idea of advanced feedback to the brain from the machinery in order to more delicately control the devices. It all becomes extremely exiting and promising when reading that a patient “…used neural control to open and close a prosthetic hand, and perform rudimentary actions with a multi-jointed robotic arm” (Hochberg et al., 2006, p. 164; Sachtjen, 2016a).

Not to be neglected Hochberg et al. (2012) continue the work firstly stating the issue they are dealing with. “Paralysis following spinal cord injury, brainstem stroke, amyotrophic lateral sclerosis and other disorders can disconnect the brain from the body, eliminating the ability to perform volitional movements” (Hochberg et al., 2012, p. 372). With hope Hochberg et al. (2012) write “…our results demonstrate the feasibility for people with tetraplegia, years after injury to the central nervous system, to recreate useful multidimensional control of complex devices directly from a small sample of neural signals” (p. 372).

Furthermore Hochberg et al. (2012) show some more results as they describe the use of a “neural interface system” which is analogous to the brain machine-interface to demonstrate the ability of paralyzed patients to be able to reach and grasp (Sachtjen, 2016a). As quoted earlier in this paper “We have previously shown that people with long-standing tetraplegia can use a neural interface system to move and click a computer cursor and to control physical devices" (Hochberg et al., 2012, p. 372). This second article, also published in *Nature* is entitled "Reach and Grasp by People with Tetraplegia Using a Neurally Controlled Robotic Arm." But beyond simply controlling a computer with their mind a much more important development is described when Hochberg et al. (2012) reported:

> Here we demonstrate the ability of two people with long-standing tetraplegia to use neural interface system-based control of a robotic arm to perform three-dimensional reach and grasp movements. Participants controlled the arm and hand over a broad space. (p. 372)

Again, the neural interface system being analogous to the brain-machine interface providing more hope for a future where paralysis and disability caused by having limbs amputated (or being born with missing limbs) is no longer relevant. Hochberg et al. (2012) also write:

> One of the study participants, implanted with the sensor 5 years earlier, also used a robotic arm to drink coffee from a bottle. Although robotic reach and grasp actions were not as fast or accurate as those of an able-bodied person. (p. 372)

A focus of this paper however is on whether that robotic arm should continue to grasp a bottle of hot coffee if the heat might destroy the robotic arm. The robotic arm should transmit pain to the user in such cases so that they will move the robotic hand away from the bottle (Sachtjen, 2016d).

**More detail**

Described here is how improvements in wireless transmission in Electrocorticography (ECoG) for successful brain-machine interface (BMI) is needed because still (2014) the better devices are large and wired. This is quite on point as the search continues for the most powerful and least invasive devices to record, relay, and transmit electronic signals to and from the brain (Muller et al., 2014; Sachtjen, 2016a). The article cited here is "24.1 A Miniaturized 64-channel 225μW Wireless Electrocorticographic Neural Sensor." and it goes into detail of the ongoing work that strives for less invasive solutions to the problem of communication directly with the motor driving areas of the cerebral cortex. The work is by no means over and suggested is continued research to continue the progress and break through bottlenecks addressed here, "Substantial improvements in neural-implant longevity are needed to transition brain-machine interface (BMI) systems from research labs to clinical practice" (Muller et al., 2014 p. 412). This is partially because the devices are not small enough and not powerful enough as illustrated, "However, today's clinical ECoG implants are large, have low spatial resolution (0.4 to 1cm) and offer only wired operation" (Muller et al., 2014 p. 412).

**Materials**

Quite important in the search for the best methodology of solving the issues addressed in this paper are the materials used in the processes. Kong, Mannoor, and Mcalpine (2015) here describe cutting edge nanotechnology from this article published recently named "Bionic Graphene Nanosensors." Nanosensors have been developed in conjunction with biological systems on a bionic platform by Kong and his team as they work on integration to produce wireless power production and remote readout. They describe proposed uses of the graphene sensors, "… highly sensitive nanosensors, and subsequently biointerfacing such devices onto the body for real-time detection.…biotransfering graphene sensors onto biological systems to enable a unique bionic nanosensor platform…" (Kong, Mannoor, & Mcalpine, 2015, p. 269). Concerned with a wide range of human ailments that this technology could be applied to they look for methods to diagnose adverse human conditions through the exquisite sensing capabilities of the graphene sensors as well as to medicate or treat such conditions. Much promise is held in this technology to learn about deeper functions inside the human mind and body, “The synergistic integration of electronics with biological systems could enable the development of novel sensing devices that could provide new fundamental insights to biomolecular interactions, as well as facilitating the development of novel biointerfaced device architectures” (Kong et al., 2015, p. 269). With much confidence in their research they state, “The graphene bionic nanosensor platform thus represents a powerful new biointerfaced sensing paradigm, with a diverse range of applications” (Kong et al., 2015, p. 269; Sachtjen, 2016a).

**A look back and a look forward**

Penn et al. (1973), forty some years ago, reported on delving into the brain of baboon to record EEG activity directly from the surface of the brain as well as in humans in their article "Intravascular Intracranial EEG Recording. Technical Note.”, which was published in the *Journal of Neurological Surgery.* They report using single and bipolar electrodes that were recording electrical activity from vessels within the cranium of baboons. This is some background or historical information that helps demonstrate the path of progress that has been made Penn et al. (1973; Sachtjen, 2016a).

As noted previously in this paper Lebedev and Nicolelis (2006) studied the history of advancements in the field of BMIs back in 2006 and referred to bottlenecks that needed to be overcome with more research over time. Researchers work tirelessly today to clear those bottlenecks as evidenced by the reporting in this paper and they will no doubt continue to work tirelessly at clearing them up. Again, the idea of controlling an artificial prosthesis that replaces ones hand, for example, with ones mind just as one controls a natural hand with the mind is a superlative accomplishment of mankind. The title of Lebedev and Nicolelis (2006) article, "Brain–machine Interfaces: Past, Present and Future." illustrates that BMIs are a work in progress as authors report on past research and propose future areas of study. They encouraged further research into the subject back in 2006 and indeed much further research has been done and continues to be done. They stated that the breakthroughs were not "just around the corner" (Lebedev & Nicolelis, 2006, p. 537). Now in 2017 researchers are getting closer to that corner however. Sachtjen (2016d) noted that Lebedev and Nicolelis (2006) discussed different types of BMIs and the authors detail the principles behind BMI and explain their operational aspects as well as the hoped for future dream of completely functional BMIs. Lebedev and Nicolelis have a vision that they hope will come about in the next couple of decades (following 2006 so now over one decade of progress has been made) where many disabled people will be able to "regain their mobility" (Lebedev & Nicolelis, 2006, p. 543).

The quest is for less invasive methodology and techniques that can facilitate the functions of recording brain signals and then transmitting the signals from the brain to a prosthetic or a paralyzed limb. This is done in order to control the movements and also to return signals from the artificial or natural limb to the brain in the form of sensational feedback. One recent breakthrough in this field is the utilization of stent electrodes as will be described next (Sachtjen, 2016b).

**Stentrodes**

Written by Thomas J. Oxley and a host of associates, the title of the article, "Minimally Invasive Endovascular Stent-electrode Array for High-fidelity, Chronic Recordings of Cortical Neural Activity." Oxley et al. (2016) and published in *Nature Biotechnology* is extremely appropriate for the reporting done here and the purpose of evaluating the subject. To summarize they work done here it is firstly noted that over this past decade exciting breakthroughs have been made if the field of stimulating and of recording neural brain activities by using electrodes inside the brain but this has been done by opening the skull and applying the electrodes directly onto the brain which is problematic because it causes issues including inflammation of brain tissue. Oxley's team decided to experiment with electrodes on an intravenous stent to settle in a blood vein lying right next to the places in the brain that send and receive electrical signals through the neurons in order to not have to open up the skull so that they can record electrical data generated by the brain. The experiments were done on sheep because sheep have similar sized veins in the areas of the brain that they wanted to study (Sachtjen, 2016b).

The authors refer to the fact that bionics, meaning the use of artificial constructions taking the place of human limbs and other parts of the human body, is advancing rapidly and there is a need for methods of making the brain or mind control these artificial limbs. An important statement the authors make is, "Recently, advances in chronic neural recording devices have facilitated learned, willful control of robotic prosthetic limbs for the treatment of paralysis…" (Oxley et al., 2016, p. 1). Referred to by this team is an article about success in controlling robotic arms by means of neural signals. Again, this has been done only by removing parts of the skull and applying electrodes directly onto the brain. This team wanted to find a way to get the brain signals without cutting open the skull (Sachtjen, 2016b).

**Methodology**

The authors glued tiny electrodes onto wire mesh stents which they pushed through (again, all on sheep) an incision in a neck vein and guided by continuing to feed the wire attached to the stent and viewing x-rays along a path up to the veins around the brain and stopping where the brain vein is laying on the "information rich" areas of the brain that use neural electrical signals to direct the body to move different muscles. The stent electrode that they built and named stentrode is then expanded and becomes like a short tube within a long tube. They measured the distance of the stent outer side to the vein inner side, referred as the lumen, in the vessel wall incorporation sub-section. Often they did get the desired negligible approximate distance here. Then the electrodes on the stent begin to listen through the blood vessel wall to the cerebral cortex beyond the wall much like when ones little sister puts a glass against ones bedroom door and then her ear to the glass when one is talking to ones friends on the phone. The team tethered the stent electrodes by wire as described by Oxley et al. 2016: “We sutured the lead at the common jugular vein puncture site in the neck to achieve hemostasis, tunneled subcutaneously to a custom-made hermetic connector secured to the sternocleidomastiod and exited the skin via a flexible percutaneous lead, which terminated in a microcircular plug” (Oxley et al., 2016, p. 1; Sachtjen, 2016b).

The idea of the experiment was to test to find out if the recording of detailed brain signals could be done over a long period of time without causing any medical problems. They fitted forty-two Corriedale female sheep with the stentrodes and allowed them to move freely for over six months all the while recording brain signals not much like an EEG might. Along the way one sheep had a seizure which they recorded with the stentrodes and injected diazepam and watched the recording of the seizure end as a result. There were also some issues with a small number of electrodes short circuiting because of metal fatigue on the wires when the sheep moved their necks. This is one reason wireless arrays would be advantageous if they could facilitate the same amount of data. Overall, the experimentation seemed to be a great success as they move toward implanting the stentrodes into humans. Oxley and his team consider sending stentrodes deeper into the brain as they search for even more high information areas what they considered high yield targets. They also note here that there is the problem of the wires as they wear out over time because of the neck being moved about and consider a wireless transmitter system but there are none small enough at this time (Sachtjen, 2016b).

**Studies with primates**

Primates here are studied called Macaques in Shimoda et al.'s article entitled "Decoding Continuous Three-dimensional Hand Trajectories from Epidural Electrocorticographic Signals in Japanese Macaques." (2012). They consider the pros and cons of subdural vs. epidural electrocorticography (sECoG vs. eECoG) for brain-machine interfaces (BMI). Since (eECoG) is less invasive they go with that and implanted them into the Macaques for over several months. The goal follows the theme of this paper, "Brain–machine interface (BMI) technology captures brain signals to enable control of prosthetic or communication devices with the goal of assisting patients who have limited or no ability to perform voluntary movements" (Shimoda et al., 2012, para. 1). They found that hand motions of the primates could be recorded continuously over time having successfully implanted the electrodes in the hand motion part of the brain. This is important information that further demonstrates the concept of recording motion data from the brain so that it can be recognized and used to control prosthesis or to stimulate paralyzed limbs (Sachtjen, 2016a). They were able to continue the experiment for some time providing positive results considering that when the systems are implanted in humans they would need to be able to operate continuously, "A steady quantity of information of continuous hand movements could be acquired from the decoding system for at least several months…" (Shimoda et al., 2012, para. 1). They also describe another important aspect which is that of the system not harming the patient, "As one of the safest invasive recording methods available, eECoG provides an acceptable level of performance. With the ease of replacement and upgrades, eECoG systems could become the first-choice interface for real-life BMI applications" (Shimoda et al., 2012, para. 1).

**Recording sensorimotor cortices**

As previously discussed Yanagisawa et al. (2014) recorded electrocorticography (ECoG) signals from 12 people during their study. They put electrodes on each of the subject's sensorimotor cortices and told to try to move their limbs so that the signals from the brain could be recorded. Patients with damage to their central nervous system and other amputee had some difficulty in furnishing the signals needed. Others however were able to successfully control a bionic arm after the data had been meticulously analyzed. They researchers are not sure, however, if the chronically paralyzed volunteers that they studied were able to provide sufficient recordable signal data that would be able to drive a bionic prosthetic partially because "Sensorimotor function was severely impaired in 3 patients due to peripheral nervous system lesion or amputation…" (Yanagisawa et al., 2014, p. 95). For those with an injured sensorimotor cortex of the brain the methodology was not as promising, "modulations during different movement types were significantly less in patients with severely impaired motor function. In the impaired patients, cortical representations tended to overlap each other" (Yanagisawa et al., 2014, p. 95).

One patient who was only moderately impaired (and three patients with no paralysis) were able to control a prosthetic arm (Yanagisawa et al., 2014) and so was reported both negative and positive results.

**Other applications**

Neurostimulators were implanted into patients with seizure disorders in a trial meant to determine the effectiveness of therapy of the subjects. Half of the subjects received stimulation via implanted neurostimulators upon onset of a seizure and the other half did not (Sachtjen, 2016a). This work was detailed by Morrell (2012) in her article named "Responsive Cortical Stimulation for the Treatment of Medically Intractable Partial Epilepsy." and demonstrates other uses of both receiving activity in the brain, in this case seizure activity, and giving the brain feedback, in this case responsive cortical stimulation in order to alleviate the seizures.

Sachtjen (2016a) reported on her results which showed that after 84 weeks those who received the cortical stimulation found their seizures dramatically reduced and their quality of life was significantly improved, “Seizures were significantly reduced in the treatment….There were significant improvements in overall quality of life…” (Morell, Martha J., 2012, p.239).

**Tetraplegia**

Also known as quadriplegia it is the condition of a person being unable to voluntarily move any parts of their body from the neck down. It can happen when one is in a severe accident and suffers a broken neck or spine. It is common knowledge that superstar actor Christopher Reeve suffered such an injury during a disastrous accident that occurred while he was riding his horse. How ironic that the actor who played the Man of Steel in four Superman motion pictures went down and became a man bound to a wheelchair who could speak and move his head and face as he liked but was unable to move any part of his body below his neck. Speak Superman did however as he encouraged more research and more funding for research in the field of reestablishing mobility for others stricken with affliction. It is doubtful that Christopher Reeve spoke out so eloquently for research to help the paralyzed because of a selfish reason so that he might be able to walk or bring a coffee cup to his lips again unaided because the scientific inquiry into solving that problem was not close to a solution. Christopher Reeve died in 2004, less than ten years after his accident and it is reasonable to assume that his activism played a role into more research on the matter such as the discussed now.

An exciting development for a quadriplegic who’s torso and four limbs are all paralyzed is fascinating because it not only tries to help patients to be able to control a prosthetic device but also to be able to control their natural limbs. “Brain-computer interface (BCI) technology aims to help individuals with disability to control assistive devices and reanimate paralyzed limbs” (Wang et al., 2013, para. 1). Working with a person who suffered a C4 level injury to the spinal cord, the scientists recorded electrocorticographic (ECoG) signals from the sensorimotor cortex associated with hand and arm movement. Recording these signals is an important step in the process of reestablishing mobility in either an amputee’s bionic prosthetic limb or a paralyzed person’s limb. Even though this patient was not able to move their hand or arm they did think about moving their limbs and that caused hand and arm movement signals to originate from their cortex and be able to be recorded for future use. A patient with a spinal cord injury is able to control a 3D cursor using his brain when connected to an electrocorticography (ECoG) array in conjunction with a brain-machine interface (BMI). 28 days later the ECoG grid was removed and there was no adverse reaction in the patient (Wang et al., 2013; Sachtjen, 2016a).

This is described in an excellent article entitled “An Electrocorticographic Brain Interface in an Individual with Tetraplegia." Written by Wang et al. (2013) and it demonstrates the concept that thought controlled bionic/robotic limbs being one step of progress beyond the simple movement of a 3D cursor. Small steps taken continuously lead to successes and this work with a single tetraplegic illustrates a small step, “This study demonstrates that ECoG signals recorded from the sensorimotor cortex can be used for real-time device control in paralyzed individuals” (Wang et al., 2013, para. 1).

**Summary**

Reviewed here is research on the topic of brain-machine interfaces which includes the notion of  electrodes and stentrodes implanted in the brain and body to facilitate the recording, transmission and reception of motor sensory regions of the brain. Also considered is the idea of energizing the system and some results were reported showing both successes and opportunities for future successes. Some component material was described as well which were called Bionic Graphene Nanosensors and some historical research was mentioned as well. This leads into more aspects to consider which are the software that analyzes the data that directs the processes required for thought controlled mobility of bionic prosthetics. Also necessary is the brains reception of feedback that completes the loop which allows a natural limb to enjoy a pleasurable sensation such as ones small daughters cheek or a functional one that ensures that enough of ones foot is on the stair in order to safely continue. Other feedback from limb to brain is the fearsome sensation of pain that also can help ensure safety in its own way. Pain shall be reviewed after the following section.

As mentioned previously much progress in the field of thought controlled bionic limbs has been made and some of the latest technological advances have been discussed. Historical advances leading to a realization of brain-machine interfaces (BMI) that can read ones thoughts and enable the control of a robotic limb. The natural unfavorable relationship that people have with pain is discussed herein as is its usefulness as a warning signal to help ensure that one does not become damaged more than if there were no pain to sound the alarm. This section focuses briefly on the some software that can be used to help facilitate the operation that brings mobility back to the immobile. Also contemplated is the feedback involved in the process and its necessity for a more functional system enhanced with bionic replacement limbs. The delicacy of control is reviewed as well all the while contemplating the estimation that pain should be included in the artificial feedback to the brain.

**Software and Feedback**

Software has been developed for the computers acting as a go-between the hardware that is recording and transmitting data to and from the brain and the hardware that is the robotic prosthetics or simply the bionic limbs. Information on software includes Oostenveld, Fries, Maris, and Schoffelen (2011) report on open source software that can facilitate bionic control. The software is called “Field Trip” and is described as a software package that was designed to analyze brain signals from EEG and other electrophysiological signals. The software studies connectivity, time-frequency and a host of other data. This software is indeed needed to control the bionic device. It is open source software that helps experimental neuroscientists analyze their data. Its algorithms were built for the advanced analysis necessary to implement the feedback cycle between a bionic prosthesis and its users mind. Oostenveld et al. (2011) reported on this software in "FieldTrip: Open Source Software for Advanced Analysis of MEG, EEG, and Invasive Electrophysiological Data." which was published in the journal *Computational Intelligence and Neuroscience.* The software is powerful and much needed to enable the functionality of BMI and bionic systems as anyone knows how necessary adequate software is when dealing with modern day technology. It is able to analyze very large amounts of data coming from the mind via the BMI and such analysis is essential as researchers continue to try to optimize the methods used in receiving, recording and sending signals to and from the brain (Oostenveld et al., 2011; Sachtjen, 2016d).

Feedback is a very important part of the BMI as it is in many other aspects of life. When one steps on the accelerator in ones car then feed some feedback in order to be able to tell if they need to press harder or to let off the accelerator. If one does not feel the vehicle lunging forward and indeed is not able to measure *how much* the vehicle is lunging forward one is in danger of ending life. Other signals such as a speedometer readout and the visual cues of landscape passing by and even wind on face if the windows are open are all also feedback and necessary for full functionality.

People with amputated limbs that have robotic artificial limbs installed on them that are controlled by their thoughts through a BMI will have feedback included which is on a two way path between the limb and the mind. Consider that feedback for the pain and or fear when a natural limb is in danger of being damaged is a positive thing. It can be a positive thing for an artificial limb as well. Concerning the strong link between body, brain and pain it is often looked at as two sided coin since people should realize that pain can be quite useful despite the fact that they want to avoid it.

**Electrodes in vivo**

The published article: "First Long Term in Vivo Study on Subdurally Implanted Micro-ECoG Electrodes, Manufactured with a Novel Laser Technology." appeared in the journal *Biomedical Microdevices Biomed Microdevices* by Henle et al. (2010) shows how the researchers continue to test the durability of the electrodes in vivo or as they are used with living subjects over a period of 25 weeks. As mentioned previously in this paper this is another alternative method of facilitation two way communications between a brain and a machine that promises success in the field Henle et al. (2010; Sachtjen, 2016a). The two way communication between the brain and the machine is what allows the feedback from the prosthetic machine to send information to the brain.

**Material review**

As discussed previously quite important in the search for the best methodology of solving the issues addressed in this paper are the materials used in the processes. Kong, Mannoor, and Mcalpine (2015) here describe cutting edge nanotechnology from this article published recently named "Bionic Graphene Nanosensors." This is another aspect of ensuring the feedback loop is secure between the brain, the BMI and the prosthetic. Solid technological hardware cannot be underemphasized as Kong and his team work on integration to produce wireless power production and remote readout. The interface is essential, "… highly sensitive nanosensors, and subsequently biointerfacing such devices onto the body for real-time detection.…biotransfering graphene sensors onto biological systems to enable a unique bionic nanosensor platform…" (Kong, Mannoor, & Mcalpine, 2015, p. 269).

**Miniaturization**

Sachtjen (2016a) described here and previously the work of Muller et al., (2014) on how improvements in wireless transmission in Electrocorticography (ECoG) for successful brain-machine interface (BMI) is needed because still (2014) the better devices are large and wired. This is quite on point as the search continues for the most powerful and least invasive devices to record, relay, and transmit electronic signals to and from the brain (Muller et al., 2014). The feedback involved in the transmission to the brain can not be underemphasized. The article cited here is "24.1 A Miniaturized 64-channel 225μW Wireless Electrocorticographic Neural Sensor." (Muller et al., 2014) and it goes into detail of the ongoing work that strives for less invasive solutions to the problem of communication directly with the motor driving areas of the cerebral cortex. The work is by no means over and suggested is continued research to continue the progress and break through bottlenecks addressed here, "Substantial improvements in neural-implant longevity are needed to transition brain-machine interface (BMI) systems from research labs to clinical practice” (Muller et al., 2014 p. 412). This is partially because the devices are not small enough and not powerful enough as illustrated, “However, today's clinical ECoG implants are large, have low spatial resolution (0.4 to 1cm) and offer only wired operation” (Muller et al., 2014 p. 412).

**Reducing invasiveness**

Taking a second look at Oxley et al.’s (2016) article "Minimally Invasive Endovascular Stent-electrode Array for High-fidelity, Chronic Recordings of Cortical Neural Activity." which was published in *Nature Biotechnology* in regards to feedback the relationship to be pointed out is again that over the last ten years amazing breakthroughs have been made if the study of using electrodes inside the brain to stimulate and of record neural signals of the brain activities. The stimulation mentioned is feedback. The feedback is destined for the “information rich” areas of the brain that use neural electrical signals to direct the body to move different muscles (Oxley et al., 2016).

They also report on one of the sheep experiencing a seizure and they recorded the seizure activity and were alerted to the episode as well and then injected diazepam into the sheep and watched the recording of the seizure end as a result (Oxley et al., 2016).

It is safe to assume that during the seizure the feedback loop had become derailed or perhaps the feedback loop becoming unhinged is what caused the seizure. Oxley and his team consider sending stentrodes deeper into the brain as they search for even more high information areas what they considered high yield targets. Overall, the experimentation seemed to be a great success as they move toward implanting the stentrodes into humans (Oxley et al., 2016; Sachtjen, 2016b).

**Intracranial EEG**

Mentioned previously was Penn et al., (1973) who all the way back in 1973, reported on delving into the brain of baboon to record EEG activity directly from the surface of the brain. They also did so with humans as described in their article, "Intravascular Intracranial EEG Recording. Technical Note." published in the *Journal of Neurological Surgery* they report using single and bipolar electrodes that were recording electrical activity from vessels within the cranium of baboons. This would have been an early period in the history of dealing with EEG data to apply and evaluate the effect of electrical feedback however it is unclear if they did so.

**Related Idealization**

Feedback from the artificial limb to the brain is already necessary for fully functional bionic enhanced limbs as the operator would need to know by touch if that hand is securely grasping an object without crushing it or if a bionic foot is on a stair step before proceeding to move the next foot up the stairs. If there is an unseen nail on the step the operator needs to know in order to avoid further damage to the limb (Sachtjen, 2016d). When examining the idea of bionics and pain as one of the feedbacks to the brain much background information on the subject is needed in order to best determine its usefulness. This information would include a number of related thesis ideas including the medical ethics question to help determine if one should ever intentionally artificially inflict pain. It is just a little bit easier to decide to include pain when one thinks of it as a two sided coin. People obviously want to avoid pain and this is exactly what contributes to its value, as a means of alerting one to the fact that they are being damaged. Looking at a larger picture one realizes that the integration of thought controlled artificial limbs is of great interest to many people. Scientists have thought about this concept for many years because of the tremendous benefits that it can contribute to the people of the world. Bionics may also be able to help weak elderly people and others weakened because of disease or injury. Currently there are body enhancements that require no BMI but enhance the strength of a person based on their voluntary body movements.  Body enhancements can perform a number of strength required tasks such as lifting and carrying heavy objects. There are military applications with them as well. Again feedback is needed from the artificial limb to the brain for number of reasons including ensuring that not too much pressure is applied to what the person is trying to pick up so that such objects are not destroyed. Feedback should also indicate if there is danger and the task of the feedback warning a person is best accomplished with pain.

**Delicacy of Control**

There is a requirement of making small corrections when flying an airplane so that one does not over compensate for a previous error and therefore lose control. In other cases it takes very little effort to cause large changes. When one is driving down the road in a vehicle it really takes very little effort to round a curve, one simple turns the steering wheel a little bit and follows through. Even less effort if required when changing lanes on the freeway as there is less distance to turn.

Consider an interface between ones vehicle and ones self where there is a cruise control for the steering wheel similar to those utilized by the new breed of self-driving cars. Such a cruise control for the steering will in this case connect via wireless technology with the driver’s mind. An actuator manipulating the steering wheel is controlled from thought that originated in the brain through a BMI brain-machine interface. This is keeping in mind that on freeway driving only subtle movements are needed generally on the steering wheel to control of vehicle driving down the road. This application holds true for other motion involved activities such as the fact that only a minimum of control needed when skiing to change direction, one simply leans into the curve, along the same line is the control of a motorcycle, again one just leans into the curve in order to round a curve. Not that these activities never require more control applied to them and certainly the propulsion requires much expenditure of energy (with the exception of the downhill skier mentioned who is relying on gravitational force) but for the most part only little energy is expended for maneuvers. This hearkens back to previously discussed solutions for energy needs of the feedback loop as Ho et al. detail a method to power miniaturized medical devices implanted in the body wirelessly (2014). They really would need a small amount of energy which they harvest from the body tissue itself to re-direct to power the BMI system. Again, although they are concerned with powering different surgically implanted medical devices such as pacemakers their technology may also be useful for the deep brain piece of the BMI to power the transmission, recording and reception of feedback data. Miniaturization is used in the process, “We use the method to realize a tiny electrostimulator that is orders of magnitude smaller than conventional pacemakers” (Ho et al., 2014, p. 7974). Fortunately the performance exceeded the energy needs required for number of implanted devices to function. The team continues to perfect this task by engaging “…a method, termed midfield powering, to create a high-energy density region deep in tissue inside of which the power-harvesting structure can be made extremely small” (Ho et al., 2014, p. 7974).

Consider feedback as the mind, with technological assistance, as an essential element in the task of controlling physical objects in its environment. This occurs simply by a user thinking certain thoughts. The thoughts need to be recognized by the system as specific electric signals emanating from the brain. When the brain thinks about moving the user’s finger those specific signals are sent through the hardware that links the brain to the interface where the software receives and interprets and relays signals from the interface out to the significantly more advanced hardware which is the bionic prosthesis where the prosthesis, with artificial sensors will relay electronic signals describing how much pressure is being applied to an object or a person back to the user. An analogy to describe this involves a professional liar. Such a liar is able to defeat a lie detector test so now think or the EEG leads of the lie detector hardware being analogous to the brain-machine interface. There would be no feedback involved in the loop if the lair was not able to view the needle swinging up and down as it scribed and scrolled across the paper on the rotating drum of the machine. If the lair could see it then some feedback would be available. Suppose a mechanism on the device was set to perform a specific action when the needle pegged out because of a horrible lie. Well, the liar can not only make a lie mimic the truth on such a test but can also make the truth register as a lie. So the lair can say whatever they want to but when the liar wants the specific action to occur they will simply cause the statement to appear as a lie. In all likelihood they would not even need to make the statement out loud and could simply think about the lie. Next hook up the EEG or lie detector electrodes to someone with an artificial limb which has electronic actuators on it and wirelessly enables them to be controlled and actuated to perform specific predetermined motions when the needle or the virtual needle of the EEG moves. Now the user of the artificial limb can simply think of a lie order to cause the critical ‘switch’ to ‘flip’ enabling an actuator to cause an artificial limb to grasp. Of course the actual BMI methodology described previously does this with the person thinking actual thoughts of moving their limb and not proxy thoughts such as lies. Another such proxy idealization is also illustrated in the idea that when a person thinks about lemons very deeply they will, in most cases, experience an actual change in their mouth as the mind readies itself to bite into a lemon or mimics the experience of having lemon in the mouth when the lemon does not come much in the way that drug addicts experience anticipatory physical changes in mind and body when they sense that their next dose is imminent. However, if thinking about lemons or telling lies to a lie detector in order to actuate motion in a prosthetic via the delicate control is utilized one wonders if there will there be extinction of the effect with time.

**Summary**

The software involved in the BMI process is an essential part of the equation and the open source software describe previously, FieldTrip, is but one of a number of solutions used to facilitate the transfer and analysis of data to and from the brain, to and from the prosthesis. It includes the feedback aspect from the artificial limb which is indeed necessary for a fully functional enhanced prosthetic limb. This is because of a number of reasons including ensuring that too much pressure is not applied when the limb picks up a Champaign glass or an infant. A concern is whether pain should be included in that feedback loop as well understanding the horrible aspect of pain. It is common knowledge that a person working a suicide hotline will be alerted immediately that disastrous results are imminent when the caller states something along the lines of, “I just want the pain to end.”

## Pain

Beginning a look at pain might begin with some thoughts of a child’s concept of it. It is difficult to think of anyone experiencing pain and much the worse when thinking about children suffering pain. Pain has different significance as one grows. Gaffney and Dunne (1986) studied this idea in their article, "Developmental Aspects of Children’s Definitions of Pain." and they discuss a research project conducted to learn about how children think about pain utilizing 680 children from 5 to 14 years old (Gaffney & Dunne, 1986, p. 105). The researchers wanted to learn if a pattern of development could be found as the children verbally discussed pain. They found that a previous model was upheld which indicates that the children’s concept of pain evolves with stages of cognation (Sachtjen, 2016a). When exploring the usefulness of pain it is advisable to differentiate between younger and more mature people.

**The usefulness of pain**

The usefulness of pain can be illustrated with the example of a typical rough housing child. Consider that such a child with a broken arm in a cast may very well use it as a hammer to hammer nails and/or as a weapon in order to threaten to club or to actually club others. The resulting damage is caused to the cast and perhaps even to the broken but healing bone, not to mention the others. If this child would have been supplied with some pain each time they misused their cast then they would have refrained from misusing their cast and therefore they would not have re-broken their arm. Also consider that when one’s mouth is numbed by Novocain from a visit to the dentist one might start chewing on their cheek because they can feel no pain and this will likely result in bleeding and tissue damage. These phenomena are probably most pronounced in children (Sachtjen, 2016e).

**Acute pain**

In the journal *Pain* (Melzack, Wall, & Ty, 1982) published their article "Acute Pain in an Emergency Clinic: Latency of Onset and Descriptor Patterns Related to Different Injuries." Here is discussed some statistics of pain suffered by patients in an emergency room. The researchers refrained from studying drunk, angry and other extreme cases but rather focused on the rational. They studied 138 patients and found that 37% (Melzack, Wall, & Ty, 1982, p.33) of them did not feel pain immediately upon their injury and most began to experience pain within an hour of injury. They found that the lag time between injury and the onset of pain is highly variable and that the relationship is quite complex (Melzack, Wall, & Ty, 1982). It is important to understand better the relationship between pain and injury and the mind or brain and nervous system (Sachtjen, 2016a).

Of the patients studied who had injuries only to their skin over half experienced some time without pain after the injury. Of the patients with more severe injuries the vast majority experienced pain immediately after the injury occurred. The authors find that there is much complexity and variation when studying the injury/pain relationship (Melzack, Wall, & Ty, 1982).

**Responses to pain**

Sachtjen (2016a) writes here about research that studied the notion of how one can control their perception of pain as it is viewed via neuroimaging. Stated, in the article titled "Perceived Controllability Modulates the Neural Response to Pain." (Salomons, Johnstone, Backonja, & Davidson, 2004) and published in the *Journal of Neuroscience*, is that previous studies have shown the connection between perceived controllability and the ability to cope with and tolerate pain (Salomons, Johnstone, Backonja, & Davidson, 2004).

“The response to painful stimulation depends not only on peripheral nociceptive input but also on the cognitive and affective context in which pain occurs” (Salomons, Johnstone, Backonja, & Davidson, 2004, p. 7199). The authors used magnetic resonance imaging and found specific areas of the brain active when the subject perceived to be controlling their pain. They deduce that these areas are related to cognitive variables and wonder if stimulus driven responses to pain are being compared poorly with cognitive contexts (Salomons et al., 2004; Sachtjen, 2016a).

“Using functional magnetic resonance imaging, we found that pain that was perceived to be controllable resulted in attenuated activation in the three neural areas most consistently linked with pain processing: the anterior cingulate, insular, and secondary somatosensory cortices" (Salomons et al., 2004, p. 7199). Again, more evidence is presented here of the strong association between the mind, the body, and pain. This further demonstrates the need for more research regarding the use of pain in feedback to BMIs.

### Phantom pain

Touched on previously but bearing repeating is the study done in 1988 by Sherman, Ernst, Barja, and Bruno The article, "Phantom Pain: A Lesson in the Necessity for Careful Clinical Research on Chronic Pain Problems. A Guest Editorial." Sherman et al. (1988) was published in the Journal of Rehabilitation Research and Development and the authors show how in the past phantom pain was thought by most doctors to be all in the mind but it has been found out to actually be real. Phantom pain is pain felt by an amputee in the body part or limb that is no longer present. One would automatically assume that the pain is all in the head since there is no limb but that is not to say that the pain is not real and felt 'as if" it was occurring in the missing limb. The title of the article emphasizes the fact that more critical clinical research would need to be completed on the subject to help alleviate the long term suffering of patients. The article shows how doctors would encourage their patients into not reporting their phantom pain. The purpose of the article clearly is emphasized as they encourage more research on the subject as the current (1988) state of affairs was unfavorable and caused patients to suffer. The authors reported on past research, much of which was conducted by Sherman et al. (1988) providing proof of their concepts through extensive surveys and literature review. The authors compared the "myth" that phantom pain that it is rare and all in the mind, to the "reality" that over 80% of over 11,000 amputees surveyed reported phantom pain (Sherman, Ernst, Barja, & Bruno, 1988, p. vii). They also report that phantom pain is caused by 'very real' physiological reasons according to experimental evidence. They state that they analyzed the literature and that after adjusting for effects of chronic pain on all patients that there is no evidence that indicates that suffers of phantom pain are any more abnormal psychologically than the general population. The authors cite the research as they state that there are very few rigorous studies of the efficacy of the various treatments that are used for those who suffer from chronic phantom pain. Treatment techniques have therefore been used that have little or no chance of improving the patient's condition. A clinician might try out a new treatment based on a guess as to what the problem is and often will publish the treatment method without even waiting for follow-up feedback from the patient as to whether they were relieved of the pain or not on a longer term basis. Clinicians do this based on an initial belief that the pain is reduced but do not learn if the pain reduction continues or not and, as discovered by the authors previously conducted extensive surveys, they find that the pain reduction does not continue for the most part. The authors look forward to clinical reviews that demonstrate efficacy and research that unlocks the secrets of the physical mechanisms that cause phantom pain. The authors implore scholarly medical journals to indicate the lack inherent in articles containing research on the subject that is not rigorous and have little follow-up data as doctors who rely on these short studies to treat their patients do not really do a service to those who suffer from chronic phantom pain. Underemphasized however, indeed totally absent in this discussion was any mention of narcotics prescribed as treatment for chronic phantom pain and any resulting addiction issues. It would be surprising to learn that no doctor ever prescribed any opiates for treatment of phantom pain. Perhaps such treatments would have been included in the "treatment does not work" category for the reason of the adverse side-effects associated with addiction (Sachtjen, 2016c).

The authors, Sherman et al. (1988), explain that the myth of phantom pain continued for such a long time because when an amputee went to a doctor for phantom pain initially they were told either directly or indirectly that the pain was all in their head and that most amputees were afraid to continue complaining about their pain for fear that the doctor would consider them crazy. Indeed, often when a patient persisted in complaining about their pain they would be referred for psychiatric examinations. Nevertheless, some scientists and doctors did try to find out a physiological cause for phantom pain. One failed method for doing so was by attempting to figure out the difference or differences between amputees who reported phantom pain and other amputees who did not report it. They reasonably believed that this would help them determine what caused phantom pain. The problem, according to Sherman et al. (1988) was that the group that reported no phantom pain actually did experience it but were reluctant to say so because of fear. So the results of comparison showed little differences between the groups. When patients continued to complain of chronic phantom pain some physicians did attempt to treat it but they would usually try to treat the amputees stump believing that there was something wrong with the nerves, the nervous system or blood circulation around the stump. The authors reported on medical and surgical treatments performed by doctors on the relatively small number of amputee patients who persisted in asking for treatment. Reported in previous articles the authors surveyed almost every single location in the United States that might treat amputees to find out what treatments they used. They found 68 different treatments that included everything from re-amputation to lobotomies to relaxation training (Sherman et al., 1988, p. vii). Unfortunately, the efficacy of these treatments remained unproven as for one there was very little follow-up and for two the follow-up conducted was often proven to be documented incorrectly as all treatments that were reported as successful by the treating clinician were reported as unsuccessful by others in the patient's records. When measuring the effectiveness and efficacy of treatments Sherman et al. (1988) surveyed over 11,000 amputees (the vast majority being military veterans) and found that only 0.4% reported being cured and only 1.7% reported any major reduction on a permanent basis of their pain (Sherman, Ernst, Barja, & Bruno, 1988, p. vii). The authors decry the failure of practitioners to have follow-up evaluations with which to measure the results of their treatments and state that one problem is that when a patient is either cured or unsatisfied they usually don't come back to the doctor and so the doctors do not even know that their treatments usually did not help the patient (Sachtjen, 2016c).

Also of relevance the authors discuss behavioral and psychiatric treatments and note that such treatment was usually applied the few patients who continued to complain about their phantom pain and continued to demand treatment who were referred to behavioral clinicians. Lacking in this article however is a discussion of results from such referrals. The authors state that before 1988 amputees' phantom pain was treated very poorly because the medical field thought it to be rare and not real but rather completely psychological in origin. Research conducted by Sherman in the recent years before publication began to expose the fact that there was a real pain that amputees suffered and with a physiological rather than a psychological origin. Furthermore, the summary reported that treatments for phantom pain were largely ineffective and that consistent follow-up was needed in order to find appropriate and efficacious treatments (Sachtjen, 2016c).

In the textbook, *Health Psychology: An Introduction to Behavior and Health, Eighth Edition* Brannon, Feist and Updegraff (2014) also describe phantom pain as pain that is felt in a limb that has been amputated. In other words the person who had his right arm removed will feel pain in the brain that seems to be originating from the former limb. This is caused by the phenomenon of phantom pain. It seems obvious that there is a pathway pain. It seems so because the pain is felt as if the feedback to the brain from limb continues. When directing feedback which includes pain for safety reasons from a prosthesis if that pain feedback be directed along the same pathways that cause the phantom pain (and are responsible for natural pain being directed to the brain) and be activated only when the artificial limb is being damaged then that would be preferable.

This ends the pain section of the paper and now will be discussed is the idea that pain should be included in the feedback loop in a BMI system in order to help ensure that limited damage is done to the prosthetic and indeed to the user as well.

## Conclusion

Here now considered is some rational on why pain should be included in the feedback of thought controlled bionic limbs for the purpose of safety.

### Insensitivity to pain disadvantage

"... pain plays a necessary and basic role in survival; pain is the body's way of calling attention to injury" (Brannon, Feist & Updegraff, 2014, p. 145). Again, this is taken from the Health Psychology textbook mentioned previously. The authors go on to describe about a genetic disorder of people who do not feel pain and the trouble that comes along with that. Referred to as congenital insensitivity to pain, the disorder is described by stating how people with the disorder often die younger then others and should be monitored carefully. "'They often experience serious injuries without any awareness, such as broken bones, bitten tongues, cuts, burns, eye damage, and infections" (Brannon et al., 2014, p. 145). Most people experience the warning that pain provides when they break their bones or get infections. This is the idea behind and artificial pain being included as feedback to someone who is using a brain-machine interface to control a robotic a limb with their thoughts. The favorable result being for them to be able to avoid danger not only to the limb but to the rest of their body.

**Recommendations**

When considering acute and severe injuries the  necessity of pain becomes clearer. There is a number of ways that the artificial pain can be applied such as in the form of physical stabs, burning sensations and electrical shocking. Indeed the pain as feedback could be simply transmitted from a bionic fingertip causing the sensation of being physically stabbed, or heated up or electrically shocked applied to the living limb is that the prosthetic is attached to.  A myoelectric prosthesis operates when person manipulates the remaining portion of the limb to activate the mechanical prosthetic and feedback is useful in such cases. Pain as a feedback to protect limbs needs to be immediate. Often times when people are injured they don't feel the pain for sometime after the injury. The onset of the pain depends on such factors as the type of injury where more severe injuries such as broken bones will probably cause sooner onset then otherwise and the timing will depend on the person as well. ”They studied 138 patients and found that 37% of them did not feel pain immediately upon their injury and most began to experience pain within an hour of injury” (Melzack, Wall & Ty, 1982, p. 33).

Lotze et al. (1999) asked the question framed by the name of their article “Does use of a myoelectric prosthesis prevent cortical reorganization and phantom limb pain?” and published in the journal *Nature Neuroscience.* They show positive results, “…we found that enhanced use of a myoelectric prosthesis in upper extremity amputees was associated with reduced phantom limb pain and reduced cortical reorganization. Extensive use of a myoelectric prosthesis might have beneficial effects on phantom limb pain” (Lotze et al., 1999, p. 501).

These myoelectric prosthesis make the whole idea of thought controlled artificial limbs using a brain-machine interface unnecessary. BMI’s are needed when myoelectrics are not an option. Myoelectric mechanical limbs are operated by sensors in the limb itself. As mentioned previously, myoelectric prosthesis can be manipulated by the wearer utilizing the electrical signals in the wearer’s muscles. Sensors on the prosthesis will pick up electrical signals from the muscles under the wearer’s skin and will activate such actions as opening and closing fingers turning their wrist, grasping, lifting, releasing and so on and the system works well in many cases. This is a good method for providing the amputee with an opportunity to regain lost mobility and independence. In other cases however, where a person is unable to manipulate the muscles in order to indirectly control the prosthesis the BMI solution is useful.

**Lifesaving pain**

A person with such a thought controlled bionic arm could very well be in possession of a limb that is significantly better at manipulating its environment and stronger as well. Another thing to consider is if pain should be used as a feedback from the limbs to the brain. Pain follows a pathway through the neurons from points on the skin for example where damage has occurred or is in imminent danger of occurring. The pain follows the path from that point to the spinal cord through the neurons in the nervous system and then continues up the spinal cord through gateways to the brain where was it is perceived as pain (Brannon et al. 2014). This is useful as it is acting as a warning for us to make a move that will stop the damage that is being done to a natural limb and it could work the same for an artificial limb so that the expensive machinery is not damaged or destroyed. At risk of purporting these ideas as being initiated simply in order to save insurance companies money the warning of pain has great potential to save the life of the user and possibly others as well. There are numerous scenarios that will undoubtedly reveal themselves in the future when bionic prosthesis are common that will demonstrate this. Indeed one could envision a situation where this pain as a feedback from the artificial limb could also warn the person about damage to their entire self. One extreme example would be perhaps simply walking with two artificial legs into hot lava where someone with natural legs would not get very far at all before they turned around because of the pain associated with getting near the hot lava. But if a person had no pain as feedback from their artificial limbs and unknowingly walked into an area hot lava they may very well get in so far that other parts of their body would feel the pain of heat on them too late and this would result in them accidentally destroying them selves. A person therefore needs feedback to protect artificial limbs. The response to danger needs to be immediate. Often times when people are injured they don't feel the pain for sometime after the injury. The onset of the pain depends on such factors as the type of injury as more severe injuries such as broken bones will probably feel the pain much sooner then otherwise. This will depend on each individual as well.

### Related idealization

The idea of pain is discussed for the reasons of both its natural unfavorable relationship with people as well as its usefulness as a mechanism that reduces damage. It would be advantageous if bionic limbs would relieve some of the phantom pain that many amputees suffer from. Again, when considering a brain-machine interface (BMI). The idea that pain be included in the feedback involved from a person with a thought controlled artificial limb requires careful contemplation. Bearing in mind the advantages of feedback for a person who has a thought controlled artificial or bionic limb such as a hand or any combination, including pain in the mix would provide additional safety (Sachtjen, 2016d).

### Lemon analogy and fail safe

Learning about the effect of thinking about lemons and the chemical change that occurs in the mouth when doing so can have importance in the quest to help amputees possessing "bionic" limbs as well as others. Consider a theory that electronics installed in the mouth can detect the chemical change, probably an increase in acidity, and then flip a switch when acid is detected which would actuate an artificial limb in order to elicit a response such as grasping, walking or etc. In other words, having a person control an artificial limb with their thoughts. Sensors may be installed on a persons tooth or elsewhere in the mouth for these tasks. As discussed previously the work in the field is more advanced at this time and the idea of thinking about lemon juice in order to activate mechanisms is more of an analogy or as a possible safe guard. There are issues to consider involved including feedback from the artificial limb to the person, their mind or their brains that are addressed (Sachtjen 2016e).

Consider a brain-machine interface (BMI), the thesis here posited purports that pain be included when considering the feedback involved from a person with a thought controlled artificial limb. Bearing in mind the advantages of feedback for a person who has a thought controlled artificial limb otherwise known as a bionic limb such as a hand or a leg or a foot or arm or any combination of them from either sides of the body. For example, if one begins to think about lemon juice squirting down their throat this will cause a chemical change in your mouth that one can actually taste and sensors in ones mouth, perhaps installed in a hole in one of your teeth. This aspect could be used as an on/off fail-safe switch that would shut down the other systems of inflicting artificial pain when that system malfunctions.

**Meta-analysis**

Clearly pain is quite an unfavorable condition that humans endure. It is difficult to reconcile this aspect with the idea that artificial pain should ever be inflicted on anyone.

However, pain does have the one favorable aspect in that it really does act as an alarm or a warning to make people aware of imminent danger to life and limb. It is for this reason that pain should indeed be included in the feedback loop of a system including a thought controlled bionic prosthetic limb facilitated by a brain-machine interface.

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