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Article

Cyborgs and Enhancement Technology

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Abstract: As we move deeper into the twenty-first century there is a major trend to enhance the body with "cyborg technology". In fact, due to medical necessity, there are currently millions of people worldwide equipped with prosthetic devices to restore lost functions, and there is a growing DIY movement to self-enhance the body to create new senses or to enhance current senses to "beyond normal" levels of performance. From prosthetic limbs, artificial heart pacers and defibrillators, implants creating brain–computer interfaces, cochlear implants, retinal prosthesis, magnets as implants, exoskeletons, and a host of other enhancement technologies, the human body is becoming more mechanical and computational and thus less biological. This trend will continue to accelerate as the body becomes transformed into an information processing technology, which ultimately will challenge one's sense of identity and what it means to be human. This paper reviews "cyborg enhancement technologies", with an emphasis placed on technological enhancements to the brain and the creation of new senses—the benefits of which may allow information to be directly implanted into the brain, memories to be edited, wireless brain-to-brain (i.e., thought-to-thought) communication, and a broad range of sensory information to be explored and experienced. The paper concludes with musings on the future direction of cyborgs and the meaning and implications of becoming more cyborg and less human in an age of rapid advances in the design and use of computing technologies.

Keywords: cyborg; enhancement technology; prosthesis; brain–computer interface; new senses; identity

1. Cyborgs and Prostheses

The human body is in the process of experiencing a rapid transformation from a completely biological entity created based on instructions provided by human DNA to a body becoming far more "computational and technological" [1]. While this paper focuses on the theme of "human" enhancement technology, we also review some computational enhancements to animal subjects because such studies provide examples of the future direction of enhancement technology and in some cases these very technologies will be implemented into the human body and likely within one or two decades. Generally, body-worn and implantable technology serves to identify cyborgs as a constellation within which the identities of the members of cyborg groups "negotiate" their individual significance. We describe "cyborg culture" or "cyborg being" as a particular way of life, or set of beliefs, which expresses certain meanings in the context of cyborg technologies; particularly in the case of many self-imposed cyborgs that "way of life" is to become transhuman [2,3]. Broderick describes a transhuman as a person who explores all available and future methods for self enhancement that eventually leads toward the radical change of posthuman—which is to ultimately become nearly unlimited in physical and psychological capability (i.e., to go beyond human) [4].

Using a semiotic framework, cyborg enhancement technologies can be viewed as signs which are subject to the criteria of ideological evaluation [5] which for self-enhanced cyborgs is a culture of "technologically savvy" and to some extent nonconformists, and, as noted, transhumanists. In general, we use the term "cyborg technology" to refer to technology integrated into the human body which not only restores lost function but enhances the anatomical, physiological, and information processing abilities of the body [6]. With this definition in mind a person with a heart pacer is a cyborg as is a person with an artificial arm controlled by thought. In terms of scope and content, the focus of the paper is not on drug enhancements to amplify human performance or methods of genetic engineering to enhance the body, nor does the paper focus on mobile consumer products such as smartphones or tablets which some refer to as a cyborg enhancement. Instead the paper focuses more so on the body itself—which we theorize is becoming an information processing technology based on the implantation of computing technology directly within the body. Finally, we use the term "cyborg prosthesis" to refer to artificial enhancements to the body providing computational capability, one example is an artificial hippocampus another is a brain–computer interface.

Table 1 provides an overview of cyborg technologies and enhancements designed to augment human abilities and is organized around: (1) technology which "externally interfaces" with the body; (2) implants within the body; and (3) technology which modifies in some way brain activities. The last category may include devices like Google Glass and other types of "eye-worn" technology, that while not directly implanted within the body, do in fact help to augment the world with information and thus enhance the information processing abilities of humans. Further, many refer to people wearing such devices as "cyborgs" therefore the following table includes a brief section—"Computing Attachment as Enhancement", to more fully represent the range of technologies available that help create what to some is the "common view" of a cyborg. And, to a lesser extent, enhancements to aid mobility in the form of exoskeletons are included in Table 1 to provide a more complete range of cyborg technologies that are emerging now. Additionally, there are currently a large number of enhancement technologies that are available either as commercial products or as emerging technologies, to review them all would be beyond the scope of this paper, therefore Table 1 is provided mainly to motivate discussion on the topic and to provide some organizing principles and categories to frame the debate on our future as cyborgs. Finally, two examples in Table 1 are of animal studies, again to show the direction of cyborg technology and to give the reader a more complete overview of the cyborg future which awaits us.

Similar to our Table 1, Kevin Warwick in this special edition on *Cyberphenomenology: Technominds Revolution* [7] presented a four-case description of enhancement (or cyborg) technologies. Case 1 represents technology positioned close to the human body, but not integrated into the body; case 2 is technology implanted into the body but not the brain/nervous system (whether for therapy or enhancement); case 3 represents technology linked directly to the brain/nervous system for therapeutic purposes; and case 4 is technology linked to the brain/nervous system to create "beyond normal" levels of performance. We present Warwick's classification as an alternative method for parsing distinctions between cyborg enhancements keeping in mind the fluidity of some of these, and our, categories—namely that Warwick's case 3 technology may only be a matter of a software rewrite away from a case 4 technology and that a prosthesis in our table may also have direct neural links.

Table 1. Overview of Cyborg Enhancement Technologies.

Enhancement Type/Category	Description	Significant Example
I. General External Enhancements to the Body		
Prostheses to Replace or Restore Lost Functions Prostheses are becoming more controllable through the use of control theory principles, and are integrally connected to the body, upgradable, and under some circumstances controlled by thought via a brain–computer interface (which may or may not be wireless).		
Limb Prostheses to Restore Mobility	Artificial limb replacement with multiple degrees of freedom, more and more controllable by thought	• DEKA Arm's, among other, myoelectric and brain-controlled prosthesis [8]. See also 'modifying the brain' in part III of this table.

Table 1. *Cont.*

Enhancement Type/Category	Description	Significant Example
Retinal Prosthesis to Restore Vision	Rectify visual sense degradation; provide enhancement to visual sense	• Implantable Miniature Telescope for treatment of AMD (age-related macular degeneration) [9] • Argus II Retinal Prosthesis System, an implanted device to treat adults with severe retinitis pigmentosa. The System has three parts: a small electronic device implanted in and around the eye, a tiny video camera attached to a pair of glasses, and a video processing unit that is worn or carried by the patient [10]
Cochlear Implant to Restore Hearing	Improve auditory sensitivity, the implant consists of an external portion that sits behind the ear and a second portion that is surgically placed under the skin	• Med-Els SYNCHRONY Cochlear Implant [11]
Computing Attachment as Enhancement Increasing our computational resources through technology directly integrated with our bodies allows us to scale our capabilities, senses, and interaction with our environment and with external technology. Insomuch as wearable computing integrates with our senses and responds to our thoughts, it represents a significant move towards becoming a cyborg.		
Computing Device Worn by the Body	Extraneous computing directly integrated with prosthetic part	• Jerry Jalava's USB Fingertip [12]
	Direct-interface wearable computing, such devices allow information to be projected into the world whenever and wherever it is needed	• Steve Mann's Eyetap Wearable Computer [13] • Google Glass [14]
Computing Grafted onto the Body	Attached computing device providing sensory input	• Neil Harbisson's "Eyeborg" auditory-augmented vision, allows color to be heard [15]
	Attached computing not directly integrated with the brain but accessible by the user and others with wireless capability	• Rob Spence's eye camera records and transmits images [16]
Epidermal Enhancement	Epidermal printed circuits on the surface of the skin	• Biostamp digital tattoo interacts with smartphones [17,18]
	Attached via surface	• Cyborg Nest's magnetic north sensor attached by surface-to-surface "barbells" [19]
II. Enhancement Technology Implanted Within Body		
Passive Implant Cyborg technology implanted within the body, such technology might not interact with the body through a feedback loop but be worn by the body, either collecting or storing information.		
Radio Frequency (RF) or Wi-Fi Subcutaneous Technology	Programmable storage/transmitter implanted under the skin	• RFID chips for location and medical information [20] • Anthony Antonellis "Net Art Tattoo" sends pictures to smartphones [21]
	Interactive implanted chips/LEDs	• LED tattoos' programmable lights [22]
Active/Sensor Implants Implants with closed-loop feedback coupled with computational capabilities providing medical information, technological interaction, and extra-sensory input.		
Biometric Sensors	Closed-loop measurement systems	• Heart pacemaker & defibrillator monitor and correct heart function [23] • Inflammation treatment implants: a nerve stimulator that interfaces between the immune and nervous system to treat a broad range of inflammation-related diseases, from diabetes to congestive heart failure [24]
	Open-loop measurement systems	• Implantable sensors measure and transmit glucose levels [25] • Tim Cannon's "Circadia" measures temperature [26]
Non-Medical Functional Implants	Extra-sensory detection	• Moon Ribas' seismic sensor vibrates to earthquakes [27]

Table 1. *Cont.*

Enhancement Type/Category	Description	Significant Example
	Functional computational implants	• Tooth implanted microphone/speaker [28] • Brain activated wireless controller [29]
Interfacing with Nervous System This class of implants are more thoroughly integrated with the body and provide higher levels of integration with the wearer. Through this integration, the feedback loops their systems create can be considered artificial extensions of our own body's.		
Direct Nervous System Interfacing	Nerve to nerve and nerve to machine communication	• Kevin Warwick's proof-of-concept research allowing him to control a robot arm and to create artificial sensation [30] (Warwick also experimented with BrainGate technology which is a neural interface allowing movement of an external device using thought)
Recreating Sensation	Computer generated sensation transmitted to nerves	• "Bionic" fingertip creates sensation of roughness in amputee [31]
III. Brain Enhancement or Modification		
Neuron Control Technologies that directly interface with the brain are the height of cyborg integration. This first class deals with interfaces with the least specificity, generally used to suppress large groups of neuron clusters affected by disease.		
Suppressing Neuron Activity	Implants to control neuron groups	• Deep brain stimulation for treatment of movement disorders [32]
	External brain stimulation	• Transcranial direct-current stimulation for treatment of depression (and others) [33]
Reading the Mind To interface with the brain, technology is required to observe neuron activity and technology is required to affect specific neuron groups. Neuron activity is first measured, then translated by a computer, and finally sent as some form of output, the most compelling of which are affective of other neuron groups—that is, a direct mind link. Telepathy, new sensations, and expanded senses are all resultant technologies from this area of cyborg enhancement.		
Interacting with Technology	Linking thoughts of movement with limbs	• Battelle Memorial Institute partially restores motor control in paralyzed hand via brain chip [34] • Similar techniques can be used to control a robotic arm [35]
Modifying the Brain	Linking thoughts between subjects	• Electroencephalogram linked minds coordinated in virtual game [36]
	Linking sensory areas between subjects	• Miguel Nicolelis directly linked senses between two animal subjects [37]
Influencing Memory The specificity required to read and create neuron activity in relation to senses and thought can also be applied to memory, the recursive core of the human self. Cyborg technologies that influence memory can create and dismantle identity as well as cure degenerative disease, assist in learning, and expand knowledge bases.		
Memory Encoding	Aid in memory creation	• Theodore Berger's artificial hippocampus [38]
	Aid in memory retrieval	• DARPA Restoring Active Memory program [39]
Memory Content	Memory modification	• MIT's Ramirez & Liu creating false memories in lab mice [40]
IV. Exoskeletons and Mobility Aids		
Prostheses of Heightened Function While not technically separate in cyborg classification from 'normal' prostheses, these prostheses tend to be more non-anthropomorphic, have reduced thought control functions, and have more specific design specifications intended to enhance certain abilities.		
Sports Prostheses	Provide performance greater than the biological analogues'	• Ossur's Cheetah Xtend [41] • Hugh Herr's climbing prosthetic [42]

Table 1. *Cont.*

Enhancement Type/Category	Description	Significant Example
Exoskeletons Technology designed around existing limbs to increase mobility. These enhancements can greatly increase our natural capabilities or restore lost functionality. All are closed-loop feedback systems with the body, and, in addition, the powered exoskeletons contain computational systems which increase their level of cyborg enhancement.		
Unpowered	Mechanical extensions of limbs towards performance goal	• Powerskip aids in dramatically increasing jump height [43]
Powered Load Reinforcement	Power-assisted leg exoskeletons designed to take loads off wearer	• Hugh Herr MIT's load bearing leg exoskeleton [44]
Powered Mobility Assist	Powered and computer controlled leg exoskeletons for walking	• Homayoon Kazerooni's exoskeleton [45]

1.1. Medical Necessity Creates Cyborgs

With Table 1 as background for the discussion which follows, recently people's bodies have become enhanced by use of technology with computational capabilities (that is, have become more "cyborg"), based on medical necessity; for example, debilitating disease affecting the central nervous system in the case of Parkinson's patients, or due to accidents or injuries (see [46] for additional examples of cyborgs). One example of a current cyborg is Jerry Jalava who, after suffering injuries sustained from a motorcycle accident, embedded a 2 GB USB drive on the tip of his prosthetic finger, essentially converting his finger into a hard drive; however, unlike other cyborg technologies, the USB drive isn't permanently fused to his finger, instead its inside a rubber tip that fits directly onto the nub of his prosthesis [12]. In contrast, another DIY cyborg, Tim Cannon, has integrated technology directly into his body by implanting a computer chip in his arm that can record and transmit biometrical data [26]. The above devices compute and provide information to the wearer, both characteristics of cyborg technology and of being a cyborg.

Considering cyborg enhancements (Table 1), as indicated by Dietrich and Laerhoven [47], interesting questions are raised related to how technology mediates the relation of person to the "world and self" as reflected in Verbeek's work, which is a postphenomenological approach that technology only bears meaning in a use context (e.g., how cyborg technology is actually used), and specifically the concept of embodied interaction [48]. In fact, the concept of "embodiment" is at the center of phenomenology, which rejects the Cartesian separation between mind and body on which many traditional philosophical approaches are based. In place of the Cartesian model, phenomenology explores our experiences as embodied actors interacting in the world, participating in it, and acting through it, in the absorbed and unreflective manner of normal experience. In terms of our identity resulting from the use of cyborg enhancements (see [3] and [48]), Locke's discussion of personal identity is relevant [49] to the technology presented in this paper. To Locke, personal identity is a matter of psychological continuity, a person psychologically evolves from "an adventure" (that is, becoming cybernetically enhanced) to a new evolved identity (say a transhuman), afterwards, the person's desires, intentions, experiential memories, and character traits may reflect the reality of a new cyborg identity.

Considering the above discussion, an interesting question is how one's perception of their body, that is, their embodiment, is affected by cyborg technologies—for example, are cyborg parts considered an extension of the body, or as separate from the body creating a new sense of identity for an individual? And will one's sense of identity change with the use of neuroprosthetic devices that allow memories to be edited, stored, and transferred? Surely one's sense of identity will be radically altered if one's experiences and memories become artificial and not necessarily tied to actual experiences. Additionally, in the coming cyborg age, will enhancements to human abilities, for example, in the form of telephoto vision or the ability to detect magnetic fields, change not only our functionality but our sense of experiencing the world?

On the point of increasing the computational capabilities of the body, for Canadian filmmaker Rob Spence, loss of vision was the motivating factor for converting him into a cyborg [16]. After an accident left him partially blind, he decided to create his own electronic eye in the form of a camera, which can be used to record everything he sees just by looking around. Even more interesting, though, the eye-camera has wireless capability; the system could allow another person to access his video feed and view the world through his artificial right eye. Unlike with a biological eye, Spence can upgrade the hardware and software of his cyborg enhancement. In our view the ability to upgrade the body is a major benefit of becoming a cyborg (and is likewise a fundamental characteristic of a cyborg) and essentially allows people to transcend human abilities resulting from evolution. It would be easy to imagine fundamentally new ways of seeing, experiencing, and feeling the world through these enhancements.

Given that necessity spawns invention, people paralyzed from spinal cord injuries are beginning to receive brain implant technology which may allow them to move again. How does the technology work? Generally, the "cyborg technology" bypasses the patient's severed spine by sending a signal from the brain directly to technology placed on the patient's muscles [36,45,46]. In the procedure, the surgeons first map the exact spot in the patient's motor cortex that control the muscles in a particular part of the body, then implant a tiny computer chip at that location. The next step is to "teach the chip" how to read the patient's thoughts. This is done by placing the patient inside an MRI machine where the patient watches a video of a hand moving in specific ways and at the same time imagines moving his own hand that way. The implanted chip reads the brain signals, decodes them, and translates them into electrical signals where they are transmitted to the muscles of the patient's forearm. Next, the patient is "plugged into" technology by running a cable from his skull to a computer and then to electrodes on his arm. Effectively, when the patient focuses his mind on moving his hand, it moves. This aspect of cyborg technology—creating a feedback loop between the body and technology—is not only a characteristic of what it means to be a cyborg but a potential "game changer" in connecting our senses and mind to external technology (especially to control the technology using thought), and, given appropriately powerful new technologies, may even influence our sense of experiencing that world. However, this experimental and developing cyborg technology, still needs improvement before it will become common treatment for paralyzed patients and accessible to other populations (for different reasons than medical necessity); for example, it needs to be wireless so there is not a cable plugged into the skull and researchers need to figure out a way to send a signal from the body back to the brain (that is, close the feedback loop) so the patient can sense when his body is moving [6].

As another example of an implantable device which is used due to medical necessity, Setpoint, a technology company, is developing computing therapies to reduce systemic inflammation by stimulating the vagus nerve using an implantable pulse generator [24]. This device works by activating the body's natural inflammatory reflex to dampen inflammation and improve clinical signs and symptoms. Thus far, the company is developing an implanted neuromodulation device to treat rheumatoid arthritis, a disease currently afflicting over two million people in the U.S. alone. Each advance in cyborg devices spurred by medical necessity is leading to advances in technology which make the body more computational, with closed-loop feedback and upgradeable technology, and in some cases controllable by thought—these are all characteristics of the future direction of cyborg technologies.

1.2. Enhancements, Thought Control, and Communication

Even with the brain's tremendous complexity (estimated to be 85–100 billion neurons, with 100 trillion synaptic connections) as shown in the table above, progress is being made towards the integration of the human brain with machines and sensors—this idea will ultimately allow the brain to be "cognitively enhanced" and to have additional computational capabilities [6]. For example, researchers at the Rehabilitation Institute of Chicago, have developed a thought-controlled bionic leg which uses neuro-signals from the upper leg muscles to control a prosthetic knee and ankle [50].

The prosthesis uses pattern recognition software contained in an on-board computer to interpret electrical signals from the upper leg as well as mechanical signals from the bionic leg. When the person equipped with the prosthesis thinks about moving his leg, the thought triggers brain signals that travel down his spinal cord, and ultimately, through peripheral nerves, are read by electrodes in the bionic leg, which then moves in response to the proceeding thought.

Among other things, what's interesting about the human enhancement movement is that it's not just major research centers that are developing thought controlled prosthesis and other enhancement technologies, hackers are beginning to enter the fray which will increase the speed at which the body will become computational (from a digital sense) and will challenge our sense of identity as a new technologically enhanced person. Take body hacker and inventor Shiva Nathan, a teenager, who after being inspired to help a family member who lost both arms below the elbow, created a robotic arm which can be controlled by thought [51]. The technology uses a commercially available MindWave Mobile headset to read EEG waves and uses Bluetooth to send the data to a computer which then translates them into limited finger and hand movements. In addition, in Sweden, researchers at Chalmers University of Technology are developing a thought-controlled prosthesis for amputees in the form of an implantable robotic arm. And in the U.S., the FDA has approved a thought-controlled prosthetic limb invented by Dean Kamen that provides multiple degrees of freedom, is the same size and weight as a natural human arm, and works by detecting electrical activity caused by the contraction of muscles close to where the prosthesis is attached [8]. The electrical signals, initially generated by thought are sent to a computer processor in the prosthetic arm, which triggers a specific movement in the prosthesis. In FDA tests, the artificial arm/hand has successfully assisted people with household tasks such as using keys and locks and preparing food [8].

Researchers at Brown University and *Cyberkinetics* in Massachusetts, are devising a microchip that is implanted in the motor cortex just beneath a person's skull that will be able to intercept nerve signals and reroute them to a computer, which will then wirelessly send a command to any of various electronic devices, including computers, stereos and electric wheelchairs. In this case a person's sense of identity will expand to accommodate feedback not only from the body's sensors, but from sensors on external devices. And consider a German team that has designed a microvibration device and a wireless low-frequency receiver that can be implanted in a person's tooth [28]. The vibrator acts as microphone and speaker, sending sound waves along the jawbone to a person's eardrum. Given that our sense of identity in the world is derived partially through mind-world interactions, developments extending our body's reach and methods of influence upon the world may create a new, or at least significantly different, human phenomenology.

Further, there is also research on brain-to-brain communication, including major efforts in this area from the Defense Advanced Research Projects Agency (DARPA) in the U.S. But in a university research laboratory, University of Washington researchers have created a system that represents a noninvasive human-to-human brain interface, allowing one person to send a brain signal via the Internet to control the hand motions of another person at a different location [52]. The system uses electrical brain recordings and a form of magnetic stimulation, in which one person wearing a cap with electrodes is hooked up to an electroencephalography machine (which reads electrical activity in the brain) that sends a signal to another person with a cap equipped with the stimulation site for a transcranial magnetic stimulation coil which is placed directly over the person's left motor cortex, (which controls hand movement). As a proof-of-concept study, Professor Rao looked at a computer screen while playing a simple video game with his mind. When he was supposed to fire a cannon at a target, he imagined moving his right hand, causing a cursor to hit the "fire" button. Almost instantaneously, another person who wore noise-canceling earbuds and wasn't looking at a computer screen, involuntarily moved his right index finger to push the space bar on the keyboard in front of him, as if firing the cannon. The technologies used by the researchers for recording and stimulating the brain are both well-known. Electroencephalography, or EEG, is routinely used by clinicians and researchers to record brain activity noninvasively from the scalp. Transcranial magnetic stimulation is a noninvasive way of delivering stimulation to the brain to elicit a response. Its effect depends on where the coil is placed; in this case, it was placed directly over the brain region that controls a person's right hand. By activating these neurons, in a proof-of-concept study, Rao and his team concluded that the stimulation convinced the brain that it needed to move the right hand [53].

1.3. Computational Skin

If we can design artificial limbs controlled by thought and if we can implant technology into the body, can we enhance the skin, the largest sense organ, with computational capabilities? If so, this would be a major step in our cyborg future. Based on recent advances in technology, the answer is yes, but first a digression into popular culture. Enhancing the body's surface such that it is transformed into a "computational device" represents a change in our very self-identity as our skin is perceived as the barrier between our internal self and the external world—the *surface* of a person's identity, if you will. We theorize that any change to that visual biological-self model has the potential to increase our capabilities and interactiveness with the world, but also to potentially shift the normal of human "appearance".

On the point of popular culture and our cyborg future, a recent study showed that nearly forty percent of Americans under the age of forty have at least one tattoo (see generally [54,55]); however, like any trade, the tattoo industry must innovate to expand and gain new clients. In an analog world, one way to innovate is to make the switch to digital technology. Rather than being passive as are current tattoos, digital tattoos are active, they *do* things, and they are getting smart [17]. Digital tattoos have the potential to do more than serve the function of art or self-expression, even though these are laudable goals, they will indeed become digital devices as useful as smartphones—and may even monitor our health.

It is possible now to use a type of ink in a tattoo that responds to electromagnetic fields, which raises a host of new opportunities for cyborgs. In fact, Nokia patented a ferromagnetic ink technology that can interact with a device through magnetism. The basic idea is to enrich tattoo ink with metallic compounds that are first demagnetized (by exposing the metal to high temperatures) before the ink is embedded in a person's skin. Once the tattoo has healed, the ink is re-magnetized with permanent magnets. The resulting tattoo is then sensitive to magnetic pulses, which can be emitted by a device such as a cellular phone. Interestingly, a digital tattoo would allow a person's ringing phone to result in a haptic sensation experienced by the body; that is, the person would experience the phone ringing literally through the tattoo; an interesting computational capability for cyborgs and an interesting change in our use of technology and of our body.

If the tattoo consists of putting electronics on the surface of the skin, many more possibilities for body hacking exist. For computational skin, materials scientist and University of Illinois Professor John Rogers is developing flexible electronics that stick to the skin to operate as a temporary tattoo [18]. These so-called "epidural electronics" (or Biostamp) are a thin electronic mesh that stretches with the skin and monitors temperature, hydration and strain, as well as monitoring a person's body's vital signs [17,18]. The latest prototype of the Biostamp is applied directly to the skin using a rubber stamp. The stamp lasts up to two weeks before the skin's natural exfoliation causes it to come away. Rogers is currently working on ways to get the electronics to communicate with other devices like smartphones so that they can start building apps (eventually such devices will communicate with devices that are implanted within the body). Developing sensors worn by or implanted within the body that communicate with and controls external devices is a new capability for humans, essentially extending the "reach of the body" beyond that of the body's physical boundaries. Google, isn't far behind in developing digital tattoos, as the company's Advanced Technology and Projects Group patented the idea of a digital tattoo consisting of various sensors and gages, such as strain gauges for tracking strain in multiple directions (how the user is flexing), EEG and EMG (electrical impulses in the skeletal structure or nerves), ECG (heart activity), and temperature.

Considering another digital tattoo designed for a medical monitoring purpose, University of Pennsylvania's Brian Litt, a neurologist and bioengineer, is implanting LED displays under the skin for medical and bio-computation purposes [55]. These tattoos consist of silicon electronics less than 250 nanometers thick, built onto water soluble, biocompatible silk substrates. When injected with saline, the silk substrates conform to fit the surrounding tissue and eventually dissolve completely, leaving only the silicon circuitry. The electronics can be used to power LEDs that act as photonic tattoos. Litt is perfecting a form of this technology that could be used to build wearable medical devices—say, a tattoo that gives diabetics information about their blood sugar level. These examples highlight the use of cyborg devices to compute data, monitor the body, and eventually form closed-loop feedback systems with the body. Additionally, they demonstrate our increasing tendency to electively distance ourselves from our natural biology and technologically modify our very human form.

1.4. Body Hackers and Implantable Sensors

The body hacking movement, especially about implantable sensors within the body, gained momentum from the work of Professor Kevin Warwick starting in 1998 at the University of Reading [30]. Professor Warwick was one of the first people to hack his body when he participated in a series of proof-of-concept studies which first involved implanting a sensor into his shoulder (see his paper, this special edition). Warwick's "cyborg application" consisted of the use of an RFID implant which allowed Professor Warwick to switch on lights and open doors as he entered rooms (thus Warwick was-able-to link his body directly to external devices). Later, others extended Warwick's seminal work using RFID devices and other implantable sensors. For example, in an extension of Professor Warwick's early work, Dr. John Halakha of Harvard Medical School, chose to be implanted with an RFID chip used to access medical information [56]. His implant stores information which can direct anyone with the appropriate reader to a website containing his individual medical data. He believes that implantable chips such as these can be valuable in situations where patients arrive at the hospital unconscious or unresponsive.

Another person with an RFID implant, Meghan Trainor has a less pragmatic but highly creative application for her implant [57]. Trainor received the implant as part of her master's thesis for NYU's Interactive Telecommunications Program. Her implant serves as part of an interactive art exhibit; RFID tags are embedded in sculptures which can be manipulated to play sounds stored in an audio database. Trainor can use the implant in her arm to further manipulate these sounds. Additionally, body hacker Anthony Antonellis implanted an RFID chip into his hand which can be wirelessly accessed by a smartphone [21]. While the chip holds only about 1 KB to 2 KB of data, it allows Antonellis to access and display an animated GIF on his phone that is stored on the implant. Since the RFID chip can transfer and receive data, Antonellis can swap out 1KB files as he pleases. Antonellis views the implant as a "net art tattoo", something for which quick response codes (QR, or matrix barcode), are commonly used. Similarly, Karl Marc, a tattoo artist from Paris designed an animated tattoo that makes use of a QR code and a smartphone [58]. The code basically activates software on the phone that makes the tattoo move when seen through the phone's camera. The use of cyborg technology to transform the body into electronic art is surely a new mode of interacting with the world and a hint of what is to come in the future.

1.5. Vision Enhancements

Given that the eye is a major sensory organ in terms of providing information about the world, there is extensive current research oriented towards creating an artificial eye with "telephoto capabilities" (and research to detect energy beyond the range of our sensors). Who would benefit from such technology? Clearly the cyborg movement would benefit from providing the visual system enhanced computational abilities, but so too would the millions of people worldwide who have the advanced form of age-related macular degeneration (AMD), a disease which affects the region of the retina responsible for central, detailed vision. For such people an implantable telescope could help restore the essential visual modality [9]. In fact, in 2010, the U.S. Federal Drug Administration (FDA) approved an implantable miniature telescope (IMT), which works like the telephoto lens of a camera [9]. The IMT technology reduces the impact of the central vision blind spot due to end-stage AMD and projects the objects the patient is looking at onto the healthy area of the light-sensing retina not degenerated by the disease.

The tiny telescope is implanted behind the iris, the colored, muscular ring around the pupil and represents a tantalizing vision of our cyborg future consisting of enhanced sensory modalities. And of course, since our sense of identity is derived, among others, from sensory information—"hacking" the visual modality could potentially alter the information we use to perceive and make sense of our position in the world.

Some people appear intent on changing their senses and, by extension, their identity by becoming transhuman. For example, Neil Harbisson, who was born with a rare condition (achromatopsia) that allows him to see only in black and white and shades of grey, has become a cyborg due to necessity [15]. After viewing a talk on cybernetics, in the spirit of a hacker, Neil wondered if he could turn color into sound, based on the idea that a specific frequency of light could be made equivalent to a specific sound wave. To become a cyborg, Neil had a sound conducting chip implanted in his head, along with a flexible shaft with a digital camera on it, attached to his skull [15]. With his latest software upgrade, Neil says he is able to hear ultraviolet and infrared frequencies, can have phone calls delivered to his head, and has a Bluetooth connection which allows him to connect his "Eyeborg" to the Internet. Using "cyborg technology" Neil has created a new way of perceiving the world and has thus expanded the boundaries of human experience and interaction with the world.

2. Brain Enhancements and Neuroprosthesis

Through the Restoring Active Memory (RAM) program, the U.S. defense research institute, DARPA, is funding research to accelerate the development of technologies able to address the public health challenge of helping service members, and others, overcome memory deficits by developing new neuroprosthetics to bridge gaps in the injured brain [59]. The end goal of RAM is to develop and test a wireless, fully implantable neural-interface medical device for human clinical use. A number of additional and significant advances, however, will be targeted on the way to achieving that goal; such advances may be milestones for our cyborg future.

To start, DARPA is supporting the development of multi-scale computational models with high spatial and temporal resolution that describe how neurons code declarative memories—those well-defined parcels of knowledge that can be consciously recalled and described in words, such as events, times, and places [39,59]. Researchers will also explore new methods for analysis and decoding of neural signals to understand how targeted stimulation might be applied to help the brain reestablish an ability to encode new memories following brain injury. "Encoding" refers to the process by which newly learned information is attended to and processed by the brain when first encountered. Building on this foundational work, researchers will attempt to integrate the computational models developed under RAM into new, implantable, closed-loop systems able to deliver targeted neural stimulation that may ultimately help restore memory function [59]. Interestingly, RAM and related DARPA neuroscience efforts are monitored by members of an independent Ethical, Legal, and Social Implications (ELSI) panel [60]. Communications with ELSI panelists supplement the oversight provided by institutional review boards that govern human clinical studies and animal use. Given that cyborg technology can be used for multiple purposes, this panel provides the oversight needed to monitor developments in the field.

Additional progress is being made in other areas of brain–computer interface design, Figure 1 provides a broad overview. For example, scientists have used brain scanners to detect and reconstruct the faces that people are thinking of. In one study, Yale scientists hooked participants up to an fMRI brain scanner—which determines activity in different parts of the brain by measuring blood flow—and showed them images of faces in two sets [61]. The first set established a statistical relation between the images of the faces and corresponding areas of brain activity while the second set attempted to recreate those faces from observation of brain activity alone. Alan Cowen and Professor Marvin Chun were, in fact, able to recreate images of these faces to some degree of likeness [61]. One can imagine in the future that a witness to a crime might reconstruct a suspect's face based on "extracting" the image from his mind (of course, this will raise privacy issues). However, Yale researchers pointed out that an important limitation of the technology as it exists now, is that this sort of technology can only read active parts of the brain, not passive memories.

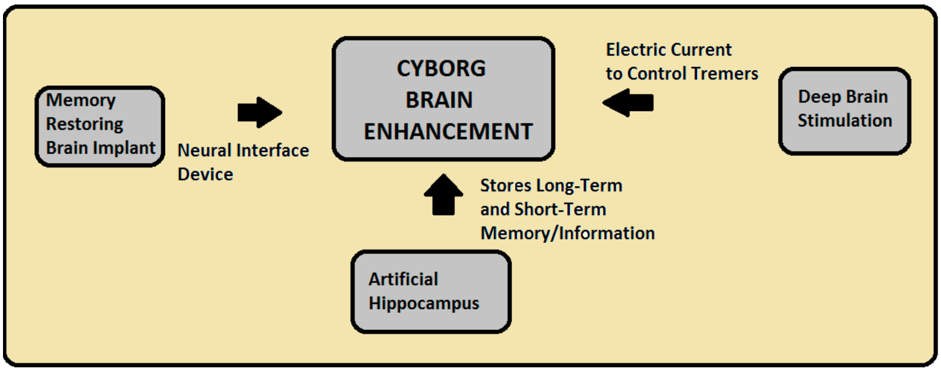

Figure 1. Some basic technologies of cyborg brain enhancement.

A major advance in cyborg technology is the development of a hippocampus prosthesis, which we view as a type of cognitive prosthesis (a prosthesis implanted into the nervous system in order to improve or replace the function of damaged brain tissue) [62]. In some cases, prosthetic devices replace the normal function of a damaged body part; this can be simply a structural replacement (e.g., reconstructive surgery) or a rudimentary, functional replacement. As an important cyborg technology, University of Southern California researchers are testing the usefulness of an artificial hippocampus which will mimic the brain's memory center [62]. The device may one-day help those with brain damage, epilepsy, and Alzheimer's disease. Additionally, the same device could, with additional developments, allow one's brain to be directly connected to the Internet which could potentially project our self-identity to the emerging Internet of Things. To create the neuroprosthesis, lead researcher Theodore Berger and his team used principles of nonlinear systems theory to develop and apply methods for quantifying the dynamics of hippocampal neurons. In this approach, properties of neurons are assessed experimentally by applying a random interval train of electrical impulses as an input and electrophysiologically recording the evoked output of the target neuron during stimulation [62]. The input train consists of a series of impulses, with interimpulse intervals varying according to a Poisson process. Thus, the input is "broadband" and stimulates the neuron over most of its operating range; that is, the statistical properties of the random train are highly consistent with the known physiological properties of hippocampal neurons. Nonlinear response properties are expressed in terms of the relation between progressively higher-order temporal properties of a sequence of input events and the probability of neuronal output, and are modeled as the kernels of a functional power series [38]. This example highlights the complexity of the engineering behind cyborg technologies designed for the brain and the importance of algorithms for our cyborg future.

Another "cyborg" brain technology is deep brain stimulation (DBS) which consists of a surgical procedure used to treat several disabling neurological symptoms—most commonly the debilitating motor symptoms of Parkinson's disease (PD), such as tremor, rigidity, stiffness, slowed movement, and walking problems [32]. The procedure is also used to treat essential tremor and dystonia. At present, the procedure is used only for individuals whose symptoms cannot be adequately controlled with medications. DBS uses a surgically implanted, battery-operated medical device called an implantable pulse generator (IPG)—similar to a heart pacemaker and approximately the size of a stopwatch to deliver electrical stimulation to specific areas in the brain that control movement, thus blocking the abnormal nerve signals that cause PD symptoms [32]. Before the procedure, a neurosurgeon uses magnetic resonance imaging (MRI) or computed tomography (CT) scanning to identify and locate the exact target within the brain for surgical intervention. Some surgeons may use microelectrode recording—which involves a small wire that monitors the activity of nerve cells in the target area—to more specifically identify the precise brain area that will be stimulated. Generally, these areas are the thalamus, subthalamic nucleus, and globus pallidus. The lead (also called an electrode)—a thin, insulated wire—is inserted through a small opening in the skull and implanted in the brain. The tip of the electrode is positioned within the specific brain area. The extension is an insulated wire that is passed under the skin of the head, neck, and shoulder, connecting the lead to the implantable pulse generator. The IPG (the "battery pack") is usually implanted under the skin near the collarbone. Once the system is in place, electrical impulses are sent from the IPG up along the extension wire and the lead and into the brain. These impulses block abnormal electrical signals and alleviate PD motor symptoms.

Additionally, the work by Professor Potter and his team [63] involving embodied networks of cultured neurons in simulation and robotic studies is relevant for our cyborg future. A "cultured neuronal network" is a cell culture of neurons that is used as a model to study the central nervous system, especially the brain. For future cyborgs, cultured neuronal networks may be connected to an input/output device such as a multi-electrode array, thus allowing two-way communication between the person and the network. Interestingly cultured neurons are often connected via computer to a real or simulated robotic component, creating a hybrot or animat, respectively [64]. Hochberg and Donoghue [65] with colleagues have created brain–computer interface technology to demonstrate that people with paralysis can control external devices by translating neuronal activity directly into control signals for assistive devices (specifically a robotic arm) [66].

Extending his original work with RFID sensors, Professor Warwick had a BrainGate interface implanted into his nervous system to link his body to technology external to his body. Most notably, Professor Warwick could control an electric wheelchair and an artificial hand, using the neural interface [30]. In addition to being able to measure the signals transmitted along the nerve fibers in Professor Warwick's left arm, the implant was also able to create artificial sensation by stimulating the nerves in his arm using individual electrodes. This bi-directional functionality was demonstrated with the aid of another person and a second, less complex implant connecting to her nervous system. Based on Warwick's results, this was an early proof-of-concept display of electronic communication between the nervous systems of two humans.

3. Towards "New Senses"

With regard to modifying and enhancing the body, can a new sense be created? In our view, new senses will certainly be developed if by "new sense" one meant to enhance a current sense in such a way that sensory information beyond the range of its sensory receptor(s) can be experienced. Substituting one sense for another is a well-researched topic and represents another way to modify the body and create a cyborg future. Increasing and/or extending the range of our senses may be desirable given we see and hear across certain frequencies, and that the eyes and ears can only detect information within a given distance to the sensory receptors. Given this explanation, Neil Harbisson already has an extra sense, thusly new states of identity for Neil are already being created. In the future, by hacking and modifying the bodies already existing senses, we may develop enhanced vision and greater sensitivity to olfactory, gustatory, or haptic information—we may even combine senses. As we create new senses for humans by the use of cyborg implants, without considering post-human levels of modification, will one's identity change? In the sense of Locke, would it even be possible for our identity not to change?

While EEG and fMRI technologies are leading to significant advances in the use of brain scans for lie detection, other research in neuroscience is more directly related to the topic of telepathic communication, a totally new mode of communication. How will telepathic communication impact one's sense of their individuality if brains are telepathically networked together? Professor Miguel Nicolelis from Duke University has developed important technology for the brain in this area that we believe is leading to a cyborg future for humanity [37]. His research is oriented toward brain-to-brain communication, brain machine interfaces and neuroprosthesis in human patients and non-human primates. Based on his studies, Dr. Nicolelis was one of the first to propose and demonstrate that animals and human subjects can utilize their electrical brain activity to directly control neuroprosthetic devices via brain–machine interfaces. As early as 2012 Professor Nicolelis speculated about the possibility that two brains could exchange information [37], and later, Nicolelis reported that his research team at Duke University Medical Center had achieved a back-and-forth exchange between two rodent brains. To test his brain interface technology, his team trained two animals to press one of two levers when an LED turned on in exchange for a drink of water. Microelectrodes were placed in each of the two animals' cortices and when one rat pressed the correct lever, a sample of cortical activity from that rat's brain was wired to the second animal's brain located in a chamber where the "it's-time-to-drink" LED was absent [37]. As evidence that information was exchanged between the two brains, the rat on the receiving end of the prosthesis proceeded to press the correct lever (to receive a drink) that had been messaged over the brain link. Summarizing the results—Nicolelis and his team provided proof-of-concept technology and preliminary results that telepathy may be possible as a future form of communication.

Related to Professor Nicolelis's work, results from studies with human subjects show that telepathy may in fact be a viable technology for the general public within a few decades (or less!). For example, using EEG technology, researchers at the University of Southampton, England, reportedly demonstrated communication from person-to-person using thought [67]. More recently, as described earlier in this paper, at the University of Washington, researchers demonstrated a working brain-to-brain interface with human subjects also using EEG technology [68]. According to the researchers, the next step is to determine *what* kind of information can be sent between people's brains.

In a study which has importance for our cyborg future, Duke University neuroscientist Miguel Nicolelis, and his team report that they have created a "sixth sense" through a brain implant in which infrared light is detected by lab rats [37]. Even though the infrared light can't be seen, lab rats are able to detect it via electrodes in the part of the brain responsible for the rat's sense of touch—so remarkably, the rats reportedly feel the light, not see it. In order to give the rats their "sixth sense", Duke researchers placed electrodes in the rat's brains that were attached to an infrared detector [37]. The electrodes were then attached to the part of the animals' brains responsible for processing information about touch. The rats soon began to detect the source of the 'contact' and move towards the signal. In addition to these important findings, the Duke scientists found that creating the infrared-detecting sixth sense did not stop the rats from being able to process touch signals, despite the electrodes (providing input for the infrared detection system) being placed in the tactile cortex. Sixth sense or not, in our view, the study by Nicolelis and his team is another step toward integrating brain–computer technology into the human body; and thus contributing to a cyborg future that will alter our senses and change our sense of identity as mere products of biology [6,37].

Additionally, in the military domain, DARPA, through funding, is trying to build "thought helmets" to enable telepathic communication using brain–computer interfaces to give soldiers extra senses, such as night vision, and the ability to "see" magnetic fields caused by landmines [39]. Finally, as another example, to create a "sixth sense", some DIY cyborgs have implanted magnets in their fingertips [69]. A cyborg with a magnet implanted in their finger, can sense magnetic fields that would otherwise be completely undetectable. The implant allows those who have received it the ability to not only sense magnetic fields, but to pick up tiny metal objects with their fingertips, and determine whether metals are ferrous. How extra senses will affect our sense of identity as a human being will be a fascinating topic of discussion in the near future.

4. Modifying Memory

As a future cyborg technology, neuroscientists foresee a future world where minds can be programmed in order to create artificial memories. In terms of challenges to one's sense of identity in the world, cyborg technologies which can edit memories [6], or add new memories to one's repertoire of experiences, has the potential to fundamentally change our self-identity, world view, and more [53]. Based on recent advances in brain-to-brain communication, some scientists argue that memories may be implanted into a person's mind, and that memories from one mind can be transferred to another. In fact, scientists have already successfully implanted a false memory into the brain of a mouse. To create a memory interface, MIT scientists Steve Ramirez and Xu Liu tagged brain cells in one mouse associated with a specific memory and then tweaked that memory to make the mouse believe an event had happened (to that mouse) when it hadn't; other laboratories are producing similar results [40]. While implanting a memory in humans equipped with a neuroprosthetic device won't happen in the immediate future, Ramirez et al., have shown that in principle, it should be possible to isolate a human memory and activate it [40]. In fact, Michael J. Kahana, who serves as director of the University of Pennsylvania's Computational Memory Lab commented on the MIT study, "We would have every reason to expect this would happen in humans as it happened in mice" (see [70]). Clearly, improvements in neuroprosthetic technologies are occurring rapidly and moving humanity toward a cyborg future.

5. Conclusions and Future Directions

Barfield [6] proposed that the capabilities of "cyborg technology" consists of several characteristics: (1) the technology is upgradeable allowing software and hardware improvements to be applied to the body in ever shorter cycle times (see [71]); (2) the technology offers the body additional computational capabilities, thus transforming the body into an information processing technology; (3) cyborg technology is integrated with the body through closed-loop feedback systems; and (4) is becoming more and more controllable by thought [6]. If these trends of innovation and research continue, we will soon be faced with a very new sort of human with very different sorts of capabilities [6]. How the law and public policy relates to technologically enhanced people is addressed in another paper by the authors [72], but surely, major changes in public policy and law will need to be debated and enacted to account for people with superior and quite different abilities.

In light of our impending cyborg future, how we view ourselves as individuals and as humans is certain to become subject to upheaval and change. As prostheses become more advanced, and additional capabilities more integrated within the body and brain, it would not be difficult to imagine an individual electing to replace their basic biological parts with the upgraded cyborg version—but how will this capability affect our sense of identity? Add that to the growing trend of body hacking and modification and it does not seem unreasonable to assume that in the near future we humans may look very different than we do today [73]. Our sense of humanness, insomuch as it is rooted in our biology, will quickly erode as these enhancement technologies develop and grow in use. The body of a human may have little to do with the destiny of their birth; as we replace our bodies with the customizable and the upgradable, so we replace the old world of biological phenotypes with a new, creative world of our making.

The mind is also on the verge of transformative changes. Brain implants that repair damaged memories might one day lead to the creation of new memories or telepathic communication (see [74]). Brand new and exotic experiences could be purchased and uploaded. Entire lives could be lived in an instant. Couple this with the potential for memory modification and we would be left with a sense of self and identity decoupled from memories derived from interacting with the world. Psychologically continuous "selves" would no longer indicate distinct persons. Expanded consciousness's through brain implants and computer interfacing could make tracing identity through biological continuity equally problematic. If we are no longer what we remember ourselves to be and have expanded far beyond our biology, then who are we? If we can modify our bodies and our memories, then we can modify our senses and our very ways of being in the world. The core phenomenology of being human will change, perhaps to the point of unrecognizability. What then could we say of human nature if all that we hold to be consistent and true is subject to modification—or even attack? Certainly, new philosophies on identity will be required in parallel with new social structures and technological advancements.

The phenomena and minutia of our existence have forever been locked to the biology of our brains, but as dynamic and varied as brains are, they are limited by their finite physicality. The human of the near future could be nearly unlimited in their cognitive capabilities. How could the man who sees in radio and feels the solar wind relate to the old human? However the future human manifests, the new human could very possibly be beyond our current understanding. The first steps in that journey have already been made.

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