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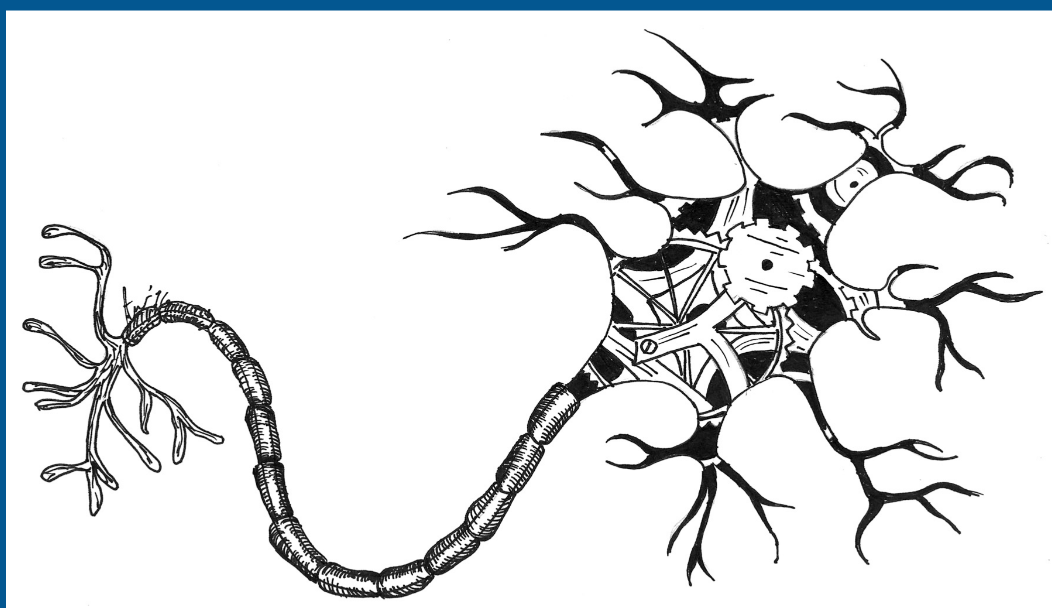

Original artwork by Ashley Wang '16

# Upper Limb Prosthetics

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Losing an arm or a hand, or being born without one, can greatly decrease a person's ability to fully function in society (Jarrassé, Maestrutti, Morel & Roby-Brami, 2015). Thankfully, humans have found ways to augment these missing body parts with artificial devices, called prosthesis ("Prosthesis," 2016).

Prosthetics can fall into three general categories: those that are non-functional and are worn just for aesthetic purposes, those that are controlled mechanically by other, remaining body parts, and lastly, and most recently, those that are controlled by the remaining nerves and muscles on the stump of the missing limb (Jarrassé, Maestrutti, Morel & Roby-Brami, 2015). As functioning prosthetics advance, they have been developed with increased mobility and resemble an arm in function as well as appearance. Prosthetics are unique to hybrid biotech systems in that they are not added on to the body system, but they actually replace a missing part. Prosthetics both functions as part of the body, and requires humans to train with it to incorporate it into regular functioning (Jarrassé, Maestrutti, Morel & Roby-Brami, 2015).

There are 24 muscle groups in the hand alone, and three major nerves in the arm and hand – the ulnar, median, and radial (Taylor & Schwarz, 1955). The motor cortex area that is devoted to the hand is close to equal to the areas for the rest of the arms, body, and legs, giving the hand an unparalleled amount of complex motion control and dexterity (Taylor & Schwarz, 1955). When a hand reaches for an object to pick it up, it relies not only on these muscles, but on sensory organs on the skin surface. The threshold for touch on the tip of the finger is 2 gm per sq. mm, while the forearm is 33 gm per sq. mm, demonstrating unparalleled sensitivity (Taylor & Schwarz, 1955). Hands can thus perform tactile tasks that rely on extreme sensitivity, for example, recognizing the shape of an object just by holding it, and detecting vibrations with amplitudes that are only 0.01 μm at 300 Hz (Jones, 2006). The upper limb, as a mechanism that can be imitated by the technology of prosthetics, should be viewed as a neurobiological system because motor actions are only possible due to signals sent from the brain that allows for muscle contractions, and conversely, tactile sensitivity at the skin receptors sends neural signals to the cerebral cortex, which creates sensory perception (Jones, 2006). As Frederic Wood Jones, who wrote *The Principles of the Anatomy as Seen in the Hand* (1919) said, “It is not the hand that is perfect, but the whole nervous mechanism by which the movements of the hand are evoked, coordinated and controlled” (Jones, 2006).

Recently, researchers have been developing technology that can harness an individual’s existing nerve and muscle signaling capabilities on a remaining part of a limb, so that just like a biological arm, a prosthetic limb can be controlled neurologically. This rapidly developing field is creating a true neurobiological-technology hybrid system. The basis of the technologies is that electromyography signals are picked up from the surface of the skin on the residual limb by electrodes, and then turn the muscle contractions into computerized directions for the prosthesis (Li, Schultz & Kuiken, 2010).

Targeted muscle reinnervation is one of the newest, most successful techniques using myoelectric signals. Through a surgical procedure, nerve endings from the arm stump are transferred into muscles in the chest, which allows the electromyogram signals to be amplified (Kuiken *et al*, 2009). The signals are then recorded on the surface of these muscles and turned into corresponding hand movements for the prosthetic. In clinical trials done by Kuiken *et al,* participants using targeted muscle reinnervation were able to complete 96.3% of the elbow and wrist movement tasks, compared to the control participants, who were able to complete 100%. This was discussed as a high success rate (Kuiken *et al*, 2009).

Yet another new, exciting technology is the Implantable Myoelectric Sensors (Pasquina *et al*, 2015). Electromyography signaling relies on electrodes on the surface of the skin, which is not always reliable due to possible poor connection and therefore poor transmission. The electrodes can also only pick up muscle activity from exterior muscle groups. With the Implantable Myoelectric Sensors, more specific electrical activity can be picked up with greater accuracy, and is then transmitted wirelessly to the prosthesis. This technology allows greater degrees of freedom, and allows for multiple, simultaneous movements in a way that electromyogram signaling did not (Pasquina *et al*, 2015).

However, even with almost full motor capabilities restored using these new technologies, the prosthetic arm and hands discussed above still fall short of the full functions of the biological arm and hand. We not only rely on this neurobiological system to move and grasp objects, but also to feel these objects to know how hard to grasp them, and give us a tactile understanding of our surroundings (Light, Chappell, Hudgins, & Engelhart, 2002). Recently, scientists have found a way to restore this sensation with a prosthetic hand using something called transversal intrafascicular multichannel electrodes (Raspopovic *et al*, 2014). As we can see from Figure 1, these electrodes are implanted at the median and ulnar nerves on the remaining part of the amputated limb, and then attached to the prosthesis. When touching an object, sensors on the pads of the prosthesis then stimulate the transversal intrafascicular multichannel electrodes using electrical current, which get sent to the brain by the intact nerve, resulting in immediate sensory perception (Raspopovic *et al*, 2014). In the case study done by Raspopovic *et al* in 2014, the individual was able to vary his clasping force on command when grasping objects, and was also able to differentiate between three different objects of different firmness while blindfolded. This demonstrates an ability to not only manipulate objects, but to do so based on tactile sensory information (Raspopovic *et al*, 2014). This exciting advancement is called bidirectional prosthetics, meaning that technology is not only able to effectively harness information from our neurobiological systems and transfer them as output to control the motor function of a prosthetic, but is now also able to transfer immediate input from our surroundings back into those neurobiological systems, a loop that can be observed in Figure 1 (Raspopovic *et al*, 2014).

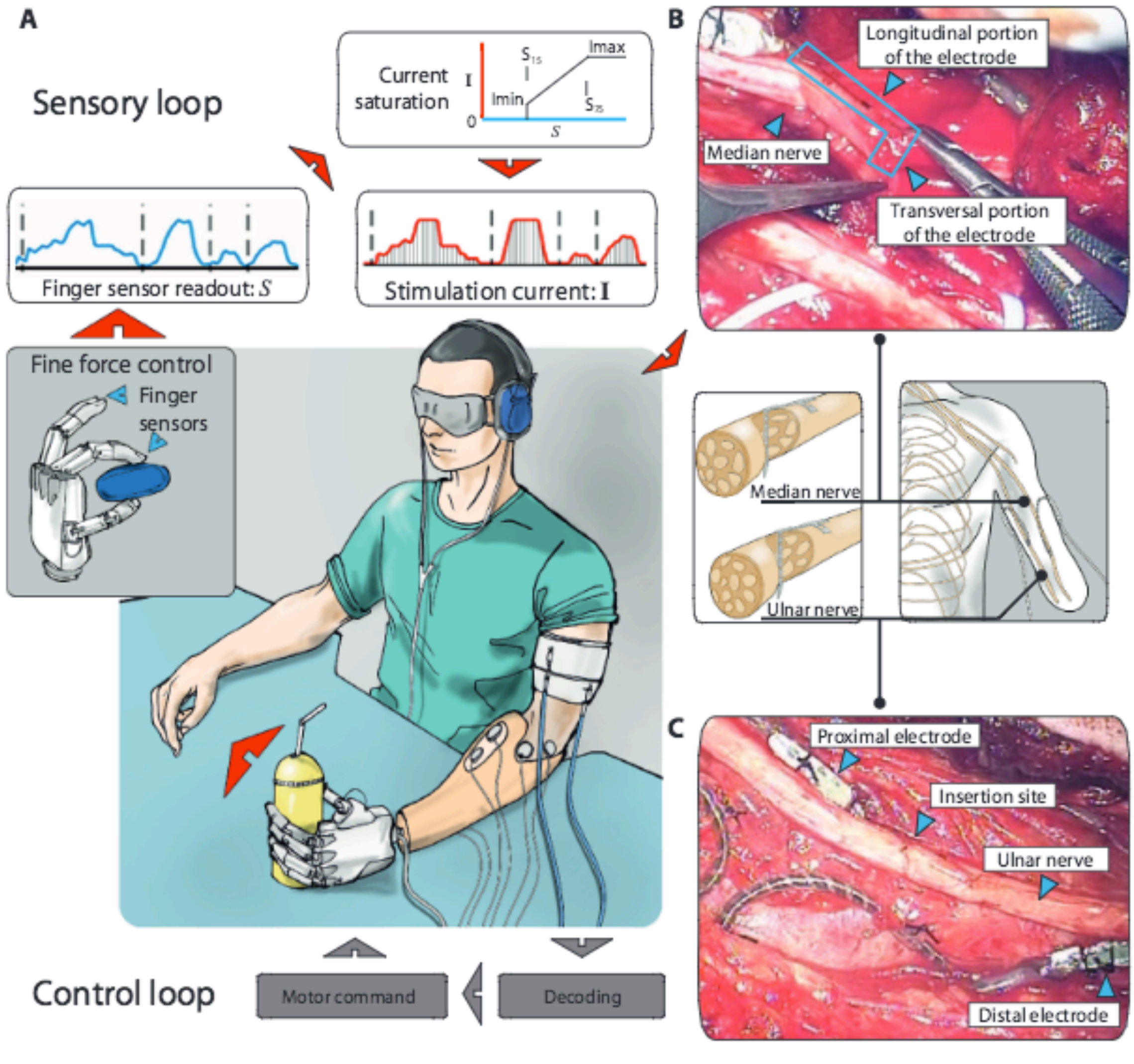


**Figure 1.** *Bidirectional Prosthesis Sensory Control Loop.* This visual depicts the bidirectional nature of prosthetics using transversal intrafascicular multichannel electrodes. A) shows the "Sensory Loop" part of the technology, where readout from the finger sensors on the prosthetic are turned into a stimulation current in the medial and ulnar nerves. B) is a photograph of the electrode at the medial nerve, with an illustration below of the location of both the median and ulnar nerve in the arm. C) is a photograph of the implanted electrodes at the ulnar nerve. Small gray arrows below the illustration show the "Control Loop" portion of the technology, where information is being decoded from the surface electrodes on the arm to perform a motor command (in the case of the image, grasping a bottle). As the man grasps the bottle, another finger sensor readout will occur, producing stimulation current, and completing the bidirectional loop. Figure from Raspopovic *et al*, 2014.

A study done by the French Health Authority in 2010 found that a quarter of upper arm amputees decide not to use prosthetics (Jarrassé, Maestrutti, Morel & Roby-Brami, 2015). This is largely due to the fact that prosthetics have never been as effortlessly part of the human body as a biological limb, which can cause frustration and discomfort on the part of the amputee (Jarrassé, Maestrutti, Morel & Roby-Brami, 2015). However, as bidirectional prosthetics advance, and the artificial limb emulates the biological arm not just in appearance and output, but also in input, it seems likely that the number of individuals who opt out will decrease, because the prosthetic can be included into the body schema (Jarrassé, Maestrutti, Morel & Roby-Brami, 2015). As prosthetics become incorporated into the body schema, they will also become more of an irreversible merger, because the new limb will begin to perform just as well, if not better, than the biological arm.

Studies are also being done to assess the economic and logistical feasibilities of printing prosthetic limbs in a 3D printer, especially as a cheaper alternative for children who grow out of prosthetics quickly (Zuniga *et al*, 2015).

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Figure 1. *Bidirectional Prosthesis Sensory Control Loop.* Jarrassé, N., Maestrutti, M., Morel, G., Roby-Brami, A. (2015). Robotic prosthetics, *IEEE Technology and Society Magazine* http://biofag.com/files/Sci_Transl_Med-2014-Raspopovic-222ra19.pdf

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I have abided by the Wheaton Honor Code in this work.

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