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Investigation of Permanent Tattoos to Increase Myoelectric Signal Connectivity in Prosthetics

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Investigation of Permanent Tattoos to Increase Myoelectric Signal Connectivity in Prosthetics

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Masters of Science In Orthotics and Prosthetics

by

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Acknowledgements

Thank you to all of my fellow “aged” classmates who kept me motivated to complete this program and let me vent when I got bogged down in the grind of doing homework in my forties. A special thank you goes to Allen Ingersoll, who introduced me to the world of prosthetics all those years ago, triggering this random idea to tattoo people to get their prosthetics to work better. I’m sorry it took so long for me to come around to the idea that I too, could be a practitioner in this profession.

Dedications

This paper is dedicated to my wife who encouraged me to drop what I was doing in life and go back to school for something I was passionate about and would affect positive change in the lives of others. You allowed me to do something that gives me satisfaction every day. I hope to be able to repay your generosity and help you find something that “fills your cup” each and every day. Thank you for believing in me.

Abstract

Myoelectric prosthetics offer users increased functionality in many facits of their lives. However, maintaining reliable connectivity between sEMG sensors and targeted muscle locations can be problematic. Volume fluctuation of the residual limb, dirt, sweat, and movement of the socket and sensor over the limb can all because of signal disruption leading some users to find the myoelectric prostheses, costing thousands of dollars, to be unreliable, and stop using it. To increase connectivity between the optimal myoelectric sites and sEMG sensors, this paper proposes the use of permanent ink tattoos to create a stable location which a sensor can move over when a prosthetic socket shifts, but still have connectivity to sites with the strongest myoelectric signal.

This study proposes to start by testing various permanent bio-compatible tattoo inks for electrical connectivity in skin. Then test for optimal pattern designs in static and dynamic sensor scenarios to determine whether or not levels of myoelectric signals are higher and clearer (less electrical resistance in ohms) than unprepared skin.

This technique may provide benefits to those using surface EMG sensor who experience interruptions in myoelectric signals, preventing the performance of intentional prosthetic functions. This could also benefit the development of implanted EMG electrodes or neural implants, as a means to provide efficient signal transmission through the skin.

Keywords: *Myoelectrics, target muscles, tattoos, conductive ink*

Table of Contents

Chapter 1: Introduction

Communication between devices and technology is a necessity in the modern world. Televisions communicating with ‘cloud’ based media services, smart phones seemingly communicating with everything from headphones to automobiles to light switches and even the notoriously non-communitive printer. Even roads that communicate with the traffic driving on them (Trubia et al, 2020). For those who have experienced limb loss, there is the long help desire regain their lost functionality by being able to intuitively communicate with their prosthetic device. Myoelectric prosthetics have been bringing the possibility to fulfill this role around for several decades, for the user to only think about the action they want to perform, opposed to needing to do unrelated movements compared to the desired action when operating a body powered prosthesis (Uellendahl, 2017), shoulder protraction to open a upper limb terminal device for example. Despite the advancements in technologies around myoelectric prostheses and all the benefits they have to offer; more natural appearance and movements, prevention of overuse syndromes, more physiologically natural control especially for those with amputations at the trans-radial level (Uellendahl, 2017), there are functional limitations preventing more widespread adaptation. Myoelectric prostheses are susceptible to malfunction or damage from “environmental factors like water, dirt and electronic interference,” lack proprioceptive feedback and increased weight versus a body powered prosthesis (Uellendahl, 2017). However, what may be the greatest limitation is the difficulty of the user to communicate their intent reliably, effectively, and intuitively to the myoelectric prosthesis, exactly the things a user needs from their prosthesis (Ngan, 2019).

Myoelectric prostheses gain their function through electromyography (EMG), where electrodes are used to identify signals produced by a working muscle (Agarwal, 2017). The most common way of acquiring these signals from the prosthetic user is through surface electromyography, or sEMG (Agarwal, 2017; Lee, 2020; Hahne, 2016). Surface EMG places an electrode directly on the skin, typically over a targeted muscle in order to acquire the strongest signal possible. While this method is minimally invasive, cost effective, and easiest for a clinician to design and assemble (Lee, 2020), it is far from perfect. For one, users are limited on the number of degrees of freedom (DOF) available by the limited number of muscles available to produce signals (Ngan, 2019). Therefore, as the level of amputation moves proximally, the number of muscles available is reduced and the number of functions in need of replacement increases. Also, there are problems related to reliable electrode signals. Moisture, sweat, residual limb volume changes, movement of the electrode relative to the muscle it is intended to detect, are some of the ways communication between user and prosthesis can be delayed, misinterpreted, or disconnected (Chadwell, 2014), rendering the prosthesis unreliable or a hassle to use by a frustrated amputee. Potentially resulting in a prosthesis worth tens of thousands of dollars ending up in a closet, never to be used (Chadwell, 2016).

To improve upon the faults of sEMGs, numerous groups have been working on implantable electrodes and sensors in hopes of obtaining more reliable signals. Acquisition methods range from intramuscular electromyography (iEMG), which inserts an electrode directly into the muscle fibers (Agarwal, 2017; Weir,2008), to tapping directly into the peripheral nervous systems (PNS) using still viable residual nerves to communicate desired movements to a prosthesis (Rijnbeek, 2018). Implanted electrodes offer advantages and possibilities over sEMG. Direct innervation of muscles takes environmental factor out of play and allow for the use of smaller or deeper muscle groups to be used, thus increasing the DOF available to the user (Ngan, 2019). Furthermore, acquiring signal from the PNS has the potential to both increase DOF by parsing out neural signals otherwise destine amputated muscles while also providing sensory nerve stimulation back to the user (Ngan, 2019; Rijnbeek, 2018). There are also limitations specific to each signal acquisition method. Intramuscular electrodes tend to move in the muscle fibers over time, leading to changes in signal strength or broken electrode lead wires (Vasudevan, 2017; Rijnbeek, 2018; Shafer, 2019). Neural electrodes using microneedles as electrodes are easily damaged and may damage the nerve itself (Vasudevan, 2017). While there is an assortment of innovative strategies to handle each problem, this author did not find any instances of powered protheses using iEMG or neural signal driven prostheses in use outside of the laboratory.

While the technology exists to create prostheses that appear and function nearly as well as what is biologically given to the average person, there lies some limitations to communicate the intended actions of a prosthetic user reliably and intuitively to their prosthesis. By exploring how surface mounted and implanted electrodes function, along with their advantages and disadvantages, this paper intends to address the feasibility of using tattoos with conductive ink as a means to improve myoelectric signal transmission through the skin and be acquired by surface EMG sensors. This can be applicable for sEMG and intramuscular EMG electrodes by acting as a permanent target location for detection of muscle activity for an electrode while also being closer to the muscle for detection of weaker signals.

It is relatively easy to understand why surface EMG is so commonly used and a good choice for most amputees, all the clinician needs to use is the sEMG electrodes to find functional muscle tissue and align that location with placement in the prosthetic socket (Hameed, 2019). The difficulties to a good sEMG bioelectric prosthesis involve correct placement of electrodes in the prosthetic socket over a muscle that provides a strong signal, fabrication of a socket that allows electrodes to maintain contact with the skin in that target location, and maintain that contact through a user's range of motion (ROM), with and without additional weight at the distal end of the prosthesis. Movement of a sEMG sensor can cause delays in intended prosthetic function or prevent intended function altogether (Chadwell et al, 2016). In real-world situations, where dynamic movement can cause the prosthetic socket to shift on the limb interrupting sEMG connectivity, users can become frustrated with the unpredictability of the prostheses functions especially if it occurs during common tasks or activities of daily living (ADLs). User experience can overcome this issue to some extent, learning how the socket shifts during certain movements and how to adjust their residual limb to maintain skin contact with the sEMG, but that takes patience and dedication of the amputee to learn those techniques instead of discontinuing use of the prosthesis (Chadwell, 2016).

In general, with standard myoelectric signal processing, a single muscle can only trigger one or two functions in the myoelectric prosthesis, with the natural antagonistic muscle performing the opposite prosthetic function (Young, 2014). The biceps and triceps brachii controlling myoelectric wrist flexion and extension for example. This is typically associated with Conventional Control myoelectric systems where one function is controlled by one target muscle. However, this can lead to a common issue with sEMG electrodes, electrode crosstalk, which is interference in signals acquired by electrodes due to electrodes picking up activity meant for another electrode. This can be due to the individual's anatomy happens to put two myoelectric sites in close proximity or a short residual limb where sensors are forced into close proximity. To overcome this situation, the clinician can opt to use a grid pattern to place sEMG sensors, which was proven to be as effective as "control site" sensor placement (Tkach et al. 2014). Alternatively, crosstalk can be caused by opposing signals generated by the user for the same DOF, such as a user trying to close their hand, but they are contracting both the hand open and hand close muscles due to lack of control. Chadwell et al. (2016) see this situation with the less experienced subjects and find it can be overcome with training and experience. While there are times when engaging opposing muscle groups, co-contraction, can be an advantage, like when it is used as a switch to toggle between prosthetic functions, it is not typically beneficial for new users who are learning the basics of repeatably performing intended prosthetic functions.

There are additional factors out of the control of the clinician as well. Daily residual limb volume changes, sweating, skin type, electrical conductivity of the individual’s skin, body temperature, and blood circulation (Hameed, 2019) to name a few. Then there is the major limitation of muscles available as previously mentioned. sEMG function well with superficial muscles (Ngan, 2019), but struggle to adequately detect deep muscle activity (Navaraj, 2020) further limiting available options.

A novel idea proposed in 1978 took on the problems of sEMG electrode contact. At the time, it was common to increase connectivity between skin and electrodes made of Ag/AgCl with gel. This method is still used today in clinical settings; however, the gel tends to dry out causing discomfort and skin irritations limiting their usefulness outside the laboratory setting (Lee, 2020; Bihar, 2018). At the time, dry electrodes were becoming available, but the technology to filter out the “noise” of other signals being generated by the body was not suitable for myoelectric prosthetics. Hoenig et al proposed that a tattoo could be a way to conduct electrical current safely and reliably through the skin as a long term no hassle solution to gel or dry electrodes (1978). Results from animal trials show that the colloidal carbon solution had better impedance values than unprepared skin, however, the impedance value was 11x higher than that of the Ag/AgCl gel electrode. Additionally, the impedance values improved with the "tattoo" over time, dropping from 700ohms (after injection) to 400ohms (170 days after injection) when measured at 10Hz. The impedance value remained stable after that point through the last measurement taken at 28 months post injection. Hoenig et al. did see further potential in permanent ink as an electrical conductor through the skin, however, the technology to filter signals was simply not available at the time, or at least not in a way allowing it to fit on a prosthesis let alone power it. The authors also questioned whether a different ink solution would benefit conductivity but were limited by time (1978).

There are many wearable inks that have shown the ability to act as an electrode. E-tattoos used as wearable biosensors have been available for several years. Researchers have used inkjet printers to print EMG tattoos onto both temporary tattoo substrates and fabric (Bihar, 2018). They have fabricated "nano-ribbons" of silver nano-wire (Williams, 2022) or silicon and gallium arsenide which are adhered to the skin via van der Waals forces, showing they are as effective as the standard Ag/AgCl gel electrodes (Kim, 2012). Gogurla et al uses silk protein nanofibers treated with MeOH to create durable e-tattoos that are applied like a temporary tattoo. They have excellent adhesion to the skin, up to 7 days, can stretch and compress with the skin, and transmit enough electrical current to power LEDs without transferring current to the skin and are sensitive enough to detect muscular signals in the throat while speaking or the fine motor movements of the hand and fingers all while being biocompatible (2021). Wang et al (2019) had similar findings in electrode sensitivity with their use of silk and graphene. They also found that the sensor was "self-healing" by adding a drop of water over any tears in the tattoo. The drawback of these solutions is that they are only temporary, requiring reapplication every week or two.

Electrodes stitched directly into fabric sleeves conforming to the body or using an embroidered textile that has enough dimensional volume to fill voids created by movement, as shown by Chadwell et al (2014), while being comfortable for the prosthetic user (Lee, 2020). Electrodes could even be imbedded into silicone liners as suggested by Agarwal (2017). Creation of effective electrode conductivity and communication via sEMG or iEMG electrodes is only one part in a list of requirements in making myoelectric prostheses function in a way that is reliable and intuitive for users. The use of conductive tattoos cannot create more muscle target sites to increase the number of DOFs. It cannot take the place of user skill and experience in the use of the prosthesis. However, they may be able to create a targeted, permanent location on the body for sEMG electrodes to obtain strong signal from, allowing myoelectric users to have uninterrupted functionality. Perhaps allowing to take the next step towards feeling like the prosthesis is a part of an amputee’s body. With current computer size and processing power, signal filtering is much easier, solving the problems experienced by Hoenig et al.

Chapter 2: Methodology

This paper intends to address the feasibility of using tattoos with conductive ink as a means to improve myoelectric signal transmission through the skin and be acquired by surface EMG sensors. The first step should focus on determining an ink solution that is bio-compatible, has increased electrical conductivity compared to unprepared skin, and has minimal break down over time. The second step is to test what pattern should be used to provide optimal myoelectric signal strength beyond a single point to a broader field within an EMG sensor’s expected range of movement across the residual limb.

Participants

To test for optimal ink material, it is recommended to use a suitable stand in for human skin and adipose tissue. Previous studies have used pork as a stand in for humans as they have a similar makeup of skin and adipose tissue, so it is reasonable to use a pork shoulder with intact skin and adipose tissue for conducting this test (Chrysler et al, 2018). Recommended inks to test include the original colloidal carbon solution injected with a hypodermic syringe as described by Hoenig et al. (1978), a typical black tattoo ink found in a tattoo parlor (as it is known to be bio-compatible and stable over the long-term), NovaCentrix and PELCO were both suggested by Chriysler et al. (2018) as conductive inks and worth testing as well, though neither were known to be specifically biocompatible. All the inks should be tested against the baseline electrical conductivity of unprepared skin over the same distance. Conductivity should be tested in reference to impedance (resistance) which is measured in ohms.

Instruments

An electromyograph will be used to detect the strength and quality of myoelectric activity. Needle EMG can be used to provide more accurate readings within the skin, but surface EMG should also be used as this would be the real-world condition used by prosthetic practitioners.

Ink needs to be injected into the skin in a reliable pattern. A comparison between hypodermic needle and traditional tattoo guns should be made for each ink, making sure there is minimal bleed out of the ink after injection, and consistency of depth that the ink is injected at.

Procedures

Ink material conductivity testing will be conducted by injecting/tattooing the ink product into the pork shoulder. Hoenig et al. describe using a 5mm dot as their target pattern. With this in mind, testing material conductivity can use a 5mm long line, 1mm wide, should be adequate to test conductivity across skin. Testing should occur at various depths of ink injection and at various fatty tissue thicknesses to determine what ink material conducts a signal in differing conditions. Ink materials should be tested over time to ensure there is no breakdown of the ink material over time and conductivity is maintained. As Hoenig et al. found, electrical resistance decreased over time, and was viable at 28 months (1978), suggesting initial results may not prove out at the time of initial testing.

Pattern design was previously tested on live animals by Hoenig. It would be best to avoid this unless necessary so if it is possible to a use cadaver to test myoelectric conductivity, it would be preferable to prove feasibility of the techniques prior to live animal or human tests. Cadaver testing for myoelectric impulse testing has been used previously by Sharkey & Hamel (1998) to simulate muscle contraction and myoelectric detection during gait, suggesting cadavers would be appropriate for myoelectric signal testing for sEMG sensors. Patterns to be tested should include the 5mm dot as described by Hoenig et al. or otherwise covering a surface area similar to what would be expected by the movement of a sEMG sensor over the skin in a prosthetic socket, lines parallel the muscle fibers to provide adequate myoelectric target site coverage, and individual dots covering a similar surface area described in the first pattern test condition. As it is unknown to what the optimal pattern design is for myoelectric signal detection, multiple pattern designs should be encouraged for testing.

Statistical Analysis of Data

Data will be collected on electrical resistance for each ink tested and each pattern. Lower resistance levels will be considered as increased conductivity and therefore better suited to act as a pathway for myoelectric signals. One-way ANOVA testing will be used to compare variables in each test, conductivity of ink and efficiency of pattern.

Ethical Considerations

The technique proposed in this paper involves a permanent ink tattoo to be placed in the skin. While the benefits of this technique hopefully outweigh reservations one may have about being permanently marked, testing the feasibility and safety of this method is better done on something other than human participants. This is why it is proposed to use a butchered animal to test inks so no further harm will be done during testing. In the same vein, it is reasonable to test pattern designs on cadavers as no discomfort will be felt, and the biocompatibility of the inks is negated.

Conclusion

As this proposal requires permanent markings be put into the skin with unknown levels of risk over the long-term, it is best that testing for electrical conductivity of various inks within the skin, be first tested on dead tissue, similar to human skin and adipose tissue. Testing will be done in two parts. First, testing the conductivity of the chosen inks. Second, testing ink placement patterns that best increase the surface area of the optimal myoelectric signal site. The author expects to see an increase in electrical conductivity through the skin with inks versus unprepared skin, and what pattern will work best is a complete mystery.

Chapter 3: Discussion

Maintaining connectivity between sEMG sensors and an amputee's skin within the socket is a key component of intentional operation of a myoelectric prosthesis. Maintaining contact between the sensor and skin is relatively easy in the controlled setting of a clinic or training lab, but in real-world use, there are many hurdles to consistent connectivity. Dirt from the environment interferes with the direct skin to sensor contact. Sweat build up on the skin affects the sensor's ability to detect myoelectric impulses from the muscle as the chemistry of sweat interferes with the changes in ion levels present when a muscle fires. And perhaps most directly related to this paper, movement of the prosthetic socket over the residual limb, changes the sEMG sensor location relative to the muscle or even separates completely from the skin, disrupting quality myoelectric signal detection and causing loss of prosthetic function. Permanent tattoos that use an electrically conductive ink may provide a means to take a small target on a muscle that provides a strong myoelectric signal and increase the surface area on the skin which can maintain that strong, optimal signal even if the sEMG sensor moves around the target muscle location.

Practical Applications

Assuming the proposed study can identify an ink solution that provides an increase in electrical conductivity through the skin, is biocompatible with human physiology and stable within the skin, maintaining its original injected shape instead of defusing in the tissue, there may be a variety of applications for this technique beyond single site sEMG sensor connectivity improvement. For instance, if the myoelectric target size was increased by the tattoo, the user does not need to be as precise when donning their socket to obtain reliable and predictable prosthetic function. This would be highly beneficial to the shoulder disarticulation and bilateral upper extremity amputee population as donning their myoelectric sockets may be difficult or more complicated as compared to those with more distal or unilateral side amputations. For prosthetic users that have issues with maintaining skin contact with sEMG sensors in the socket, the target location tattoo can be combined with sensors that provide a more three-dimensional shape, taking up space when a gap is formed in the socket as proposed by Lee et al (2020).

Conductive tattoos may also enhance a clinician’s ability to use muscles activity that is deeper under the skin’s surface, something that current sEMG sensors are not well suited to (Navaraj, 2020). If additional muscle activity can be detected due to the tattoo ink being imbedded into the skin, placing it closer to deep muscle tissue, the myoelectric signal may be able to be filtered and produce additional signals to be used as additional degrees of freedom. Should conductive tattoos prove to have the ability to enhance detection of deeper muscle activity, this technique could also be paired with electrodes (iEMG) implanted in the muscle, like what was used by Weir and Farrell (2008). iEMG sensors need either wires or a transmitter to relay a myoelectric signal to the control unit used to process the EMG signal and turn it into prosthetic function. If a tattoo that never moves can take the place of the wire, then there is one less thing to break and disrupt signal transmission. Breakage of implanted wires is something that plagued many researchers over the years (Schafer, 2019/Hoffer, 1980). The signal detected by the iEMG could then be transferred to a sEMG via the conductive tattoo instead of using more complicated electro-magnetic couplers (Troyk, 2007).

Prosthetic clinicians may also find it beneficial to use the conductive tattoo to relocate sEMG sensors, even if by a couple centimeters. This could help eliminate sensor crosstalk in those instances where two muscle target sites are located close together. The ink could be used as a circuit where the ink starts over the muscle site providing the strongest EMG signal, then drawing the circuit to a location on the residual limb where the sensor cannot pick up the conflicting signal. This assumes the tattoo circuit does not transmit the interfering myoelectric signal itself.

Limitations

This proposal does have its limitations. It assumes that a suitable ink can be identified. It will also take time to determine the ink's long-term viability. Does it break down or diffuse in body tissue. Does it remain conductive over time. What happens when the ink is damaged and does the chosen target pattern influence the result. More importantly, is the ink safe, or at least as safe as traditional tattoo ink, for the person to have imbedded in their skin for any period of time. There is also the assumption that even if all the other concerns were addressed, that an individual would be willing to receive a permanent tattoo to improve connectivity with their myoelectric prosthesis.

Recommendations for Further Research

This research proposal is the first step of many that need to occur to provide sufficient evidence that a conductive ink tattoo improves myoelectric prosthetic function over what is currently available. Follow up research should include the introduction of a simple prosthetic socket with sEMG sensors positioned over the tattooed site on a cadaver to provide information about how tattoo ink reacts in a prosthetic socket environment, and if the optimal target site increases as expected in that environment. There should be continued tracking of the condition of the ink. Eventually testing would need to move to live animal testing as originally done by

Hoenig et al. to increase confidence that the technique is viable in living bodies and acting as expected.

Conclusion

This paper suggests the use of conductive ink materials to be imbedded into the skin via the tattooing process as a means to improve myoelectric signal connectivity between a person's body and a myoelectric prosthesis. This author came up with this seemingly original idea twenty years ago, only to come across previous research done some twenty-five years prior. The limitations in the original study revolved around technology and the inability to filter out myoelectric signal noise. With the advances in myoelectric technology, signal filtering abilities, advances in prosthetic control, and access to new materials to produce more capable ink solutions, the idea to the tattooing process to enhance myoelectric control should considered once again. Even if only to use the idea as a steppingstone to another technology.

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