Building a Myoelectric Prosthetic Hand

Abstract:

The goal of this project was to build a myoelectric prosthetic hand, which consists of three parts: detecting the muscle signals, sending the signals to an Arduino to be analyzed, and then moving the appropriate servos to manipulate the fingers of the prosthesis. In this project, two electrodes were used to acquire the muscle signal, an instrumentation amplifier was used to attenuate common noise, a bandpass filter consisting of a low-pass filter and high-pass filter to attenuate other noise not in the frequency range of the muscle signal, a non-inverting amplifier was used to amplify the signal, and then a level-shifter was used to shift the signal to within the voltage limits on the input pin. Unfortunately, no results were able to be taken due to a large amount of noise, which likely would be minimized with the use of a printed circuit board.

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30 May 2020

Motivation

This idea for this project came from browsing the "Do The Right Thing" page on the Menlo ASR website [1]. It was one of the first places I looked at for inspiration since I wanted to work on a project that could be beneficial to humanity. In choosing this project, I hoped to learn more about signal processing and microcontrollers, as well as the intersection between medicine and engineering.

In the US, there are an estimated 2 million amputees, and by 2050, this number is expected to increase to 3.6 million [2]. Prostheses are becoming a larger part of the future, and thus need to be modernized. Furthermore, they need to be cheaper. Two of the more modern prostheses, the body-powered prosthesis and the myoelectric prostheses can cost up to $30,000 and $100,000 respectively [3]. These high prices make access to these prostheses fairly exclusive, which needs to change.

History

Throughout the history of prosthetics, an effective prosthesis has aimed to be functional and aesthetically pleasing, while also giving the user a sense of wholeness [4]. The first prosthesis discovered was a small one: a big toe on an Egyptian woman from between 950-710 B.C [4]. This small passive prosthesis made of wood and leather shows that the purpose of a prosthetic is not necessarily always about how well it can function, but also how well it can give a "sense of wholeness" to the amputee; this prosthesis may not have given woman her ability to move her toe again, but it restored her cosmetic appearance and allowed her to live more normally and wear the traditional sandals [5].

Figure 1. Prosthetic toe found on mummy of Egyptian woman [5]

In Ancient Rome, General Marcus Sergius was the first known wearer of a prosthetic limb [4]. He lost his right hand in battle, and it was replaced with an iron passive prosthetic which allowed him to continue to hold his shield and fight [4]. Then, during the Middle Ages from 500-1500, there wasn't much advancement in prosthetics [6]. Scrapwood, which could easily be obtained, was often used as an artificial leg [6]. For the few who could afford a prosthesis, such as knights, iron artificial legs were typically used; however, they provided little function other than being able to ride their horse, but they did help give the wearer a "sense of wholeness [6]." Then in the early 16th century, surgeon Ambroise Paré developed the first hinged prosthetic hand, as well as a leg with a locking knee joint. He made it using lighter materials, including leather, paper, and glue [7]. These prostheses provided more functionality, but the functionality was still limited.

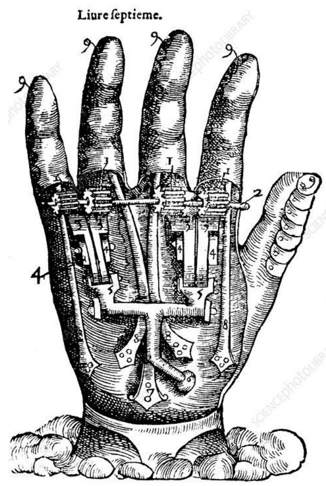

Figure 2. Paré's prosthetic hand with spring-loaded fingers [6]

In 1696, Pieter Verduyn, a Dutch surgeon, created the first non-locking below-knee prosthesis [8]. It had external hinges and a leather thigh socket, similar to modern prostheses [8]. This provided better mobility and allowed the amputee to walk, although with a gait.

Figure 3. Verduyn's modern prosthetic leg [6]

During the Civil War from 1861 to 1865, there was much more demand for prostheses as a result of the influx of amputees from the battlefield [4]. During this time the Hanger limb was invented, which was a prosthetic leg made from barrel staves and metal, and it had hinged joints at the knee and ankle [4]. This allowed even better mobility, but there was still a significant gait when walking.

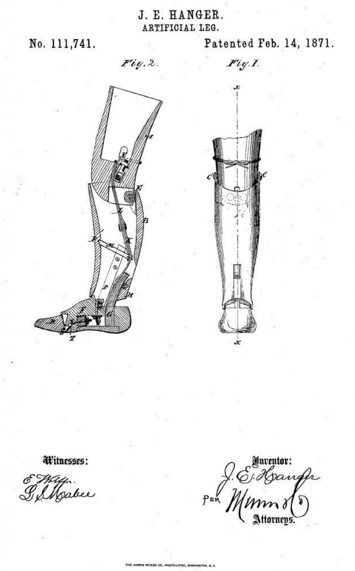

Figure 4. The Hanger limb with hinged pieces which allowed for more realistic movements[4]

In the last century, prosthetics have improved at a much faster rate. There are also several types of prostheses now available to amputees, each with their own pros and cons. One type of prosthesis, a passive prosthesis or cosmetic prosthesis, is designed to resemble the human limb and skin as much as possible [8]. This is a prosthetic for someone who values the appearance more than the functionality of their prosthetic. Another type is a mechanical or body-controlled prosthetic, which involves using cables and a harness to connect it to other parts of the body, so when those parts of the body move, the prosthesis can be manipulated [8]. Typically, a hook replaces the hand so that objects can more easily be picked up. This prosthesis is quite imprecise and lacks the dexterity of a human hand [8]. This is a prosthesis for someone who values functionality over appearance as the user can grasp objects with it. Another type involves pressing buttons and switches to make the prosthesis perform pre-programmed actions [8]. This prosthesis, however, has a fairly complicated form of control. Another fairly new type of prosthesis, the brain-computer interface, allows the amputee to control the prosthesis using their thoughts alone [8]. This is still in the research phase and is very expensive to implement. It is also invasive as the amputee has to undergo a surgery to get an electrode array placed on top of their brain [8]. Finally, a prosthesis that is quite similar to the brain-computer interface but is less new, expensive, and invasive is the myoelectric prosthesis, which relies on Electromyography (EMG). EMG records the contraction of muscles near the amputees residual limb in order to control the movement of the prosthesis [8]. These muscle contractions are caused by electric signals that occur when an action potential travels down the axons of neurons and is propagated through adjacent tissue [9]. The downside to this most prosthesis is that, as mentioned earlier, it is much more expensive than other types of prosthetics and they are for the most part still in the research and development phase.

The origins of the myoelectric prosthetic started in 1666 when Francesco Redi experimented with EMG: he discovered an organ in the electric eel which generated electricity [10]. This organ is made of electrocytes, and these cells are lined up so that a current of ions can flow through them and stacked so each one adds to a potential difference [10]. To generate electricity, the brain sends a signal through the nervous system to the electrocytes, which opens the ion channels, allowing sodium to flow through and reversing the polarity momentarily [10]. By causing a sudden difference in electric potential, an electric current is generated. Then in 1922, Herbert Gasser and Joseph Erlanger used an oscilloscope to display the electrical signals from muscles [10]. Because of the somewhat random nature of the myoelectric signal, only very rough and basic information could be obtained at the time [10]. However, the ability to detect electromyographic signals improved from the 1930s through the 1950s with the use of improved electrodes [10]. Today, there are a few commercial as well as numerous research prototype myoelectric prosthetics, such as the Bebionic hand, which are able to recognize and mimic several gestures; however, as mentioned earlier, these cost thousands of dollars, which not everyone can afford [11].

Anatomy

The EMG signals that are desired to be detected are formed by physiological variations in the state of the muscle fiber membranes [12]. The signals are based on action potentials at the muscle fiber membrane resulting from the repeated cycle of depolarization and repolarization [12].

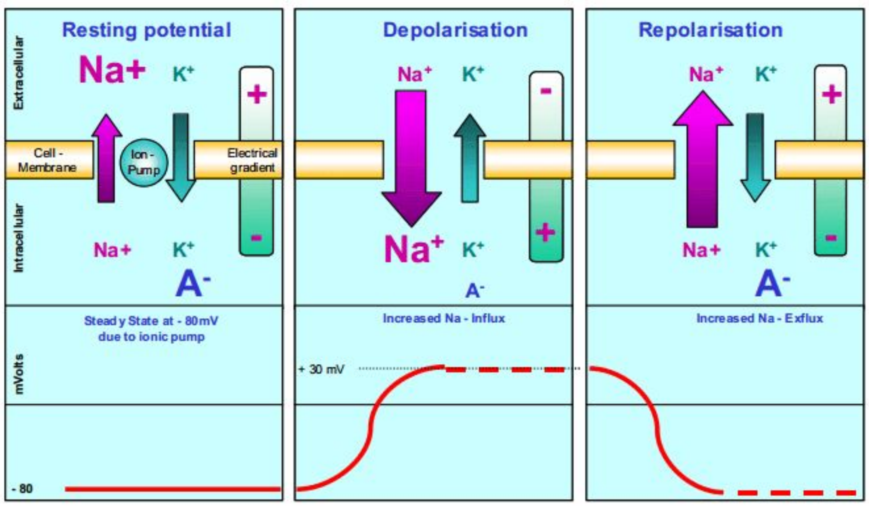

Figure 5. Repolarization and depolarization cycle within the membrane of skeletal muscle cell [12]

In the body, nerve impulses travel through action potentials, which results in contraction in muscle cells [12]. Before stimulation, there is a resting potential of about -80 mV inside the cell, but when impulses are sent into this cell, Na^+ diffuses into the cell, making the membrane less polarized [12]. When the charge within the membrane reaches a threshold value of around -40 mV, the action potential is triggered, and Na^+ enters the cell, completely depolarizing the cell and giving it an action potential around +30 mV [12]. These action potentials are sent throughout the body and are the way in which the muscles receive commands from the motor cortex.

An EMG signal is the reading of the depolarization and repolarization events of these action potentials of a muscle fiber. While these signals can be measured, they are extremely small at around +30 mV, even within the cell, and since myoelectric prostheses seek to detect these signals on the surface of the arm, the signals will be even smaller [12]. For surface EMG signals, the amplitude is in a range between 0 to 10 mV, and the frequency range is restricted from around 10 to 500 Hz [13].

Circuitry

In order to acquire the signal, electrodes are placed on the residual limb. There are two types of electrodes that can be used: needle electrodes which are invasive, or surface electrodes which are non-invasive [13]. The needle electrode gives a more accurate representation of the muscle's electrical activity as it is closer to the muscle, but it also involves poking through the skin into the muscle, so it is not an option for this project. Regardless of the type of electrode used, the placement of these electrodes is crucial in order to get the signal from the correct muscle. If not placed correctly, the signal could be much weaker or from the wrong muscle group all together.

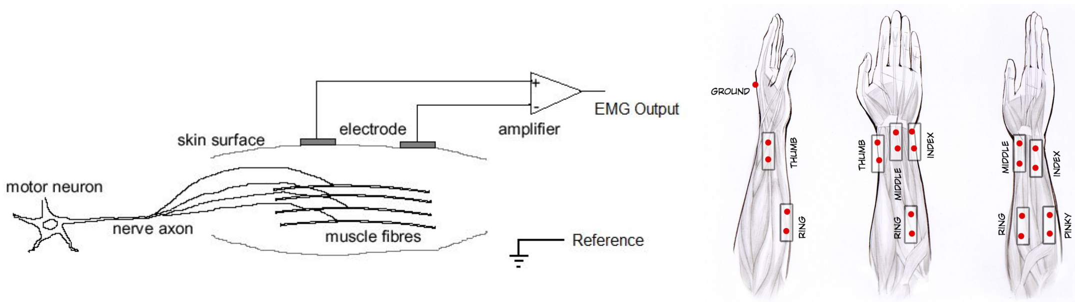

Figure 6. Electrode arrangement and placement [13,14]

For this project, electrodes were initially hand made using button snaps and wire. As can be seen in Figure 7, the wires are twisted in order to remove electromagnetic interference from the wires. Because the signal is transmitted through the wire in the form of current, an electromagnetic field of interference is formed, which can generate noise for surrounding cables [15]. By twisting the two wires together, the wires carry equal and opposite amounts of current through them, so the interference produced by one wire is cancelled by the interference of the other wire [15]. Before putting the button snaps in contact with the skin, a saline solution was applied to help improve conductivity.

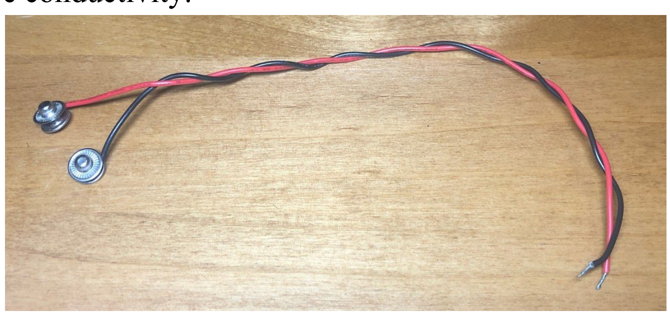

Figure 7. Electrodes constructed from button snaps and wire

However, signals could not be detected, likely because the home-made saline solution did not work well enough to help the conduction. Thus, pre-gelled disposable electrodes were purchased in hopes of simplifying the signal acquisition.

Figure 8. Pre-gelled electrode [16]

Unfortunately signals still could not be detected when connected to a human. This problem could have been combated with an electrode array that wraps around the top of the forearm. The placement of the electrodes would be less important because with many electrodes packed densely in an area, there are bound to be electrodes that are matched properly.

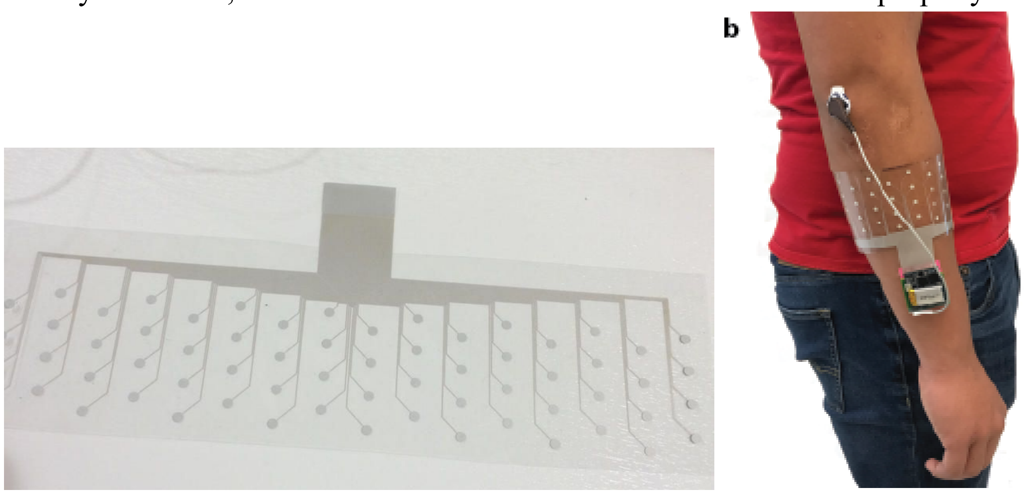

Figure 9. Electrode array built by UC Berkeley researchers and placement on arm [17]

After acquiring the signals, the signals need to be processed. The main idea is that these small signals need to be amplified to a size such that they can be seen by the Arduino that will receive the input as well as filtered for noise from a multitude of sources, including inherent noise of electrical parts and ambient noise from electromagnetic radiation in the environment. These tasks can be done using operational amplifiers (op-amps).

Op-amps are differential amplifiers meaning they take in two input voltages and output the voltage difference, which can be amplified with infinite gain. The output is between the “rails” of the positive and negative supply voltages. The first rule of an ideal op-amp is that it has an input impedance that is infinite, which means no current goes in or out of the inputs of the op-amp so that the input signal isn’t disturbed [18]. The second rule is that the op-amp tries to keep the input voltages the same; although, this only applies when there is a closed-loop configuration [18]. The open-loop configuration is the lack of a connection between the inverting or non-inverting input and the output of the op-amp. This open-loop can become “closed” by connecting a resistor between the input and output terminals [18]. This resistor provides negative feedback to control the open-loop gain as it feeds back, with the help of another resistor on the input terminal to form a voltage divider, a smaller part of the input [18]. Without this negative feedback, as is the case in the open-loop configuration, the voltage output of the op-amp is saturated to the supply voltage. The gain of this system, when the closed-loop is between the non-inverting terminal and the output is A = Rf/R1 + 1, and when the closed-loop is between the inverting terminal the output the gain is given by A = -Rf/R1 [18].

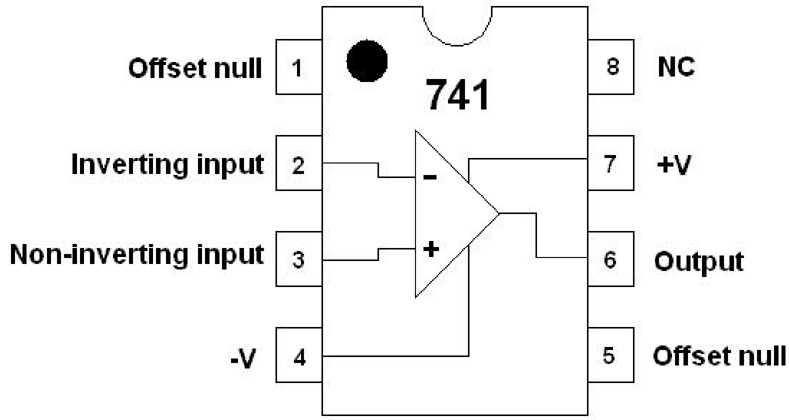

Figure 10. 741 op-amp pinout [19]

The first step in processing the signal is differential amplification. The op-amp takes in the voltages of the two electrodes, and amplifies the difference between them. By taking the voltage difference of the two electrodes, the common noise is canceled out. One such source is from mains hum at 60Hz. The common-mode-rejection (CMR) can be shown in the equation: CMR (unit: dB) = 20 log [(1 + R2/R1)/Rt] [20]. Rt is the total mismatch of the resistor pairs in fractional form; R1 = R3 and R2 = R4, and the gain = R2/R1 [20].

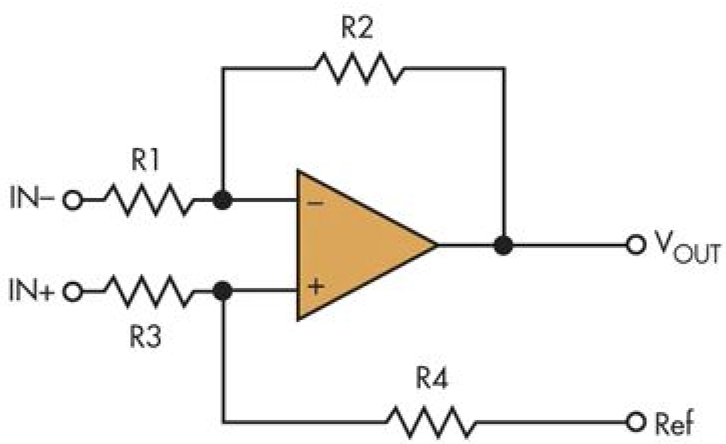

Figure 11. Difference amplifier circuit [20]

However, there is another IC that can have a better CMR: the instrumentation amplifier. In the difference amplifier in Figure 10, the input impedance is relatively low and the input impedances aren't matched, meaning a different current will flow through each leg, causing the CMR to suffer [20]. Furthermore, any mismatch in these resistor pairs will reduce the CMR [20]. On the other hand, in the instrumentation amplifier, the circuit gain is set via the value of the resistor labeled RG. Looking at the input stage, consisting of the two op-amps, any common-mode signal is only amplified by unity gain, regardless of the differential gain in the first two amplifiers [20]. The difference amplifier will then remove any common-mode components. The CMR performance depends on the resistor ratio matching: CMR = 20 log (gain * 100Rt) where Rt = total mismatch of the resistor pairs [20].

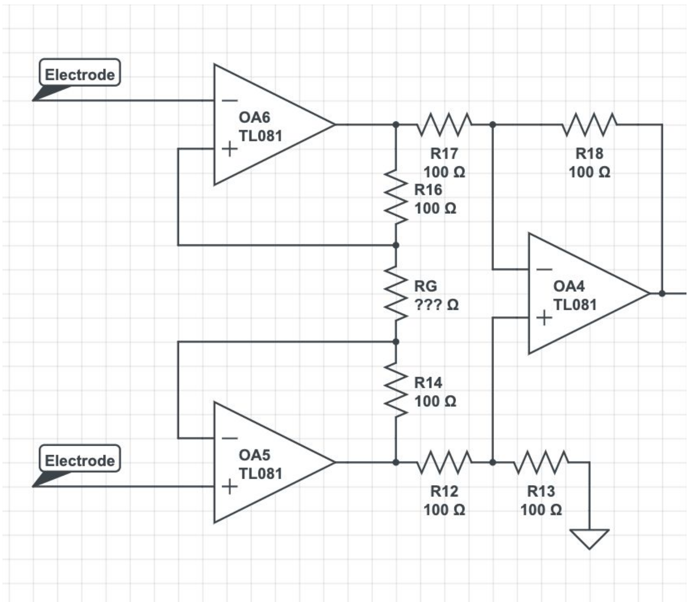

Figure 12. Instrumentation amplifier circuit

As mentioned earlier, noise plays a major role in extracting information from the EMG signal, so a band-pass filter needs to be used. A band pass-filter has two parts: a high-pass filter, and a low-pass filter. A high-pass filter is used to pass high-frequency components, while a low-pass filter passes low-frequency components of an input signal. There are also two filter types, passive and the type used in this project, active. Passive filters are designed using resistors, capacitors, and inductors and are most responsive to frequencies between 100 Hz and 300 MHz [21]. They are not as responsive to lower frequencies because at low frequencies the capacitance and inductance values become exceedingly large, which requires larger components [21]. In contrast, active filters are constructed from op-amps, resistors, and capacitors [21]. Active filters are capable of handling very low frequency signals (approaching 0 Hz), and they can provide voltage gain if needed [21]. They are also able to restore or control the loss of signal through amplification.

The signal will first pass through a high-pass filter, which will attenuate frequencies below the cut-off frequency. Frequencies above the cutoff are carried through the circuit as they are in the passband region.

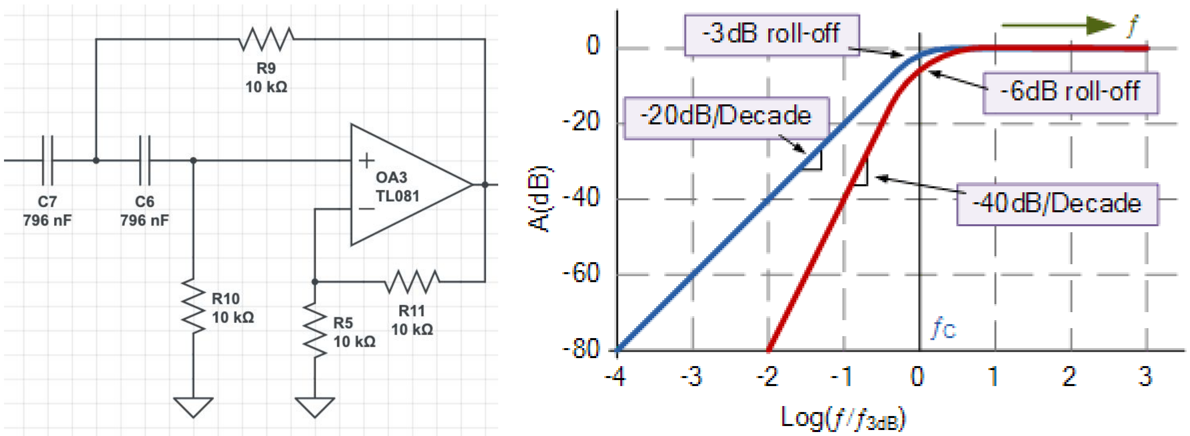

Figure 13. Second order Sallen-Key high-pass filter circuit with frequency response; red line is for a first-order filter, and blue line is for a second-order filter [22]

The lower frequencies go to ground and the higher frequencies pass through because the reactance of C6 and C7 vary inversely with frequency. With low frequencies, the reactance ($X_c = 1/2\pi fC$) is very large compared to the resistive values of R9 and R10 [22]. This means that the voltage, (Vc) across C6 and C7 will be much larger than the voltage drops (Vr) at R9 and R10. This makes any high frequency signal that passes through get shorted by R10. This also makes the output voltage very small, creating a virtual ground. Therefore, C7 and R9 form the first stage of the filter, and C6 and R10 form the second stage of the filter. At high frequencies the reverse is true with (Vc) being small and (Vr) being large due to the change in the capacitive reactance value. Since a proportional amount of current takes the path of least resistance, lower frequencies will go to ground, and higher frequencies will pass through. This cut-off frequency is determined by the equation below. [22] This equation is then solved for such that R9 = R10 and C6 = C7, the cut-off frequency is around the typical 20Hz for EMG, and 10k Ω resistors are used.

$f = 1/2\pi\sqrt{R9R10C6C7}$

$f = 1/2\pi R9C6$

$C6 = 1/2\pi R9f$

$C6 = 1/[2\pi(10k\ \Omega)(300Hz)] = 0.796\text{uF}$

As shown in Figure 13, the attenuation near the cutoff frequency isn't very steep, even with a second order filter, but with an even higher order filter it could be steeper. One source of low frequency is the DC offsets on the electrodes, which are a result of charges building up on the electrode [13].

Then the signal will go through a low-pass filter, the opposite of a high-pass filter. Frequencies less than the cut-off frequency are carried through, and frequencies above the cutoff are attenuated.

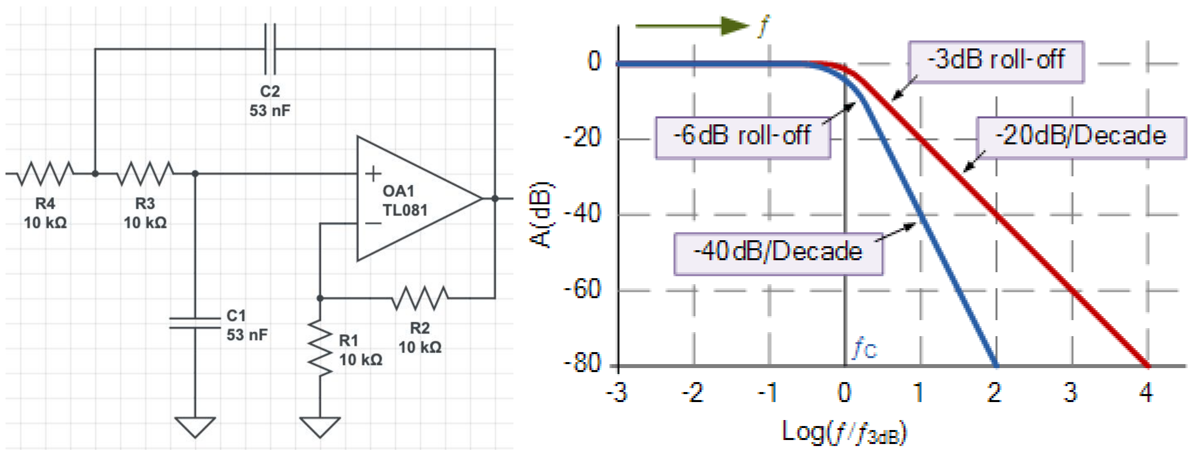

Figure 14. Second order Sallen-Key low-pass filter circuit with frequency response; red line is for a first-order filter, and blue line is for a second-order filter [22]

The low-pass filter works in the opposite way as the high-pass filter, thus the capacitors and resistors are switched [22]. The cut-off frequency is also determined by the same equation as the high-pass filter [22]. This equation is then solved for such that R3 = R4 and C1 = C2, the cut-off frequency is around the typical 300Hz for EMG, and 10k Ω resistors are used.

$f = 1/2\pi\sqrt{R3R4C1C2}$

$f = 1/2\pi R3C1$

$C1 = 1/2\pi R3f$

$C1 = 1/[2\pi(10k\ \Omega)(300Hz)] = 0.053\text{uF}$

Again, as shown in figure 14, the attenuation near the cutoff frequency isn’t very steep, specifically only a roll-off of -6dB, but with a higher order filter it could be steeper. Some sources of high frequency noise are nerve conduction, computers and cellphones [13].

After the signal has been filtered for noise, it goes through a non-inverting amplifier to amplify the signal between the range of -2.5V to 2.5V. The explanation for how this circuit works is discussed earlier when op-amps are introduced. The equation for the gain of this circuit is A = 1 + R6/R5. The values for both these resistors is unknown since it has not yet been empirically determined what the voltages are for the EMG signals.

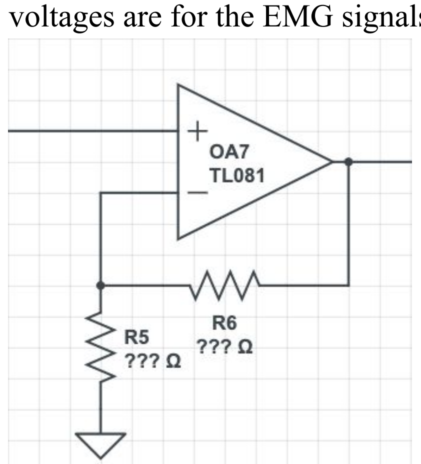

Figure 15. Non-inverting amplifier

Finally, before the signal is sent to the Arduino Uno, the signal needs to be DC shifted such that it fits within the 0V to 5V range of the input pins on the Arduino. While this could be done with a resistor adder, the signal would be attenuated. On the other, using a non-inverting summing amplifier that contains an op-amp, the signal will be maintained. In figure 16, R10 and R11 form a voltage divider, such that if there is -2.5 V on the Vin input, the non-inverting input will be 0V, and thus 0 V will be output. Furthermore the rails of the op amp are 0V on the negative supply rail and 5V on the positive supply rail, meaning the signal will clip if the input is attempted to be amplified to more than 5V. The rest of the circuit works much like the non-inverting amplifier.

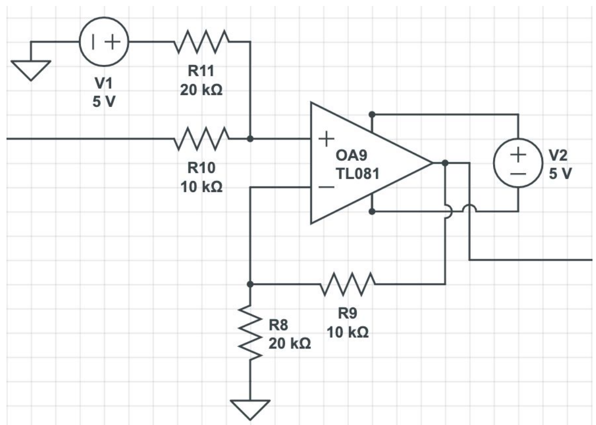

Figure 16. Non-inverting summing amplifier.

After the analog signal has been filtered for noise, amplified, and DC shifted, it is sent to an analog pin on the Arduino Uno, which digitizes the signal using the built-in ADC. While this part has not been done yet, an algorithm would then process the signal and activate the appropriate servos connected to digital pins to move the fingers on the prosthetic hand.

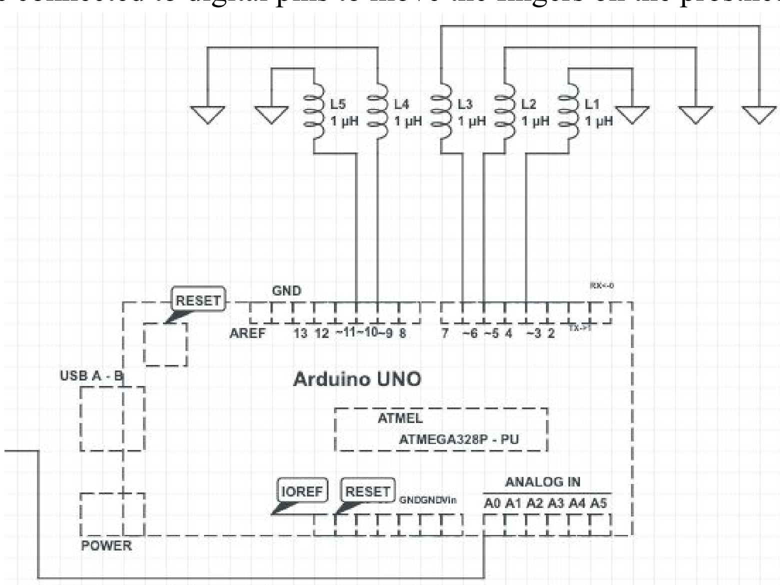

Figure 17. Arduino connected to 5 servos

Prosthesis[1]

[1] While the prosthesis was not built, it only needed to be 3D printed and assembled which likely would have been fairly straightforward.

The human hand has 27 bones and more than 30 muscles; needless to say, it is complex. The fingers in the hand are moved through the contraction of muscles and tendons. This contraction is caused by the signals as previously mentioned. Currently, no prosthesis is able to mimic the dexterity or fluidity of a human hand.

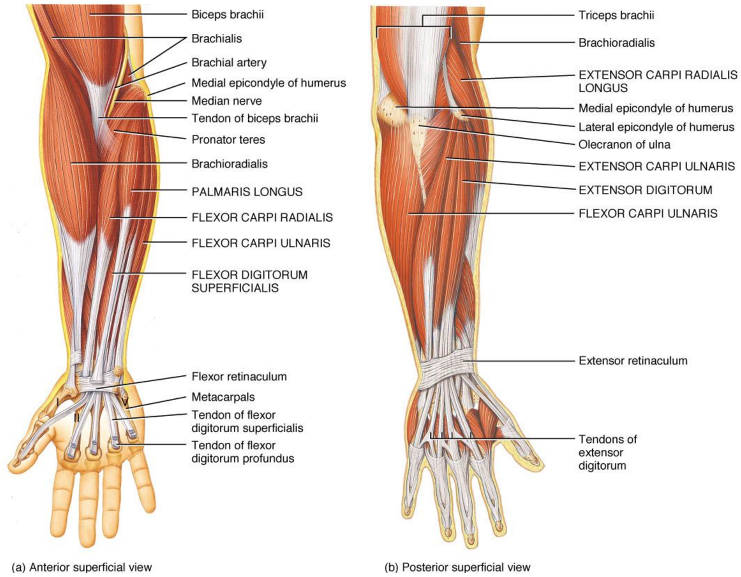

Figure 18. Muscles in the forearm that control the hand [23]

In the prosthetic hand that was planned to be made for this project, servos would play an important role in controlling the fingers. Inside a servo, there is a small DC motor, potentiometer, and a control circuit [24]. The motor is attached with gears to the control wheel [24]. As the motor rotates, the potentiometer's resistance changes so that the control circuit can regulate how much the motor moves and in what direction [24]. When the shaft of the motor is at the desired position, the power supplied to the motor is stopped. The desired position is sent via electrical pulses through the signal wire [24]. The motor's speed is proportional to the difference between its actual position and desired position, so if the motor is near the desired position, it will turn slowly, otherwise it will turn fast [24].

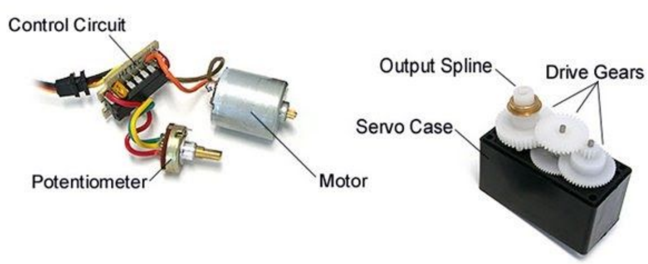

Figure 19. Internals of servo [24]

Servos are controlled by sending a pulse width modulation (PWM) signal through the control wire. There is a minimum pulse, a maximum pulse, and a repetition rate [24]. A servo motor is usually able to turn 90° in either direction for a total of 180° movement. The motor's neutral position is the position where the servo can rotate the same amount in both the clockwise and counterclockwise directions [24. The servo motor expects to see a pulse every 20 milliseconds, and the duration of the pulse determines how far the motor will turn.

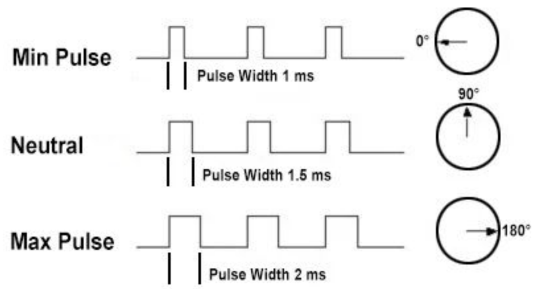

Figure 20. How duration of pulse controls servo position [24]

When servos are told to move, they move to the position and hold that position and resist change from it, even if an external force pushes against the servo. The maximum amount of force the servo can exert is called the torque rating of the servo.

On most commercially available prosthetic hands, the fingers are moved through a linkage system powered by a motor or servo. This is a simple system to implement; however, a problem with this design is that the joints in a finger cannot move independently as one motor or servo controls the entire finger. Numerous organizations, such as Enabling The Future and InMoov, have released CAD designs of prosthesis that can be 3D printed and then constructed with some other materials fairly easily and cheaply [25]. A modified version of the InMoov prosthesis is hoped to be used.

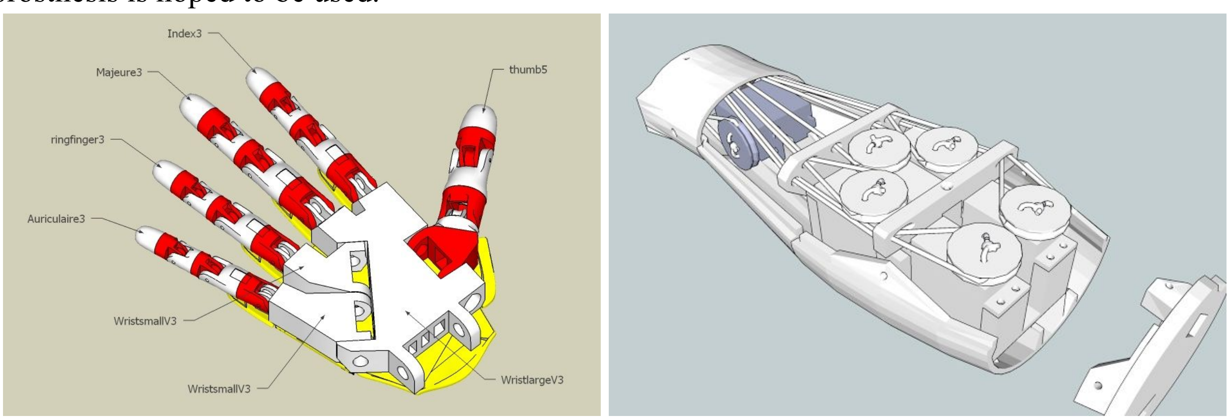

Figure 21. InMoov hand and forearm with joint-linkage system [25]

This hand will then be controlled by the myoelectric signals produced by contracting muscles. Detecting these signals accurately is hard: there is a lot of cross talk between muscle signals because the muscle groups in the arm are physically close together, making it difficult to distinguish exactly which muscle is generating the measured signal via the surface electrodes. To remove this precision of electrodes needed, an electrode array—an area densely populated with electrodes—can be used instead. Then, the likelihood of electrodes matching up with the right muscle group will be better.

Results

Unfortunately, no results were able to be taken either due to the large amount of noise, or the inability to place the electrodes over the correct area. This was even after using pre-gelled disposable electrodes instead of the reusable electrodes made using button snaps, and shaving the target section of skin.

Figure 22. Area of arm shaven (hair has started to grow back)

Other setups were tried, including on the bicep and around the temples, but signals still could not be detected. However, if signals were able to be detected, some experiments could be done such as measuring muscle fatigue or muscle strength. It could also be interesting to see if different gestures could be distinguished in the signal. Additionally, the frequency of the signal could have been measured using the Arduino, and the original signal before processing could have been crudely calculated by using the equation of each of the previously discussed circuits. This would be a rough calculation, however, since it would be difficult to factor in the attenuation at each section of the circuit.

Conclusion

The original goal of building a myoelectric prosthesis was ambitious given the time constraints, even for pre-coronavirus. However, the bulk of the work was likely complete: a likely working circuit that could detect muscle signals and modify it such that it could be input into the Arduino to be analyzed. While code for the Arduino was not produced, a rudimentary system using thresholds to move servos could have been produced easily. Additionally, designs for the prosthetic hand were obtained and only needed to be 3D printed and assembled. While the desired results could not be obtained when attaching electrodes to a human, when the electrodes were attached to a function generator, the expected results were obtained. Had the circuit been transferred onto a printed circuit board, and the exact placement for the electrodes been found, results would have been more likely to be found.

Next Steps

Unfortunately, mainly due to coronavirus, there are a lot of next steps for this project. The first next step would be to make a printed circuit board for the circuit in order to guarantee strong connections and lower noise. With this improvement, signals could likely be acquired successfully. The second next step would be to 3D print the prosthetic hand and then assemble it. The third next step would be to write the program for the Arduino that analyzes the signals and then correctly manipulates the prosthetic hand.

Acknowledgements

I would like to acknowledge Dr. Dann for being very understanding during this transition to online school. Dr. Dann helped me understand the theory for many of the circuits and debug circuits, even through Google Meetings. As a result of the quarantine, Dr. Dann graciously let me take home all of the equipment I needed: an oscilloscope, two function generators, two dual power supplies, a multimeter, wire strippers, and an assortment of wires. I would also like to thank him for providing the disposable electrodes used in the project.

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