Executive summary

The loss of a dominant hand can have profound consequences for physical, psychological, and social well-being [1], however, hand prosthetics offer a solution to restore daily activities and improve the quality of life for amputees [2]. Project Echo aims to design, model, and prototype a myoelectric hand prosthesis device to empower hand amputees to write. The myoelectric prosthesis is an active device that uses EMG signals from the forearm flexor muscles to control the prosthetic hand that provides intuitive and natural control. The project was divided into six subsystems: EMG circuitry, battery power supply, Arduino microcontroller board, actuation, housing and attachments, and the end effector functional prosthetic tool. The final prototype was evaluated using a compliance matrix and Quality Function Deployment (QFD) to assess its performance against engineering requirements. The EMG circuit processes and filters the EMG signal before the Arduino microcontroller uses the signal to control a servo motor to open and close the prosthetic end effector. The housing and attachments were designed to accommodate both right and left-handed users, providing comfort and easy adjustability. Finite Element Analysis (FEA) was performed to ensure the device's housing and end effector pincher mechanism structural integrity and safety. The project demonstrates the potential for integrating advanced technologies to enhance the quality of life for individuals with limb loss. Future iterations could include improvements in utensil compatibility, active or passive damping mechanisms, and customizability for hand amputees.

I. Introduction

The hand plays a critical part in the livelihood of humans' ranging from communication to physical locomotion. The loss of a hand can have devastating implications to the amputee's psychological, physical, and social well-being. Amputees can find significant difficulty adapting to their new life without this extremity that was integral in daily activities [1]. However, hand prosthetic devices can be used to re-enable amputees to perform tasks and restore daily activities back into their livelihood [2].

In the context of Project Echo, the aim is to design, model, simulate, and prototype a myoelectric hand prosthesis device that empowers hand amputees to pick up their writing utensil and write. The primary user at focus is a university student where writing is a critical daily task, and they lost their dominant hand in an accident.

Writing requires fine motor skills and pathways that have been built and exercised over long periods of performance, thus reprogramming the brain and the motor pathways fine motor tasks such as writing in the non-dominant is challenging [3]. Myoelectric active prosthetics are eternally powered devices that intake and amplify the EMG signals of the muscle from the surface of the user's skin to dictate the behavior of motorized parts of the device. The operational effort of myoelectric prosthetics is low since the contraction of muscles to control the device are on par with that of a natural limb, making the user experience more intuitive [1].

To successfully prototype a prosthetic device for the primary user, the project was divided into six sub-systems and each playing a critical role in the overall functioning of the device: EMG circuitry, battery power supply, arduino microcontroller board, actuation, housing and attachments, and lastly, the end effector functional prosthetic tool. In the perspective of the EMG signal, the signal would first travel from the electrodes and into the EMG circuitry to be filtered and processed. The processed signal would then reach the arduino microcontroller board where code will dictate how the actuation of the servo motor will behave to dictate the end effector. The battery power supply powers the EMG circuitry, the Arduino board, and the servo motor. The housing and attachments enable all the aforementioned components to come together physically and fit onto the user's arm.

II. Design Process

A. Primary Persona

Janet is a 19 year old passionate Canadian biomedical engineering student, her characteristics and situation of concern can be found in Appendix A Tables 1 and 2 respectively. In a freak car accident Janet unfortunately lost her dominant hand in an attempt to shield her face. Janet has always been a high academic achiever and she had fears that she would no longer be able to keep up with the academic load after losing her dominant hand. She is an avid hand written note taker and hates typing notes during lectures since she has a very specific note taking and study style that has allowed her to succeed. After trying to write with her left hand, she realized she would not be able to keep up the content due to the frustration of not writing fast or neat enough for her standards. Janet was really feeling the toll of losing her hand and she was contemplated dropping out of her program, that was until she found out that another cohort was tasked with creating prosthetics for hand amputees to aid in specific tasks, and luck had it that one group was designing a prosthetic for the purpose of picking up writing utensils to enable writing. Janet felt hope again that she would not need to drop out of her program and could finally keep up with her peers during lectures. Janet, now more determined than ever, is inspired to take back her health, life and academic standards.

B. Competitor Product Research

There are varying degrees of advancement in existing myoelectric prosthetic hands on the market. The functioning of hand prosthetics depends on the location of amputation and the desired user needs. In the context of transmetacarpal amputation where approximately the entire portion of the hand distal to the carpals is lost, amputees can seek myoelectric prosthetics that are single-motor, multi-articulating or activity-specific. Single-motor can open and close the hand and does not allow individual articulation of fingers, such as the Myohand Variplus Speed sold by Ottobock [5]. Multi-articulating hands allow for different movements of each finger depending on the grip pattern. The bebionic Hand EDQ also by Ottobock allows for 14 hand and grip patterns for various different daily activities such as opening doors, eating meals, and typing

[6]. Lastly, activity-specific prosthetics are specialized enabling the user to complete a specific task such as holding specific machinery for the user's occupation.

When developing hand prosthetics, there are common requirements that user's need and want to ensure consistent usage of the device. Consumer design priorities include comfort, natural appearance, grip movement and function. Specifically for myoelectric devices, a literature review by Cordella et. al. found that body language, gripping, and manipulating were important functional roles for active prosthesis [7]. Additionally, the top three myoelectric prostheses features to improve for users were 1) Ability to move separately the fingers and the thumb 2) Ability to prevent object slipping 3) Adaptability of grip strength [7].

C. Requirements, Constraints and QFD

Considering the primary persona's goals and needs as well as the research into existing hand prosthetics and common challenges and requirements of active/myoelectric prostheses, the resulting QFD, constraints, requirements can be viewed in Appendix A as Tables 3, 4 and 5. [8]

III. Prototype and System Level Performance

A. Prototype and subsystems

In order to solve the challenge of writing after losing a dominant hand a myoelectric prosthetic, Figure in Appendix B, was researched, designed and developed to pick up or drop a writing utensil upon contraction of the forearm flexors to enable writing, Figure 2 in Appendix B. There are six subsystems, labeled in Figure 3 in Appendix B, at play to help this prosthetic function: Arduino Uno microcontroller to control the subsystems; a battery pack for power; EMG circuity to process on EMG actionpotential into one that can be measured; end-effector to to pick up a writing utensil; actuation to control the end-effector; and housing to store all the subsystems and to attach the prosthetic to the users arm.

B. Evaluation of System-Level Prototype

The final prototype's functionally was evaluated using a compliance matrix and QFD to judge the compliance of each engineering requirement as seen in Table 4 in Appendix A.

Requirement 1 (R1) states that the prosthetic should accommodate both right and left handed dominant users, on a Likert scale of 1-5 this was given a 5 and thus compliant because the device has equal functionality no matter which arm the device is placed as it is symmetric and does not depend on the direction of utensil either way.

R2 states that the prosthetic must be comfortable for long periods of time, on a Lickert scale of 1-10 this was given a 7 and thus partially compliant. While the device does perfectly mold to the user's forearm, it requires tight straps to keep the device mounted to the arm which could become uncomfortable with long periods of use.

R3 states that the prosthetic should be able to pick up and maintain a strong grip on a writing utensil without slippage. Rubber is used on the end effectors to maintain grip which has a coefficient of friction of about 1 which means that slippage will occur when the force of the utensil on the paper overcomes the normal force of the end-effector on the pencil [9]. From testing, it was found that a minimum pencil force of 5N must occur for legible writing and a force of 100N will rip paper, also, the minimum utensil force that must occur for slippage is 234.2N which is larger than 100N and thus compliant.

R4 states that the prosthetic should enable users to write with their amputated dominant hand, on a Lickert scale of 1-5 this was given a 4 and thus partially compliant. Writing utensils eligible for this prosthetic must be between 6mm and 12mm in diameter and there are no degrees of freedom between the pencil relative to the end effector which could be improved to simulate a real wrist.

R5 states that the prosthetic should be easy to adjust, remove, on a Lickert scale of 1-5 this was given a 5 and thus compliant. The prosthetic can be used completely independently as long as the user is not a double hand amputee, the two velcro straps are very easy to undo and adjust as needed.

R6 states that the prosthetic should be compact for convenient storage and travel, the volume measured from the solidworks assembly is $636 cm^3$ which is less than $1000 cm^3$ and thus compliant.

C. Limitations and Future Iterations

One limitation of this prosthetic is that the diameter of the writing utensil must be between 6mm to 12mm. The average pen diameter is 9 -10 mm, the average pencil diameter is around 7 - 8 mm and the average crayon is about 7.5 mm than these all fit within the dimensions of the end-effector, however, some markers, for example dry erase markers, can be as much as 20mm in diameter which is too large for this end-effector [10] [11] [12].

Another limitation is that the device will be difficult to place, adjust and remove for a double hand amputee individual as the straps are velcro. Of course a double hand amputee can still use the device to pick up writing utensils to enable writing but they may feel a loss of independence is the act of placing, removing or adjusting the device.

In future iterations many adjustments could be made. First, since the circuit has proved to be reliable and repeatable, the breadboard with exposed wires would be integrated into a PCB, this will reduce noise, space and weight.

Another iteration that could be made could be to implement an active or passive damping mechanism to the end-effector to simulate writing with a wrist. In the current prototype the pencil has zero degrees of freedom relative to the end effector, but by introducing a demeaning mechanism that could increase to 3 by the end effector dampening the movements on paper in the x, y and z directions, this will allow the user to have a more natural feel when writing.

IV. Sub-Systems

A. EMG Circuitry

To create the EMG circuitry an iterative design process was followed beginning with analysis of the problem, then planning, followed by development, and finally testing. At the high level, the circuit needs to convert an action potential from the forearm flexors to a digital voltage that is high when the muscle is contracted and low when relaxed to enable the arduino to spin a servo motor ultimately picking up a writing utensil. Using resources from, BME 252, BME 261, BME 284, BME 284, BME 294, and BME 294L of simple EMG circuits, the current flow of the EMG signal is shown in Figure 4 in Appendix B [13] [14] [15] [16] [17] [18].

The circuit was simulated using Falstad as seen in Figure 5 in Appendix B, keeping in mind that this software creates an ideal circuit and that actual values will differ from this theoretical simulation [19].

The circuit was then replicated on a breadboard one component at a time, taking advantage of oscilloscopes, multi meters and voltage/current sources. The final circuitry in reference to the schematic, in Figure 6 in Appendix B, functions as follows [20]:

The EMG action potential is captured using three surface EMG electrodes: ground, active and reference, the potential difference is measured between ground and active, and ground and reference electrodes and fed into the positive and negative inputs of the Instrumentation Amplifier (IA) respectively. The IA amplifies differences between the two inputs with a theoretical gain of 840 and an actual gain of 825, found by Equation 1 in Appendix C, and discards similarities, like noise and centers the signal at 2.5 by outputting a voltage divider into the reference pin found by Equation 2 in Appendix C.

The IA is followed by a series of single order, passive filters the first being a 60Hz notch filter with a low pass cutoff of 45Hz and a high pass cutoff of 75Hz to attenuate 60Hz noise caused by lights, motors, alternating current cables. The third filter is a 400 Hz low pass filter since EMG signals above 400 Hz are also not significant. The cutoff frequencies were found by Equation 3 in Appendix C and the bode plots for each of the filters can be found as Figure 7, 8 and 9 in Appendix B respectively [21] [22].

The signal is then fed into a precision full wave rectifier, so that the entire signal is above 0V inorder to eventually be integrated. A precision full wave rectifier reduces the voltage drop across a forward biased diode by implementing a super diode using an Op-Amp which improves the signal accuracy.

Next, the signal is amplified by a non-inverting amplifier with a theoretical gain of 10.8 and an actual gain of 10.5, found by Equation 4 in Appendix C. Although the signal was originally amplified, after being fed through all the filters and the rectifier, the signal amplitude decreased and required future amplification to exaggerate the difference between relaxed and contracted sections of the EMG signal.

Finally, the signal is integrated using a non-inverting, integrating Op-Amp which bleeds 5 times faster than it integrates so that relaxed signals are not integrated but contracted signals are, when contracted the signal converges to around 0.5V. A non-inverting integrator was used because the Arduino Uno is single supply, meaning that it cannot intake or supply negative voltage. The signal then gets fed into an Analog input pin on the Arduino Uno to be further processed and read.

The selection of components was limited to the circuit kits, however, special care was taken to measure each resistor value as to not depend on package tolerances. Also LM358 Op-Amps were chosen as they are single supply and each contain two Op-Amps per IC which saves space on the breadboard.

B. Battery Power Supply

The battery pack consists of four Zeus Double A batteries, and supplies the Arduino Uno board with 6V and a capacity of 3 Ah [23]. The current draw of the I/O of the Arduino Uno is approximately 40 mA [24]. Additionally, the servo motor HS-645 has a current draw of 9.1 mA at idle, and the Vin pin of the Arduino draws approximately 50-100mA [25] [26]. Thus, using Equation 5 in Appendix C, assuming that the total current drawn from all components of the Arduino sum to 200 mA, it is calculated that the battery can theoretically supply the device for 15 hours of usage. However, because of impedances in the circuitry, Arduino, leads, and the additional current drawn when the servo motor is moving, the battery will supply the device for less than 15 hours, but is enough to supply the device with a full day of usage.

C. Servo Motor

Possible motor options are Servo Motor, Stepper Motor and DC Motor, to rate each of these motors to choose which is most suited for the prosthetic a decision matrix was used to rate each important specification. The performance specifications of interest available for possible motors, seen in Appendix A, Table 6, are weight, maximum torque range, current draw at idle, step angle and external driver requirement. Ideally, from most to least important, the motor will have a high maximum torque, low idle current draw, small step angle, be lightweight and no external driver requirement. The servo motor (HS-645), stepper motor (ROB-09238) and DC motor (PAN14EE12AA1) were compared to evaluate these specifications in the decision matrix found in Appendix A Table 7 [25] [27] [28]. The servo motor came out as the best option with a score of 13, followed by the stepper motor with a score of 8 and finally the DC motor with a score of 7.

The HS-645 servo motor is controlled by the Arduino. There are three pins on the servo: ground, power and PWM. The ground of the servo is attached to ground on the arduino such that the servo has the same ground as all other circuitry. The power pin on the servo is attached to Vin on the Arduino which is connected directly to the battery pack supply, this is done because the servo drains a lot of current and this could interfere with the rest of the circuit if it was connected to the 5V power rail. Finally, the PWM pin is connected to a digital PWM pin on the Arduino, this is because in order for the servo to be positioned at a value between 0 and 180 degrees, the Uno needs to be able to send exact voltages between 0V and 5V and this enabled by a PWM pin [29] [30].

D. Arduino Microcontroller

The Arduino microcontroller intakes and reads the processed EMG signal from the EMG circuitry and the position of the servo motor, and, from the code in C++ programmed into the Arduino, it controls the behavior of the end effector of the device, see main.ino as Figure 13 in Appendix D. The Arduino Uno has a 10-bit analog-to-digital conversion (ADC) which allows the EMG signal which is analog to be converted to digital that the microprocessor recognises and is able to process [24]. Since the Arduino takes approximately 100 μs to read and convert an analog input, the maximum reading rate is 10 kHz [14].

The analog input of the signal from the EMG circuit is read from analog pin A5 in millivolts. The digital pin 2 is used to write to the LED. Digital pin 9 is where the yellow lead of the servo motor inputs where the Arduino can read the position of the motor and write to it to change position [14]. Additionally, the variables signalThreshold, openPos, and closedPos were declared for better code clarity. Lastly, the variables signalState and servoState are the only two variables that were not declared as constants since they track and need to change depending on the values read from the A5 signal pin and 9 servo motor pin. Lastly, from the Servo.h library, a Servo object is declared and is leveraged to control the servo motor [30].

The setup() function executes once when the program is first run or the device is turned on. Thus, the setup() function performs the following in Figure 10 in Appendix D. The loop() function in Arduino continuously loops and runs after the setup() function is executed and it executes, continually monitoring the input signal and adjusting the prosthetic hand position accordingly and the process of execution can be viewed in Figure 11 and 12 in Appendix D..

Additionally, a reset button was included in the device to allow the user easy access to reset the device. The button was connected to the reset pin on the Arduino and ground. If the button is pressed, the Arduino will read the Reset pin as low, causing the whole program to re-execute beginning at setup() [31].

To verify that the code is executing and dictating the servo motor behaviour correctly in response to certain signal inputs, the Arduino Unit library was leveraged, see setServoTest.ino as Figure 14 in Appendix D. A separate file to the main.ino file called setServoTest.ino contains code of the unit test that will execute the setServo() function by giving it a known signalState and verify that the servo motor's state is equal to what it was set using the assertEqual() function. The test can be executed by putting unittest_main() in the setup() function of the main code; the unittest_main() function executes all unit tests in the directory. However, ideally, the unit test is only executed during the development of the device and code, and not when the code and device is in production.

E. Housing & Attachments

The housing for this prosthetic was created using SolidWorks, the CAD assembly can be viewed in Figure 15 in Appendix E [32]. The model was created using a mixture of subtractive modeling for the main housing and additive modeling for the servo motor mount and the end-effector. The assembly includes replicas of the battery pack, Arduino Uno, servo motor and breadboard to ensure proper fit prior to 3D printing; 1 mm tolerances were used on every side of the added components to compensate for imperfect printing. The final device was 3D printed in PLA in four separate pieces that were either glued or screwed together. Finally, two velcro straps were added to mount the device to the posterior of the user's forearm as seen in Figure 1 in Appendix B.

As per the QFD found as Table 3 in Appendix A, the most important engineering requirements pertaining to housing and attachments were: R1, should accommodate right or left handed dominant users; R2, must ensure comfort for long periods of time; R5, should be easy to adjust, remove, and put on the device; and R6, should be compact for convenient storage and travel.

To ensure the device would accommodate left and right handed users the device was made to be mostly symmetric with no components blocking the view of a left handed or right handed user. To ensure comfort for long periods of time, the bottom of the device which sits on the posterior of the users forearm was tapered from a width of 7 cm to 5.5 cm and rounded to sit flush to the forearm. Special care was also taken so that the user can place the lateral side of their lateral forearm on a table as they write by only extruding the model upwards and not exceeding a width of 7cm. To ensure easy adjustability, removability and placement of the device, the model is kept small so that it can be held with one hand while placing or removing the device from the other arm. Two velcro straps are used that can be custom adjusted to fit the user's arms and can be secured with one hand. To ensure compatibility, each component was fit neatly together with the breadboard and Arduino placed in the middle of the device as they are the central and most multidisciplinary subsystems of the assembly. The battery pack is stacked on top of the Arduino and exposed for easy change of batteries if necessary. Also, the storage pocket for the breadboard doubles as storage for the servo motor cable. There are minimal exposed wires aside from access to plug in EMG leads that way the user can travel and store the device without fear of accidentally breaking the circuitry.

F. Functional Prosthetics

The end effector consists of two arms coming out from the main housing of the prosthetic and a pincher attached to the servo motor as seen in Figure 16 in Appendix E, which together will grasp a writing utensil. The pincher is attached to the servo motor via a screw which compresses the pincher to the rotating part of the motor.

As per the QFD, the most important engineering requirements pertaining to the end-effector were: R3, can pick up and maintain a strong grip on a writing utensil without slippage; and R4, should enable users to write with their amputated dominant hand.

To ensure strong grip on a writing utensil without slippage, a rubber band was used on the gripping surface of the pincher, which has a coefficient of friction of 1, which prevents slippage up to forces of 234.3N [9]. To ensure the pencil would be easy to pick up, the arms can be placed tangent to the surface that the utensil is sitting on and the pincher closes behind, pushing it into the arms.

To ensure the device enable users to write with their amputated dominant hand, the prototype was tested by drawing circles, as this causes the user to put force parallel to the paper in every direction in that plane; this test ensured that the utensil would not fall or shift no matter the direction of any lateral forces.

A finite element analysis (FEA) was also conducted on the arms and the pincher to ensure the PLA 3D printed device would not break under the force of the motor. A free body diagram (FBD) as seen in Figure 17 in Appendix E, was created to calculate forces acting on the pincher and arms when the servo is at maximum torque when supplied with 6V. This max torque is 9.6kg/cm as per the datasheet for HS-645 multiplied by perpendicular the arm length results in a force of 14.88kg acting on each arm and double that acting on the pincher [25].

For the FEA done on the arms and the pincher, a force of 146N and 292N respectively was distributed along the inside rounded face of the components as ideally the utensil sits flush to those surfaces. For the arms, the face interacting with the user's arm on the housing was constrained and on the pincher, the inside of the hole where the screw will compress the pincher to the servo was constrained. Mesh convergence was used for both FEAs to get the most accurate Von Mises Stress while maintaining low run time, as seen in Figures 18 and 19 in Appendix E. The arms were components of a much larger part than the pincher so mesh control was used at the base of the arms where stress was the highest. PLA Von Mises yield stress is about 70MPa, the max Von Mises stress seen by the arms was 3.14MPa and 65.2MPa, as seen in Figures 20 and 21 in Appendix E, for the pincher indicating factors of safety of 2.23 and 1.1 respectively found by Equation 6 in Appendix C [33].

V. Conclusion

The process of developing the myoelectric hand prosthetic aimed to enable amputees to write was achieved through six critical subsystems following an iterative design process. Simulation tools were used throughout the entire process to test and evaluate the both the EMG circuit and housing progressed. The result was a compact, adjustable device that reliably picked up and dropped a pencil upon flexion of the forearm flexors to enable writing. The impact on users is substantial, improving functionality and quality of life, particularly for amputees who have recently lost their dominant arm and find it challenging to adjust to writing with their non-dominant hand. Future iterations will enhance comfort by improving the velcro adjustable straps and better simulate wrist movement by creating a damping mechanism at the end effector. Commercialization potential exists,however, many upgrades would have to be made first, like integration into PCB and decreased size of the overall device.

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Appendix A

Table 1. Primary User Characteristics

Primary User Characteristics	
Name	Janet
Brief Characteristics	Young adult female, university engineering student, studious, ambitious, detailed, determined/driven
Reasons for using existing/new product	Recent dominant-hand amputee (Metacarpal/Transmetacarpal amputation)
User values	Comfort, maneuverability, convenience

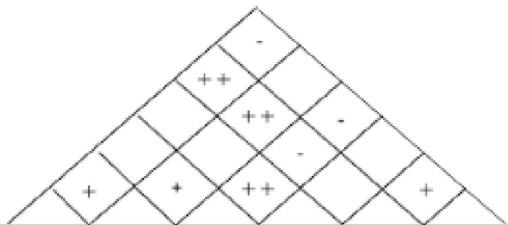
Table 2. Primary User Situation of Concern

Primary User Situation of Concern	
Use	**Customer's technical familiarity and ability:** ● Still has the majority of her dominant forearm and is still able to contract her forearm flexors. **Frequency:** ● Daily use for taking notes in class and doing homework.
Goals	**Goals user wants to achieve with product:** ● Increased efficiency while writing compared to writing with a non-dominant hand. ● Remain in control of device ● Long battery life ● Comfortable for long periods of device usage **Consider importance and frequency of goal:**

	High Frequency - device to become aid in everyday writing tasks.
Current Pains	**What are the current difficulties in achieving desired goals:** - Relieving Janet of the need to resort to typing or writing with her non-dominant hand. - Janet frequently experiences phantom limb pain which is exacerbated by stress or poorly fitting prosthetics [4].
Needs, Wants, Hopes & Desires	**Needs**: - Save time and effort - not re-teaching herself how to write with her non-dominant hand. - Compatibility - be able to bring it with her to school in her backpack - Needs to be able to write notes instead of type as she is an engineering student and thus inconvenient to type notes during core courses such as math and physics. **Wants:** - Aesthetically pleasing solution. - Comfortable solution. **Hopes:** - Not let her hand impede her hope of maintaining high academic standards. - Simplifying movement mechanics so that the device is usable to a broader demographic. Providing simplified instructions - making the solution as accessible as possible. **Desires:** - Dealing with prejudice towards prosthetic users - relieving them of some level of social anxiety and providing a sense

	of normality in the way that they are able to complete these tasks like their peers.

Table 3. Quality Function Deployment (QFD) Chart



User Needs/Functions	Importance	Engineering Requirements: Should accommodate right or left hand-dominant users. ↑	Must ensure the users comfort for long periods of usage. ↑	Can maintain strong grip on pencil without slippage. ↑	Should enable users to write with their amputated dominant limb. ↑	Should be easy to adjust, remove, and put on, the device. ↑	Should be compact for convenient storage and travel. ↓	Competitive Products: Myohand Variplus Speed by Ottobock [4]	Myo-electric Bebionic hand by Ottobock [5]
Save time compared to writing with non-dominant hand	18	9		3	9	3		1	9
Save mental effort/strain with intuitive design during writing	18	1	3	3	9	9		1	9
Comfortable for long term use	15	3	9			9	1	3	9
Solution should be cost-effective	10							3	
Allows for independent use	12	3			9	9	3	9	9
Long battery life	12		9	3	3			9	9
Compact for quick storage	10						9		3
Aesthetically Pleasing	5						3		9
Unit		Likert (1-5)	Likert (1-10)	N	Likert (1-5)	Likert (1-10)	cm^2		
Importance (HOW)		261	297	144	468	459	156		
Importance (%)		14%	16%	8%	25%	24%	8%		
Minimum Threshold		1	1	5	1	1	500		
Desired Target		4	8	70	5	8	7500		
Maximum Threshold		5	10	100	5	10	1000		

Table 4. Engineering Constraints

Constraint	
C1	Must not require the user's limbs outside the forearm flexors to operate the device. ● 0% of the EMG signals from muscles other than the forearm flexors signal the device.
C2	Must not restrict pronation and supination of the forearm, flexion and extension of the elbow, and circumduction of the shoulder. ● User relies on the locomotion of the arm instead of fine motor skills of the hand to write.
C3	Must not exceed the price of $1 500 USD [8]. ● This price was derived from Mark V by Mand.ro commercially for $1 500 USD, a single-channel myoelectric hand that took EMG signals from forearm flexors.

Table 5. Engineering Requirements Compliance Matrix

Requirement number	**Engineering requirement**	**Metric**	**Desired**	**Measured**	**Compliance**
R1	Should accommodate right or left handed dominant users ↑	Likert 1-5	4	5	Compliant
R2	Must ensure comfort for long periods of time ↑	Likert 1-10	8	7	Partially compliant

R3	Can pick up and maintain a strong grip on a writing utensil without slippage ↑	5N - 100N	70N	234.2N	Compliant
R4	Should enable users to write with their amputated dominant hand ↑	Likert (1-5)	5	4	Partially compliant
R5	Should be easy to adjust, remove, and put on the device ↑	Likert (1-10)	8	10	Compliant
R6	Should be compact for convenient storage and travel ↓	$500cm^3$-$1000cm^3$	$750cm^3$	$636cm^3$	Compliant

Table 6. Performance specifications of the available motors.

Motor	Weight (g)	Maximum Torque Range kg. / cm.	Current Draw at Idle (mA)	Step Angle (deg)	External driver requirement
Servo (HS-645) [24]	55.2	7.7 ~ 9.6	9.1	1	No
Stepper (ROB-09238) [26]	200.03	2.345	8	1.8	Yes
DC (PAN14EE12AA1) [27]	39.01 g	0.05	2.3	N/A	Yes

Table 7. Decision matrix of the considered motors

Motor	Weight (g) (weight = 3)	Maximum Torque Range kg. / cm. (weight = 5)	Current Draw at Idle (mA) (weight = 4)	Step Angle (deg) (weight = 4)	External driver requirement (weight = 2)	Score
Servo (HS-645) [24]	2	3	3	3	2	13
Stepper (ROB-09 238) [26]	1	2	2	2	1	8
DC (PAN14E E12AA1) [27]	3	1	1	1	1	7

Appendix B

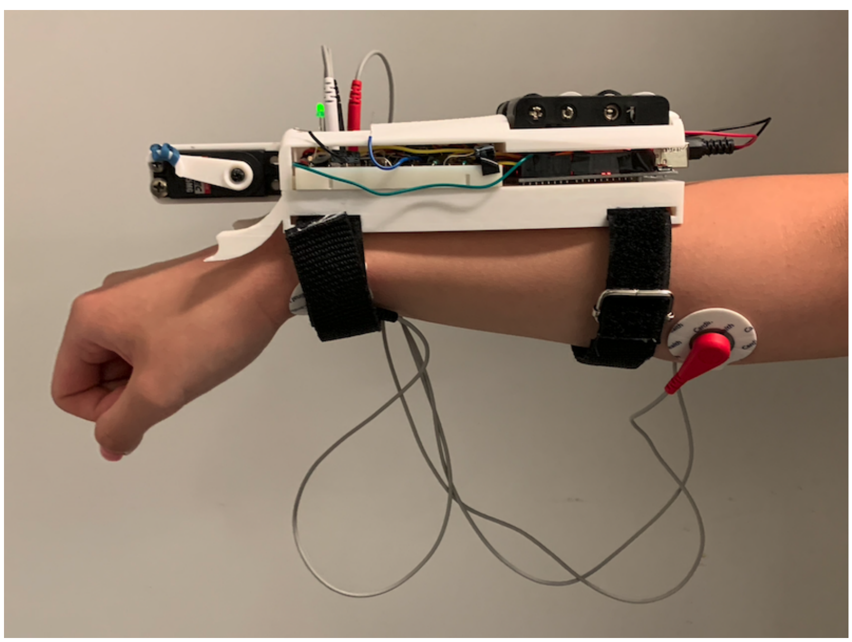


Figure 1. Echo prosthetic mounted on user arm

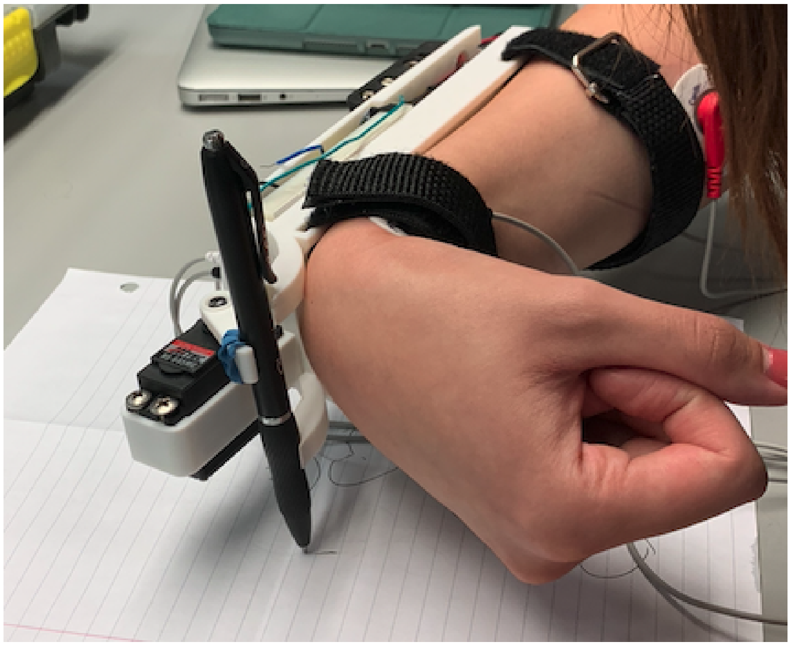


Figure 2. Echo prosthetic enabling user the write with a pen on paper

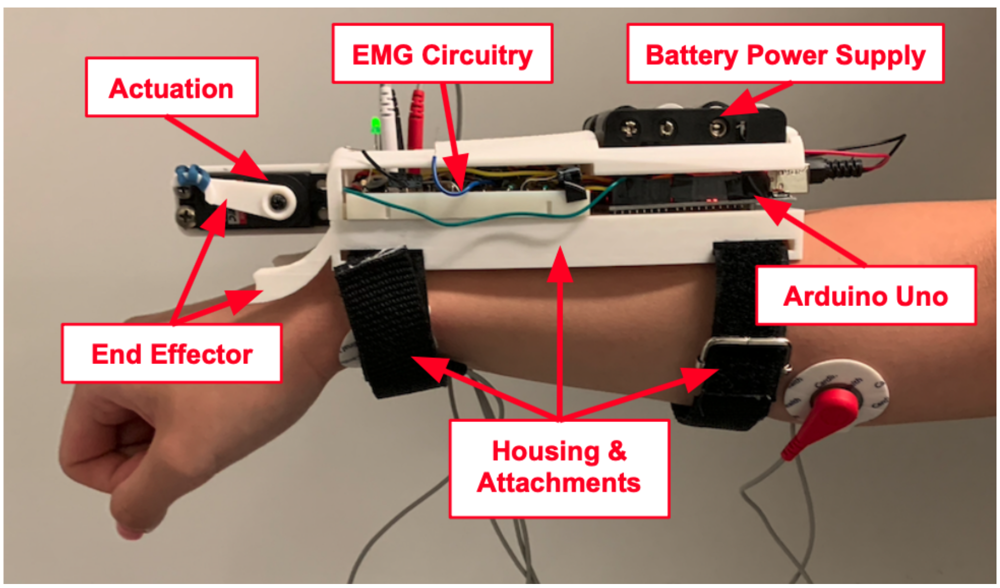


Figure 3. Echo prosthetic labeled subsystems

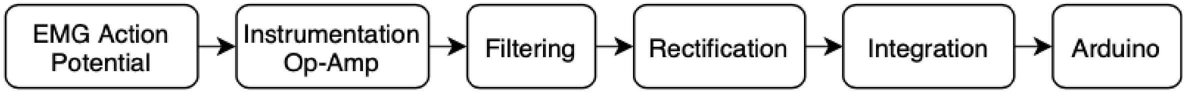


Figure 4. EMG circuitry flowchart

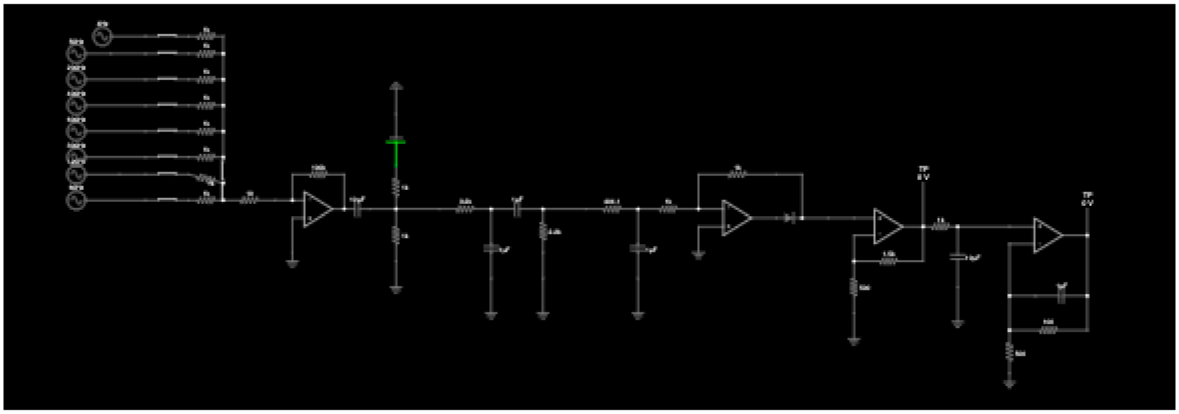


Figure 5. Falstad EMG circuit simulation

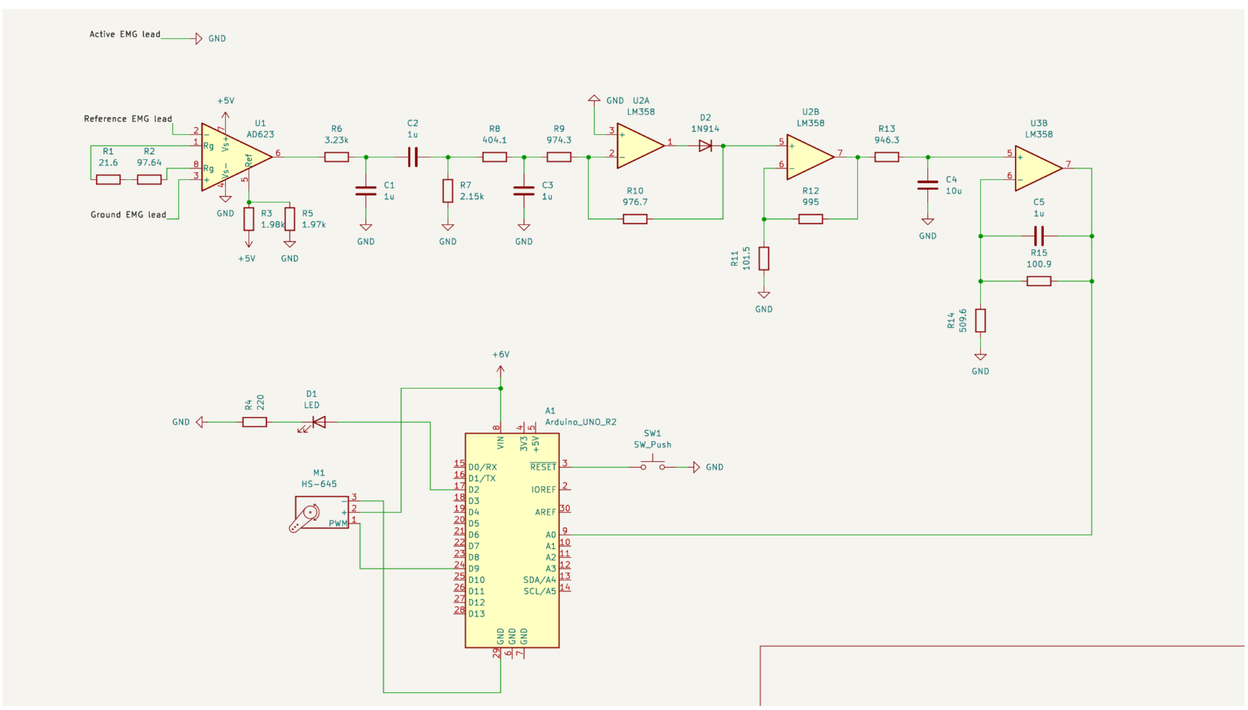


Figure 6. Final EMG circuit schematic

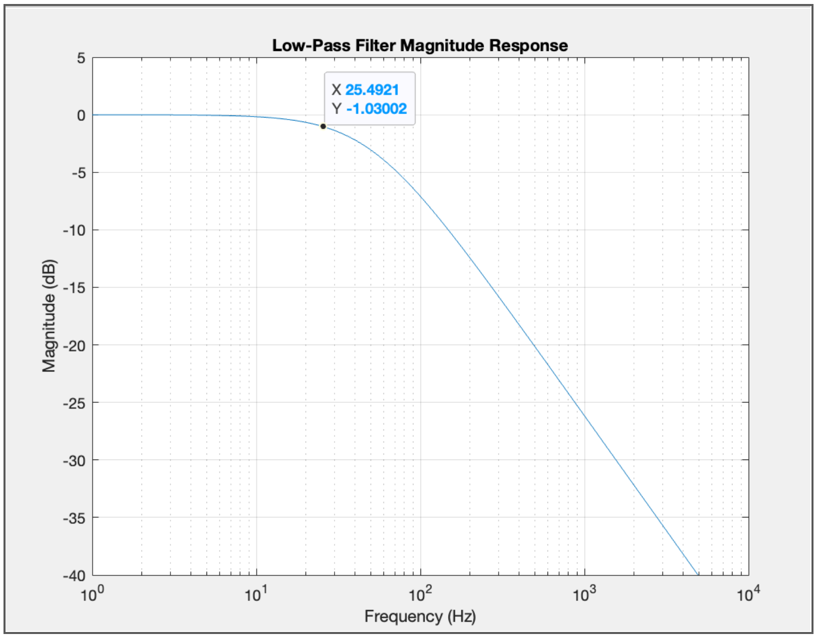


Figure 7. 60Hz low pass filter bode plot

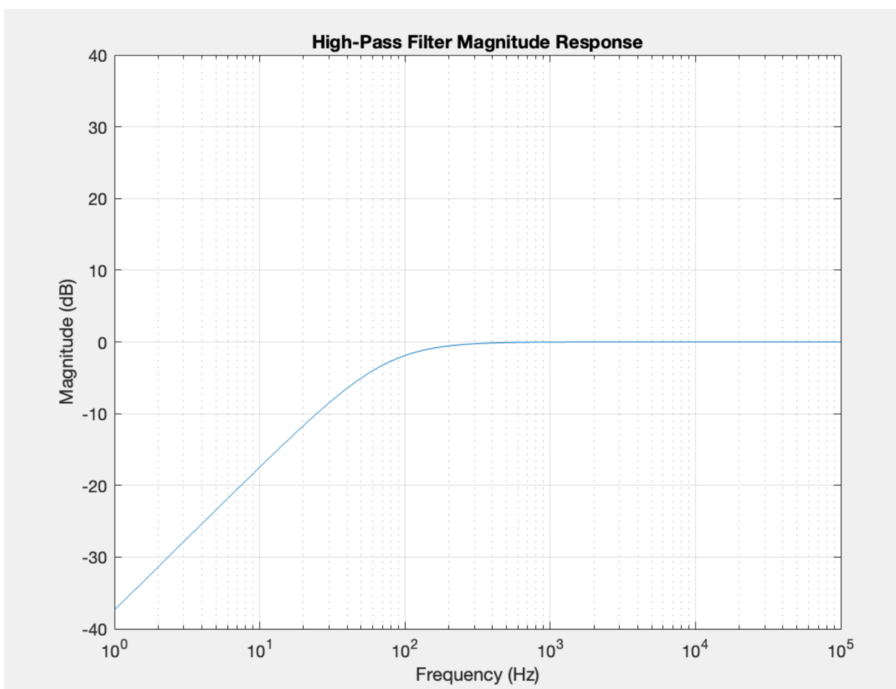


Figure 8. 60Hz high pass filter bode plot

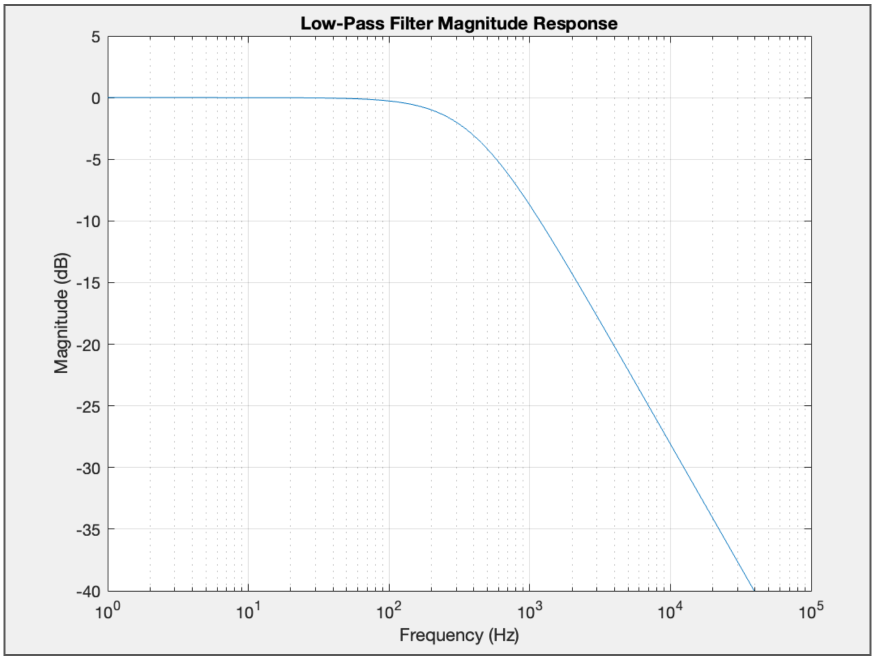


Figure 9. 400Hz low pass filter bode plot

Appendix C

Equation 1 - Gain of Instrumentation Op Amp:

$$A = 1 + \frac{100\,000}{R_g}$$

Equation 2 - Voltage divider:

$$V_o = V_{in} \frac{R_2}{R_1 + R_2}$$

Equation 3 - Low pass and high pass filter cutoff frequency

$$f_c = \frac{1}{2\pi RC}$$

Equation 4 - Gain of Non-Inverting Op-Amp:

$$A = 1 + \frac{R_F}{R_1}$$

Equation 5 - Battery Life:

$$Battery\ Life\ (h) = \frac{Battery\ Capacity\ (Ah)}{Current\ Draw\ (A)}$$

Equation 6 - Factor of Safety:

$$Factor\ of\ Safety = \frac{Maximum\ Stress}{Designed\ Stress}$$

Appendix D

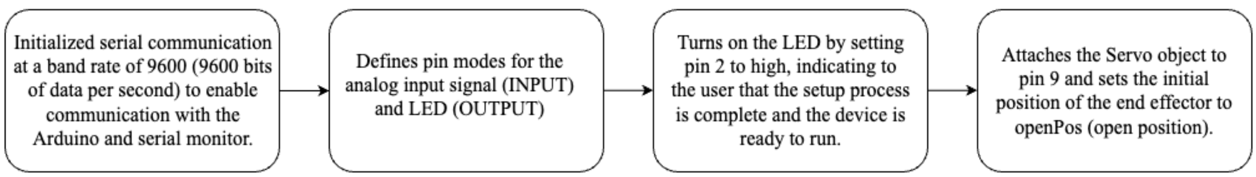


Figure 10. Flow chart of setup() function details and execution.

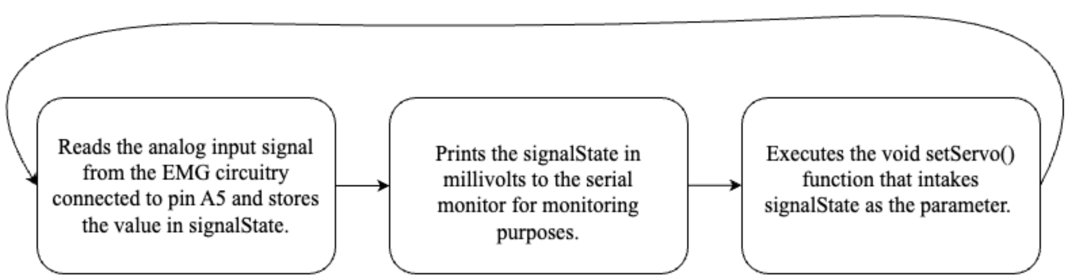


Figure 11. Flow chart of loop() function details and execution.

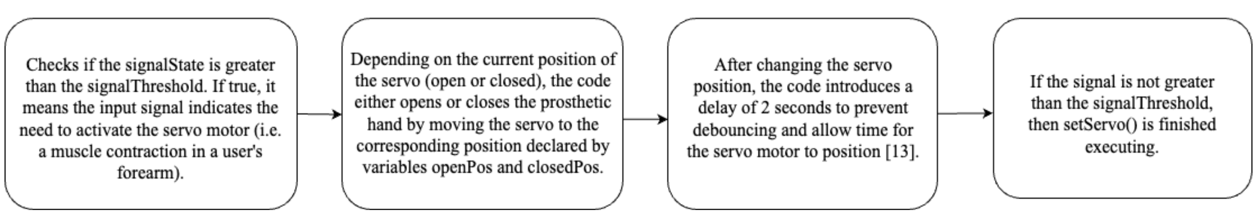


Figure 12. Flow chart of setServo() function details and execution.

```
#include <Servo.h>
Servo servo;

const int signal = A5;
const int LED = 2;
const int signalThreshold = 250;
int signalState;
int servoState;
const int openPos = 170;
const int closedPos = 104;

void setup() {
	Serial.begin(9600);
	pinMode(signal, INPUT);
	pinMode(LED, OUTPUT);

	digitalWrite(LED, HIGH);

	servo.attach(9);
	servo.write(openPos);
	servoState = openPos;

	// uncomment to execute unit test
	// unittest_main()
}

void loop() {
	// read
	signalState = analogRead(signal);

	// print signal
	Serial.print("Voltage: ");
	Serial.print(signalState);
	Serial.println();

	// moving servo
	setServo(signalState);
```

```
}

void setServo(int signalState) {
	if (signalState > signalThreshold) {
		if(servoState == openPos){
			servo.write(closedPos);
			servoState = closedPos;
			Serial.print(servoState);
		}
		else {
			servo.write(openPos);
			servoState = openPos;
			Serial.print(servoState);
		}
	delay(2000);
	}
}
```

Figure 13. main.ino Arduino Code

```
#include <ArduinoUnit.h>
#include <Servo.h>

Servo servo;

test(controlServoTest) {
	// setup
	Servo servoUnderTest;
	int openPos = 170;
	int closedPos = 104;
	int signalThreshold = 250;
	int signalState;

	// Simulate signal > threshold
	// Expected: since openPos, should write closedPos to servo.
	int signalValue = signalThreshold + 10;
	servo.write(openPos); // Reset the servo state
	controlServo(signalValue);
```

```
        // Verify servo is closed and servoState variable is updated
        assertEqual(servo.read(), closedPos);
        assertEqual(servoState, closedPos);

        // Simulate signal < threshold
        // Expected: since closedPOs, should write openPos to servo.
        signalValue = signalThreshold - 10;
        servo.write(closedPos); // Reset the servo state
        controlServo(signalValue);

        // Verify servo is open and servoState variable is updated
        assertEqual(servo.read(), openPos);
        assertEqual(servoState, openPos);
}
```

Figure 14. setServoTest.ino Arduino Code

Appendix E

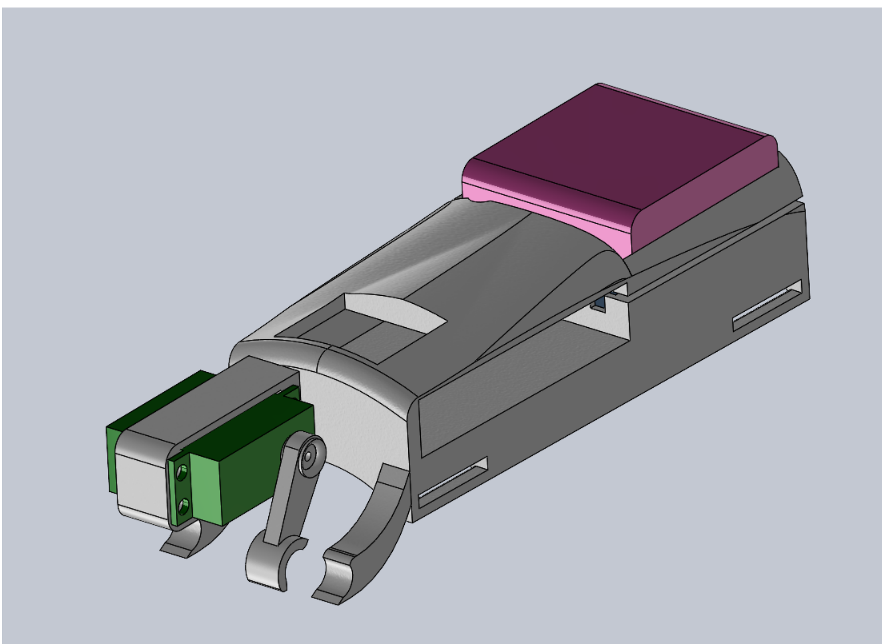


Figure 15. Solidworks assembly of Echo prosthetic housing

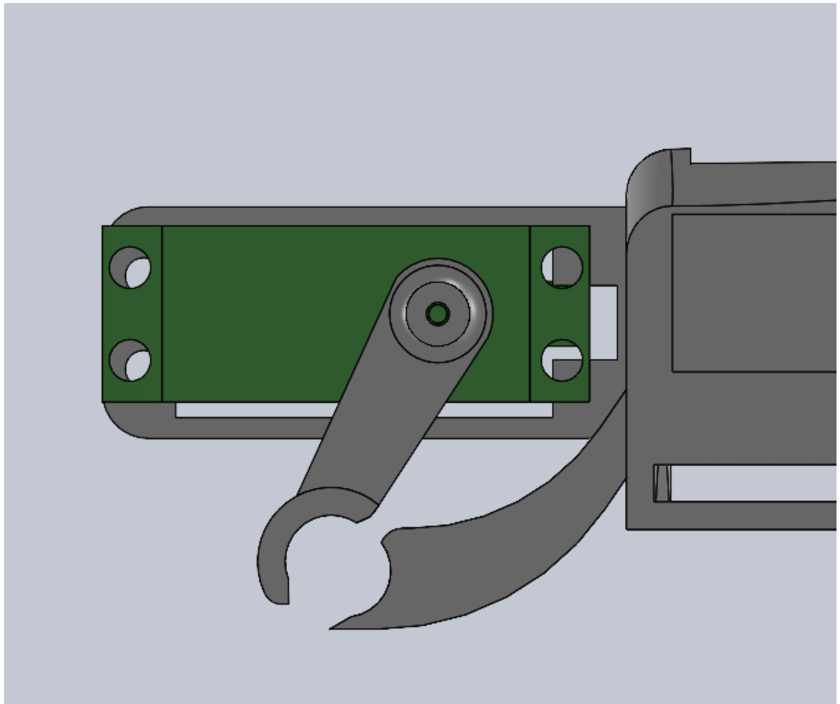
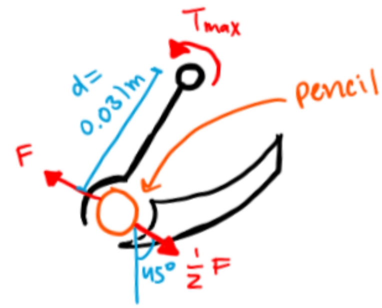


Figure 16. End effector solidworks assembly side view



$$T_{max} = 9.6 \frac{kg}{cm} = 960 \frac{kg}{m}$$

$$F = T_{max}\, d = \left(960 \frac{kg}{m}\right)(0.031\,m)$$

$$F = 29.76\ kg$$

$$\Rightarrow \boxed{\frac{1}{2}F = 14.88\ kg = 146\ N}$$

Figure 17. Free Body Diagram of End Effector Forces

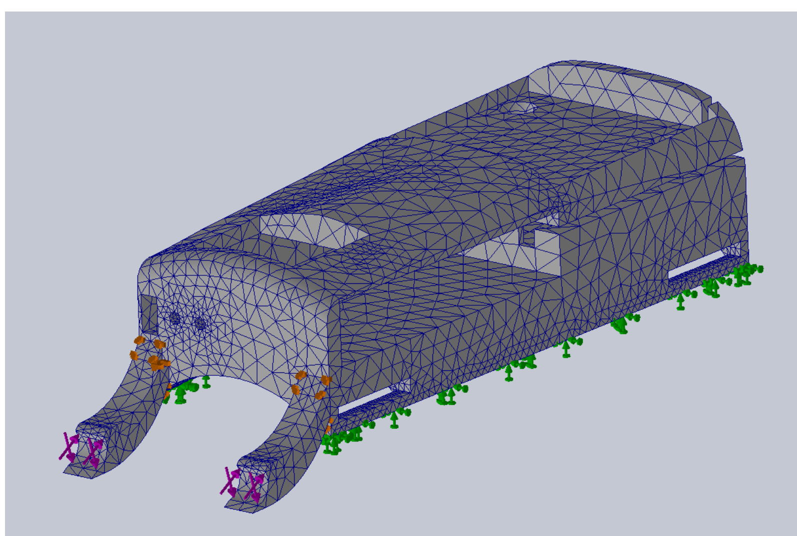


Figure 18. Force distribution and mesh for FEA of Echo prosthetic housing

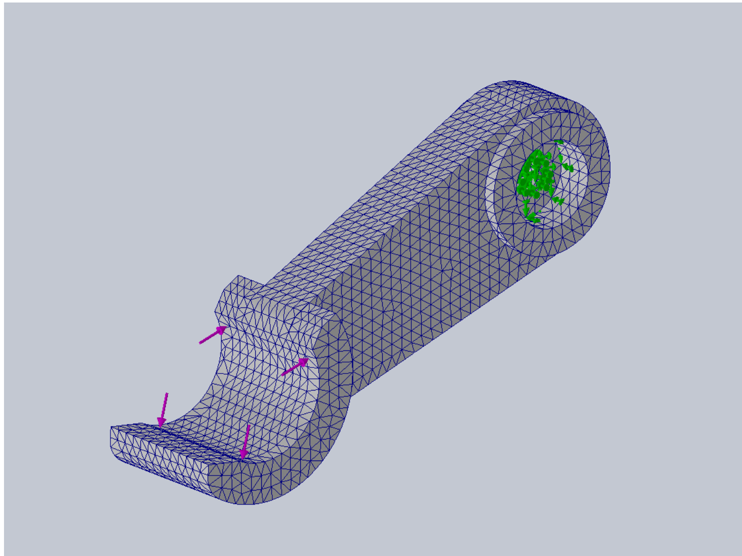


Figure 19. Force distribution and mesh for FEA of Echo prosthetic pincher

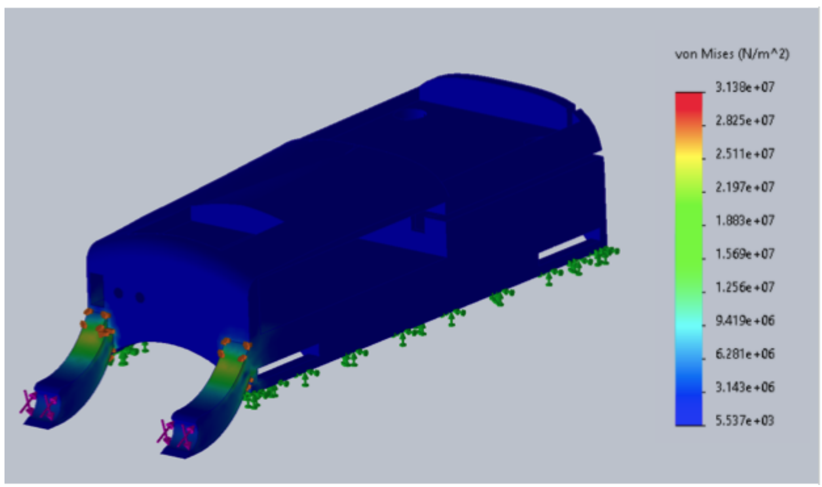


Figure 20. FEA of Von Mises Stress for Echo prosthetic housing

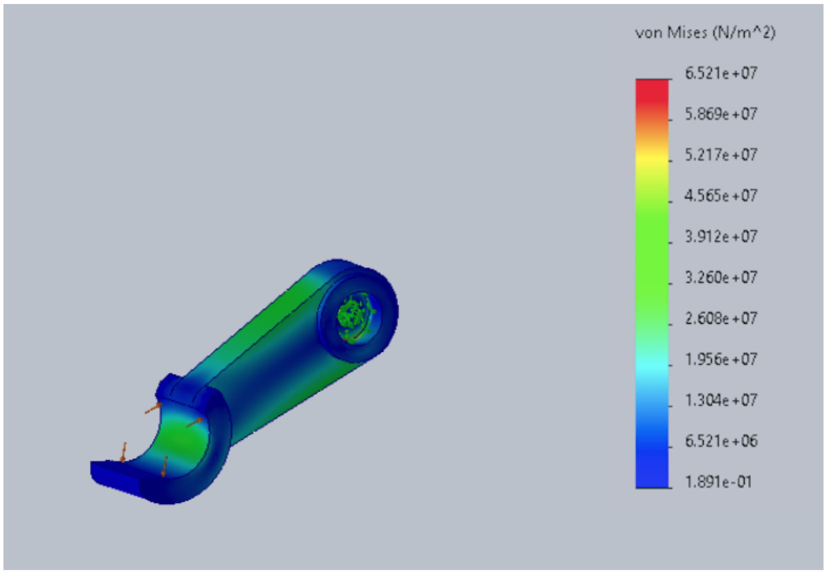


Figure 21. FEA of Von Mises Stress for Echo prosthetic pincher