Design of a Dexterous Prosthetic Arm with Gesture Recognition

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ABSTRACT: Prostheses play a vital role in improving the quality of life for individuals who have lost their limb due to trauma, congenital disease, etc. Unfortunately, bionic below-the-shoulder prosthetic options are very limited due to the complexity of the human arm's range of motion and its corresponding degrees of freedom in a prosthetic arm. The market is limited in terms of adjustable sizing options. Currently, children who use prosthetic arms need to purchase entirely new devices as they grow and adapt to such devices. Prosthetic arms are also dominated by myoelectric controls which have many limitations and face high rejection rates. In response to these challenges, this work presents a transhumeral prosthetic arm that employs additive manufacturing methods to develop a highly dexterous, attainable device for users. Leveraging the power of parametric design tools in computer-aided design (CAD) software, the arm can be customized in size and shape based on dimensions taken from the user's body. The arm is controlled by an innovative foot controller that uses a combination of buttons and sensors to control the grips and articulation of the arm. The controller contains an inertial measurement unit (IMU) that tracks the user's gestures, which are used to intuitively control the arm. Haptic feedback is sensed through a glove that processes vibrations and forces into real time feedback to the adjustable feedback band. The feedback given simulates reaction forces of different grips and textures of varying surfaces.

Index Terms—Compliant Mechanism, Actuatable, Cable-Driven Transmission.

INTRODUCTION:

Currently, there are approximately 1 in 190 people living with limb loss in the United States. The incidence of limb loss has increased in the last decade due to combat injuries in the military population and non-traumatic causes of amputation in the civilian and aging veteran populations such as peripheral vascular disease, diabetes, and malignancy. The focus of this research involves improving prosthetic devices' functionality, while addressing the main causes of prosthesis abandonment: weight, cost, repairability, and ease of control. Current prostheses are often described as too time-consuming, unreliable, non-intuitive, and mentally exhausting. Focusing on resolving these primary complaints is essential for decreasing rejection rates.

Previous iterations of the Smart Prosthetics research project at CSUN have utilized a wide range of actuators, materials, and control methods to help resolve rejection rates. Shape Memory Alloy (SMA) actuators were utilized to actuate the hand components, fused deposition 3D printing was commonly employed to inexpensively prototype components, and various innovative control systems were developed from myoelectric systems to the current design of a foot controller. This year, we strayed from the use of SMA actuators to resolve the issue of instantaneous control. SMA wires have high force and strain outputs for small weights, however extension is impractically slow, and force convective cooling systems are far too bulky for a wearable prosthetic.

The "Prometheus" prosthetic arm features a lightweight 3D-printed structure, advanced wrist actuation, mechanism, foot controller, and touch-sensitive haptic feedback system. The arm has the potential to improve the quality of life for those who have been experiencing limb difficulties, both physically and mentally, by restoring fundamental human functions which amputees have lost.

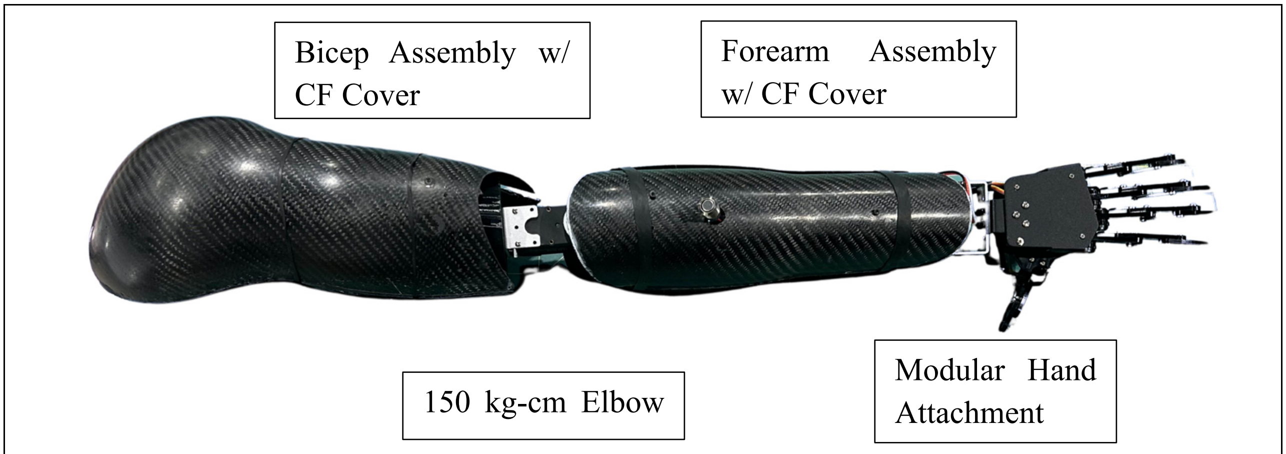


Figure 1: Real life assembly of the entire below-the-elbow prosthetic developed by the Smart Prosthetics 8th Cohort.

MODEL DESCRIPTION:

2 Arm Design

2.1. HERACLES Hand Design

The critical bottleneck of upper extremity prosthetic design has always been the control and dexterity of the hand. Human hands display extreme dexterity, precise manipulation, and impart large loads, while maintaining robustness. When designing a prosthetic device, anthropomorphism is critical for maintaining the illusion of humanity, dexterity is critical for allowing users to employ the prosthetic as they would their own appendage, fidelity is necessary to allow for repetitive use, and a comprehensive control method is necessary to allow for effective employment of the device. These contradicting design necessities are challenging to collectively meet, resulting in a gap between functional prosthetic systems and dexterous proofs of concepts. The finger actuation systems utilized from previous Smart Prosthetics cohorts all utilized revolute joints, and underactuated finger mechanisms. This is advantageous in that the control kinematics, assembly, and load resistance are simplified. Yet there is much to be desired in terms of dexterity, friction factor, and impact resistance. In contrast to this year's cohort, where a biomimetic finger and palm system was proposed, utilizing rolling contact joints, and accurate actable degrees of freedom. The first step to the actualization of this design was determining the functionality of a human hand and identifying the critical parameters that enable its diverse benefits and capabilities. Human fingers have 6 tendons for actuation, multiple joint ligaments for impact resistance, and a mixture of synovial and rolling contact joints (RCJ). Synovial joints require an unfeasible amount of tendon controls to actuate in a functional prosthetic, leading to the selection of an RCJ-focused finger actuation system. Rolling contact joints have negligible friction factors, high impact resistance, improved load distribution over each joint, and dislocate under high loads. They utilize cable-based actuation systems which are simpler to manufacture than alternative systems and allow for increased actuatable degrees of freedom. A downside of RCJ's when compared to conventional revolute joints is the increased complexity of the design, manufacturing process, modeling, and a decrease in torsional stiffness. In human hands, dislocation is advantageous compared to bone fracture, and this remains the case for prosthetic designs. However, RCJ's have lower torsional stiffnesses than real human hands, and this can be an issue for the precise manipulation of objects. As a result, the 8th cohort's HERACLES finger system includes a biomimetic tongue and groove structure to the finger joints which can be seen in **Figure *2***.

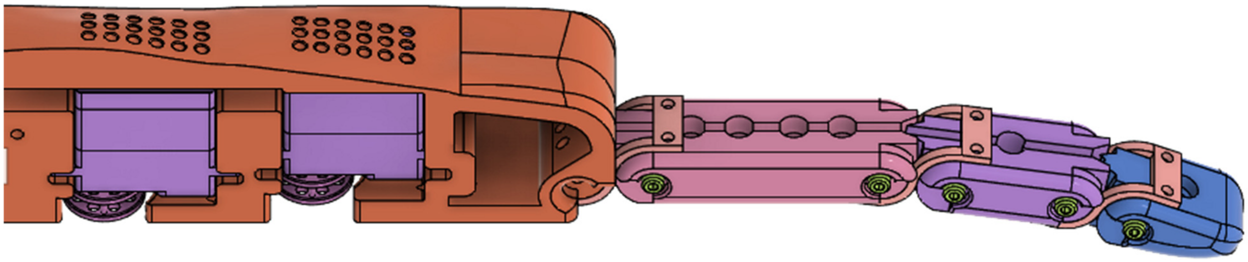


Figure 2: The Heracles Hand finger actuation system using rolling contact joints, elastic ligaments, and torsional stiffness links.

It should be noted that the through holes at each joint allow for elastic ligaments normal to the face of the contact joint. Through-holes, and 2 mm bolts are utilized to accommodate the chosen manufacturing method of SLA Resin 3D printing due to its superior tolerances, and ability to print fine detail. The fingers have 2 actuable degrees of freedom each, necessitating two servos to control the system. A higher servo count has never been attempted due to the size constraints of a prosthetic arm and overlap between the wrist actuation, electronics, and servo motors. A streamlined design philosophy prioritizing modeling around the servo motors has allowed us to develop an adult palm design that will fit numerous A12-610 servo motors as shown in **Figure *2***.

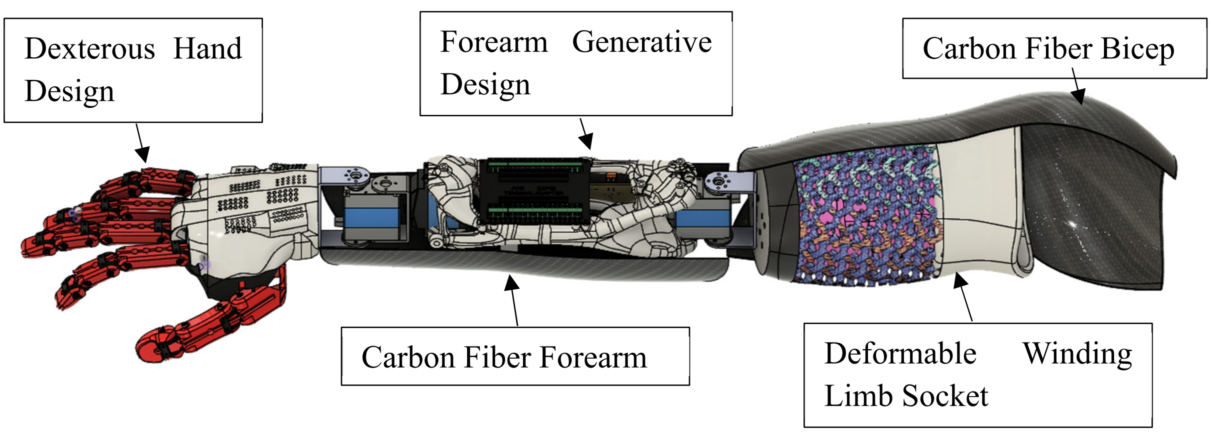


Figure 3: Full CAD Assembly of the 8th Cohort's arm design including critical sub-assemblies like the hand design, bicep assembly, and forearm generative design.

It should be noted that the increased servo count necessitates a balance between the length of each metacarpal and finger. The general hand dimensions measured indicate a tentative ratio of 77%, 90%, 100%, 94% for the pinky, ring, middle, and pointer finger to maintain anthropomorphism. Additionally, the palm design utilized a 3D hand scan or a real male adult as a reference and base. This was selected to maintain the humanness of the design, while ensuring the hand maintained biomimetic scale and form.

2.1.1 Palm Design

The design of the prosthetic palm, the description of the part containing the finger actuation motors, as well as the attachment point for the fingers, focuses on the integration of eight KST-A12-610 servo motors used to provide flexion and extension of each of the four fingers and add splay functionality to the hand, which is the ability to spread the fingers apart from one another, more technically defined as abduction and adduction of the fingers in relation to the central axis of the hand. The function of the servo motors is to produce flexion behavior based on any given command. Flexion is produced by torque originating from the servo motors. Flexion is produced by torque originating from servo motors which rotate a spool mounted on the top of each of the motors. These spools act as a guide for the actuation cables, having a radius of 20 mm, to create the proper amount of displacement as the cables are pulled. These cables are routed through designated pathways inside the finger joints, where they are attached to the fingertips. As the motors rotate up to about 30 degrees, they actuate the fingers. The extension of each finger is achieved by elastic cords that are routed through the finger joints to allow the fingers to return to a relaxed position. The outer shell for the palm originated from an open-source 3D scan of an adult hand, aimed at developing a biomimetic design to reduce prosthetic rejection rates. The 3D scan initially existed as an STL mesh, which is difficult to work with in CAD workspaces. To address this, the palm was converted into a solid model by creating cross-section sketches of the mesh model at 1 cm intervals along the hand's length. These cross-sections were then lofted together to form a solid body, allowing the outer shell to be easily edited and customized to seamlessly integrate with the mechanics of the finger and splay actuation mechanisms.

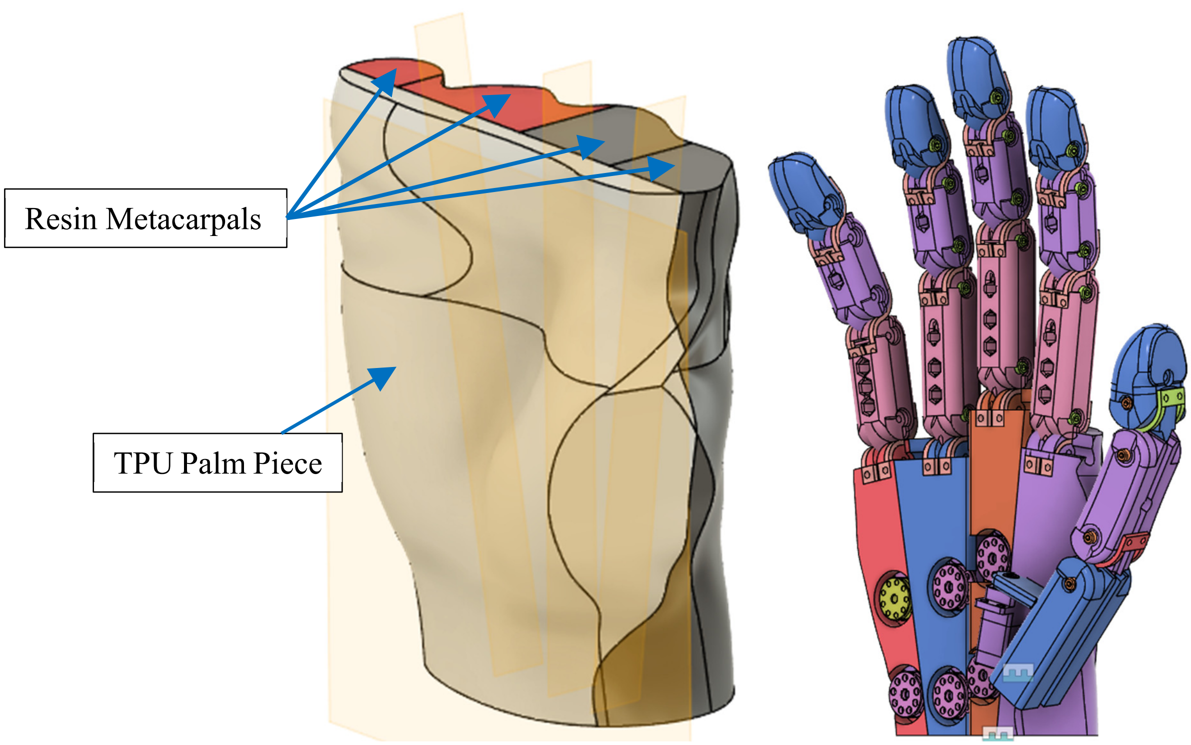


Figure 4: Thumb design with adduction, abduction, flexion, and extension. Controlled by multiple A12-610 servos and has a combination of revolute and rolling contact joints.

The thumb design was originally intended to accommodate a single coupled degree of freedom for flexion and adduction; however, this plan was altered to develop an increasingly biomimetic design. The thumb is commonly associated with multiple critical grip types such as opposed and non-opposed that make up for the bulk of hand dexterity in humans. [1] As a result, the design was altered to allow for independent manipulation of adduction and flexion degrees of freedom as shown in **Figure *4***.

2.1.2. Bicep Components

To better understand how the prosthetic arm would integrate with the human body, a replica socket and residual limb were developed to simulate the anatomy of an amputee. A 3D scan of a human bicep was used as the basis for this process, generating a mesh file that was imported into Fusion. From this file, a solid body was created to represent the residual limb, which then served as the foundation for forming a tightly fitted socket. This initial socket was 3D printed in ABS and served as the first iteration. However, after several trials, it became evident that a rigid ABS socket would be both uncomfortable and impractical for extended wear. A mold was created to cast the residual limb in silicone, and a simplified bone structure was designed to support the formation of the residual limb. The artificial stump enabled testing of the prosthetic mounting system, to determine the assembly's ability to undergo daily activities without slippage or mounting failure. The team ultimately developed a solution: a flexible, mesh-like socket design that was integrated within the outer composite shell of the prosthetic arm. This design not only enhanced comfort but also allowed for easy adjustments to accommodate individual size needs.

Figure 5: 3D Model of a residual limb utilizing a body scan.

Figure 6: Side by side comparison of the bicep assembly which houses the multi-material arm socket, and 150 kg servo attachment.

2.1.3. Forearm Design

The functionality of a prosthetic arm is one of the most important components to consider in designing a prosthetic model. Allowing the user to restore any complex functions of the human body without a heavy prosthetic arm is an advancement in medical engineering. Torque is applied to the bending mechanism that allows the hand to end 45 degrees in both directions. Rotation is achieved by 35 kg servo motors placed below the central structure within the forearm.

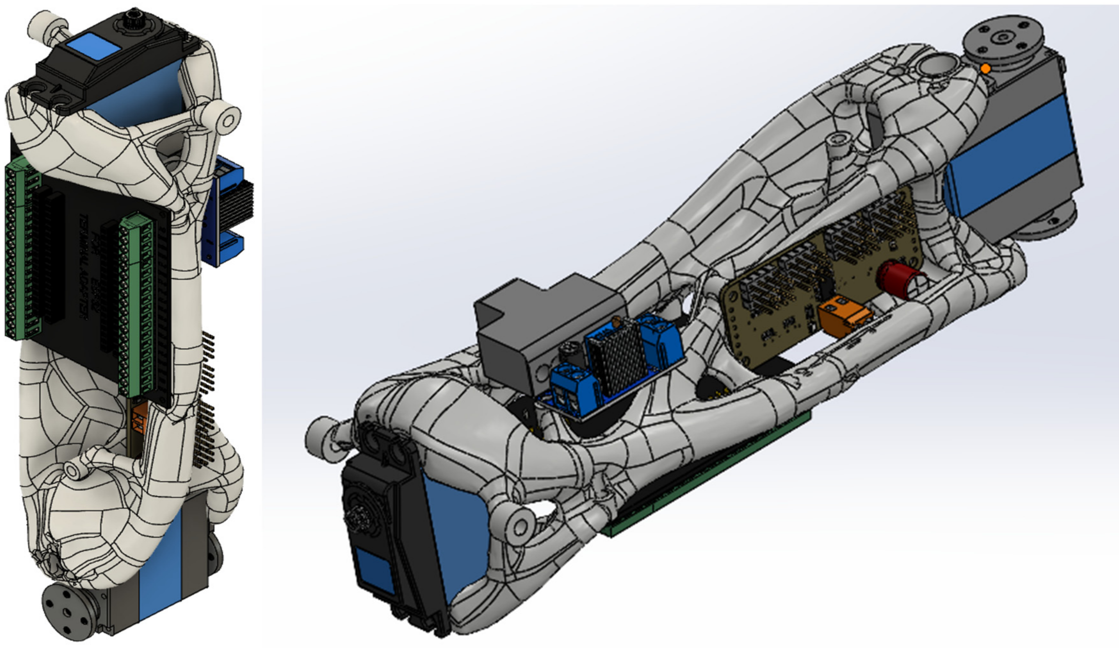


Figure 7: Forearm cage housing the full assembly of electronics. Designed using Fusion generative design to accommodate large loads and moments seen in real life applications.

An important turning point in the project's eight-year history was reached this year when the cohort added a bicep, a revolutionary addition to the prosthetic arm. Changing the design from a below-the-elbow to a below-the-shoulder system greatly improves realism and functionality. A 150 kg "DSSERVO" bending servo motor was used for the bicep's initial design because of its ability to enable elbow bending in response to foot controller directions. This particular servo motor was able to generate enough torque to simulate the arm picking up everyday objects such as water bottles, backpacks, and more. It was vital to also consider the weight of the forearm and everything below this servo motor to correctly calculate the load cases. The team used Fusion's generative design tools to construct a custom motor mount for this motor. It was made of ABS plastic and was designed to be durable and efficient even under calculated stress scenarios.

2.1.4 Manufacturing Methods and Prototypes

This year's cohort utilized a variety of manufacturing methods for the prototyping and final design of the prosthetic device. The hand design utilized MSLA printing which employs a liquid resin that is cured via stereolithography a layer at a time using a MONO-LCD. This reaction is exothermic and toxic: necessitating the use of the proper PPE such as organic vapor masks, nitrile gloves, protective eyewear, and a fume hood. The process can be seen in **Figure 8**, with evidence of the fine detail available using MSLA printing.

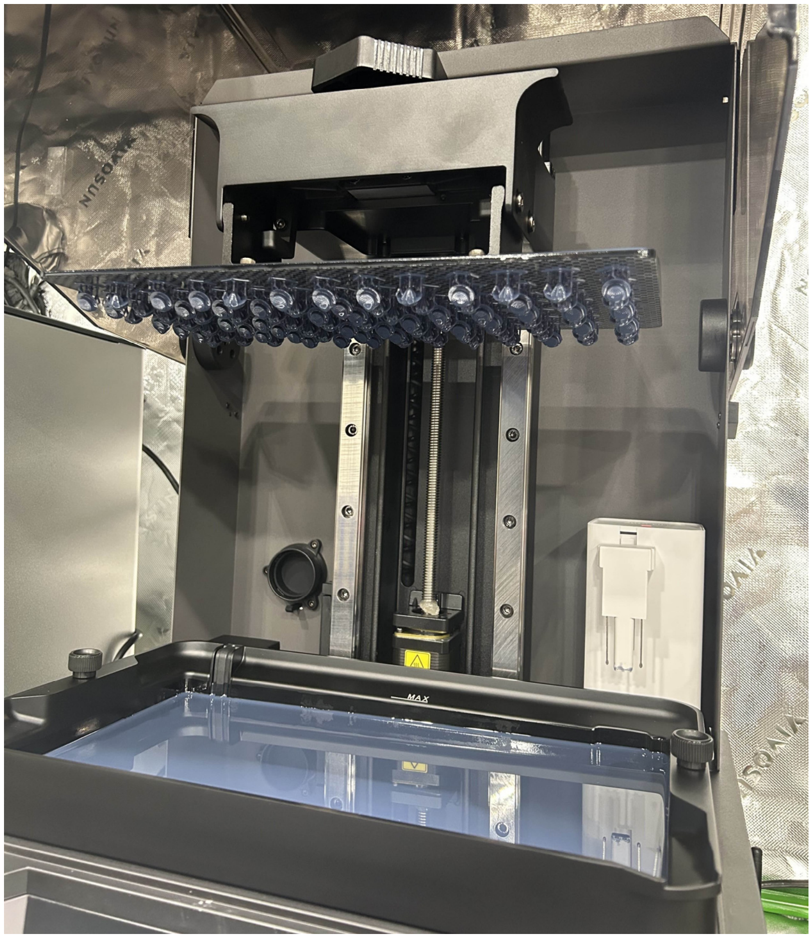


Figure 8: Resin printing process and an example of finished products. Liquid resin becomes hard plastic with attractive material properties.

The carbon fiber shell components were designed, and implemented with the objective of increasing impact resistance, while minimally increasing the weight of the device. Manufacturing the composite shells is difficult as it requires precise wet layup on molds that were properly prepared and designed. Proper composite preparation begins when designing the actual mold and ensuring the the molds are cut approximately where the draft angle is equivalent to 0 degrees. As such, draft analysis was performed on each mold, and precise cuts were performed on both surfaces of the mold as the arm shape is asymmetrical necessitating the use of multiple draft cuts. Afterwards, the molds were manufactured using fused deposition modeling (FDM) 3D printing, and the surface prepped for Duratec spraying by dry sanding through the various grits 120, 220, and 660 sandpaper.

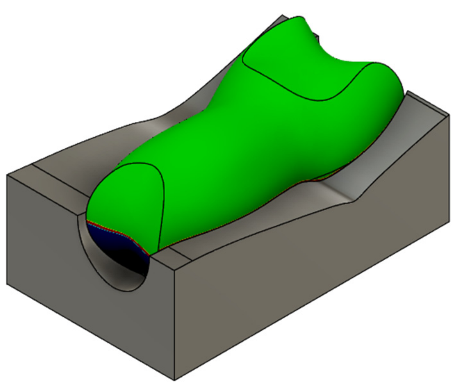


Figure 9: An example of the draft analysis of a carbon fiber bicep component.

After sanding, the tools were wiped, and sprayed with Duratec mold release to ensure proper release and surface finish upon wet layup. The mold surfaces were wet sanded after spraying at 600, 1000, and 2000 grits, before 7 layers of wax were applied to maximize the surface finish of the composite parts. Carbon fiber wet layup was performed with vacuum bagging over a glass plate. This process can be reviewed in both **Figure *10*** and **Figure *11***.

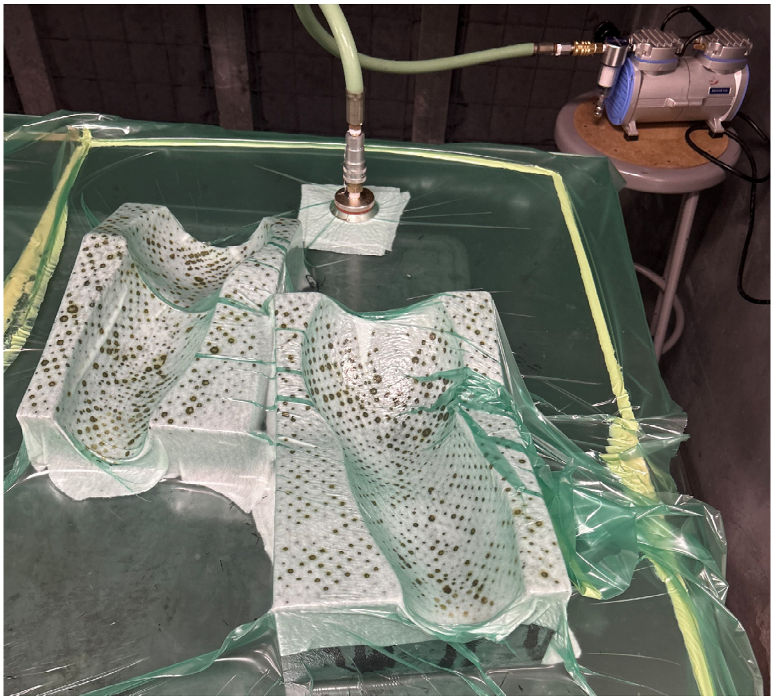


Figure 10: Vacuum bagging of carbon fiber wet layup bicep components.

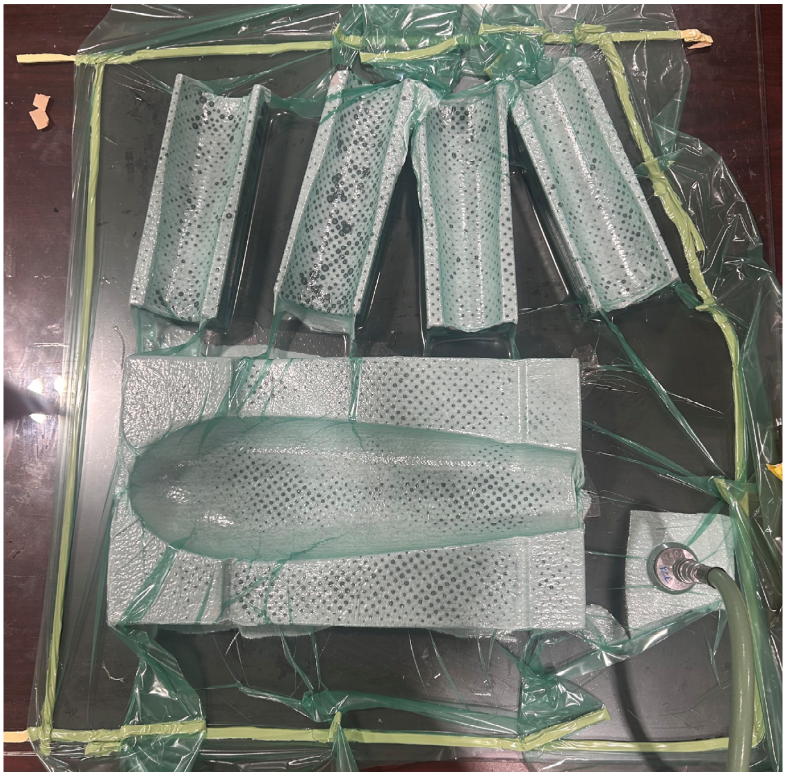


Figure 11: Wet layup of the forearm shells for the prosthetic. Utilized 3 layers of 0/90/0 carbon fiber twill. Vacuum bagged over a glass plate.

It should be noted that the composite components utilized a 0/90/0 pattern of twill carbon fiber. The components were released and trimmed to the appropriate shape using a Dremel with a carbon fiber cutoff wheel attachment. The surface finish and anthropomorphism of the forearm covers can be seen in comparison to a real human arm.

Figure 12: Unfinished composite pieces upon release alongside their respective molds.

2.2 Foot Controller

2.2.1 Introduction

This semester the foot controller team had a strong base to build off from the previous semester. Small improvements were made to the foot insole design, and more significant improvements were made to the gesture recognition and virtual interface of the foot controller. Additional modifications were made to the code to accommodate an increase in degrees of freedom, for the completion of the more dexterous Heracles hand.

2.2.2 Insole Design Improvements

The focus this semester for improving the insole design was to protect not only the user but the electronic devices themselves. Throughout the first semester we continuously had an issue where the orientation sensor would disconnect and stop sending data to the microcontroller. This made it so that until the foot controller was power cycled that only the hand could be articulated, and the elbow/wrist was inoperable. The most likely reason for the orientation sensor to be disconnecting was an interference from being in close contact to the users skin. This assumption was based on the fact that when prototyping in the first semester, anytime the sensor was grounded against a table it would also disconnect from the microcontroller.

Shown above in **Figure *13*** is the housing solution that worked best to prevent this issue and allow the foot controller to be used uninterrupted. The housing is 3D printed out of PLA filament and prevents the sensor from accidentally being grounded or exposed to static shock and therefore preventing it from disconnecting from the microcontroller. There is also the added benefit of protecting the user from any heat dissipation that may be coming from the orientation sensor. The housing comes apart in two pieces, one that the sensor rests in, and a snap fit top cover to retain the device.

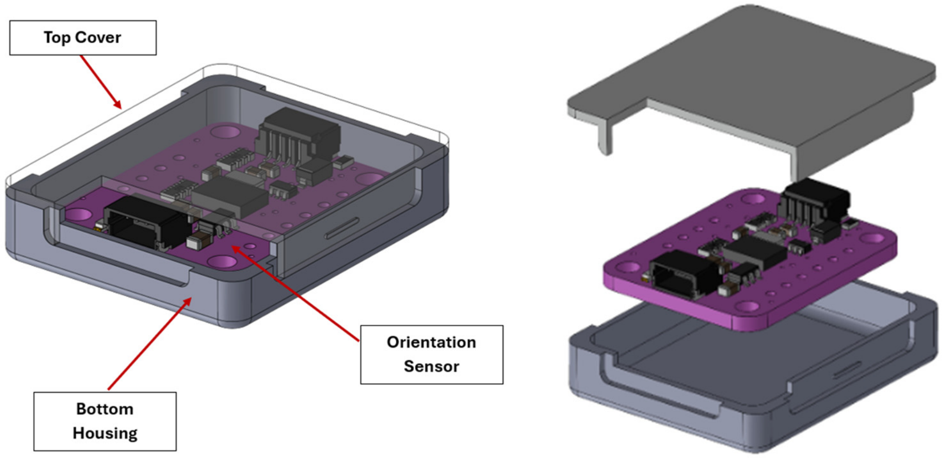


Figure 13: BNO055 Orientation Sensor with Housing with Exploded View

We saw a reduction of approximately 50% less sensor disconnections after implementing this design change. Obviously, this is still a huge issue, and no disconnections should be happening for a crucial device such as a prosthetic control device. Had time permitted a proposed solution would be to write a function that would allow the microcontroller to detect if the sensor had disconnected and force it to reinitialize instead of waiting to be initialized when it is power cycled.

Figure *14* & **Figure** *15* show an overview of the completed insole design in a child's & Adult's size. Key changes for this semester were the orientation sensor housing as previously mentioned and the addition of a cutout for a vibration motor shown in the child size foot controller. The cutout allows for a small vibration motor to be placed on the foot controller's wings side opposite the side which houses the electronics. This vibration motor can be used to haptically notify the user when a particular event occurs with either the foot controller or the prosthetic arm. For example, if a gesture is recognized a short quick vibration could notify the user of the recognition's occurrence. Another example regarding the arm is that the vibration motor can continuously vibrate to notify that the arm is low on battery and needs to be charged immediately. This approach to a prosthetic notification system is extremely versatile because of how the vibration motor can be actuated in various intensities and durations allowing for numerous notification types.

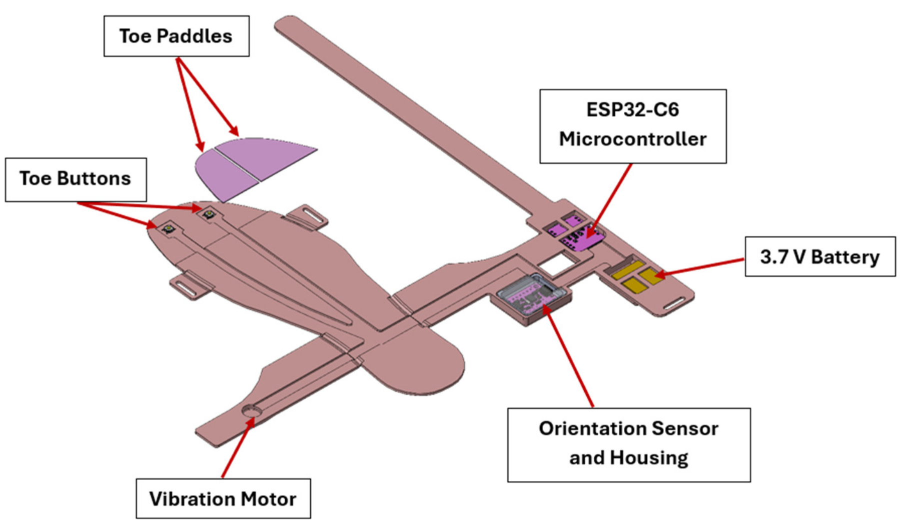


Figure 14 Child Size Foot Controller Assembly

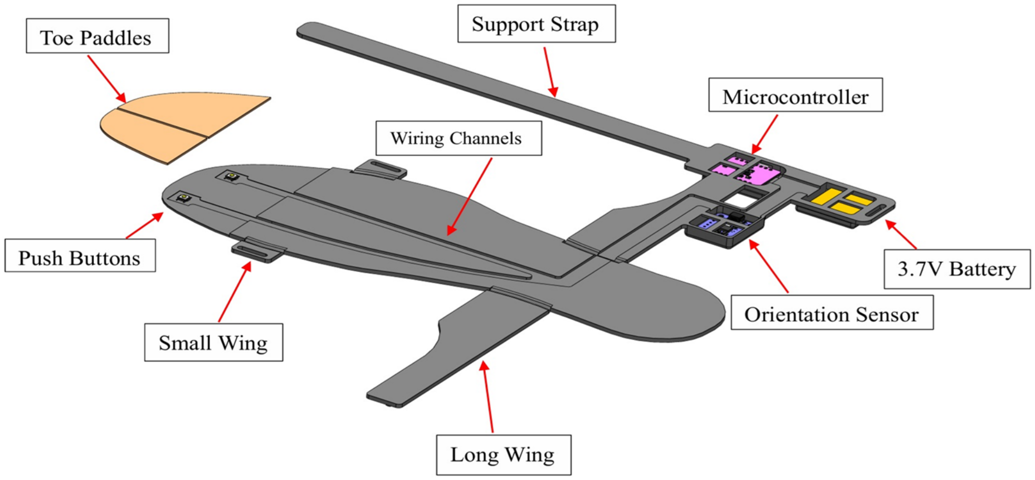


Figure 15: Adult Size Foot Controller Assembly

The last change made this semester was to the location of the foot controller power switch. Initial prototypes of the foot controller utilized an ESP32-C6 manufactured by Xiao. These microcontrollers were slightly smaller than other manufacturers designs and allowed the power switch to sit flush above the microcontroller. When assembling a foot controller with a microcontroller manufactured by DF Robot we realized that there would be fitment issues where the microcontroller came close to the power switch. This prompted the team to make a small adjustment to the placement of the power switch which required modification of the CAD files for the foot controller.

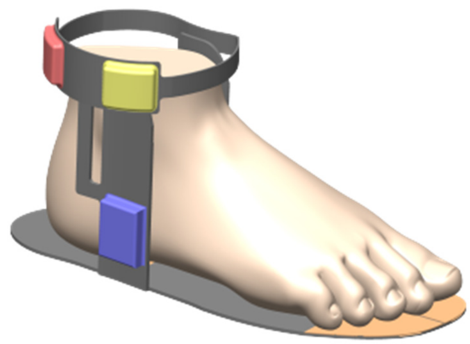


Figure 16: Adult Foot Control Secured to Foot

Figure 17: Foot Controller Prototype

Figure 18 shows a closeup of the finalized foot controller electronics layout. As previously mentioned, the power switch was moved from on top of the microcontroller to the right above the channels used for placing power and signal wires. This movement allows for the use of different branded ESP32-C6 and removes the risk of fitment conflicts between the microcontroller and power switch.

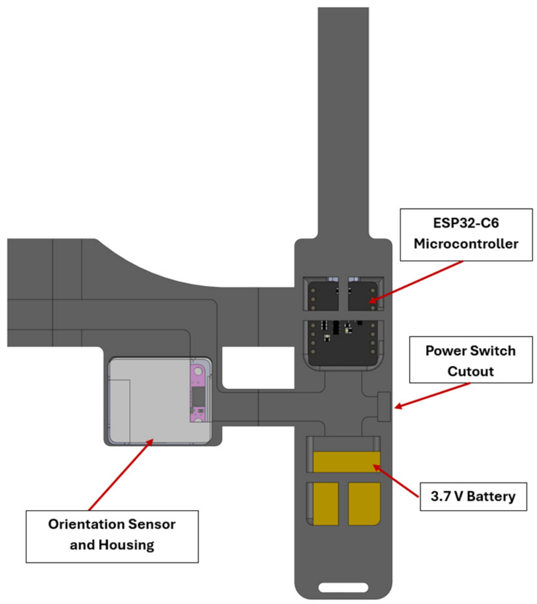


Figure 18: Foot Controller Electronics Closeup

2.2.3 Arm & Controller Hardware

This semester there were minimal changes to the foot controller and arm electronic hardware. The only addition of hardware to the foot controller was the vibration motor that connected to an analog pin on the microcontroller for variable output. Shown below in **Figure *19*** is the updated foot controller circuit diagram which includes the vibration motor that was added this semester.

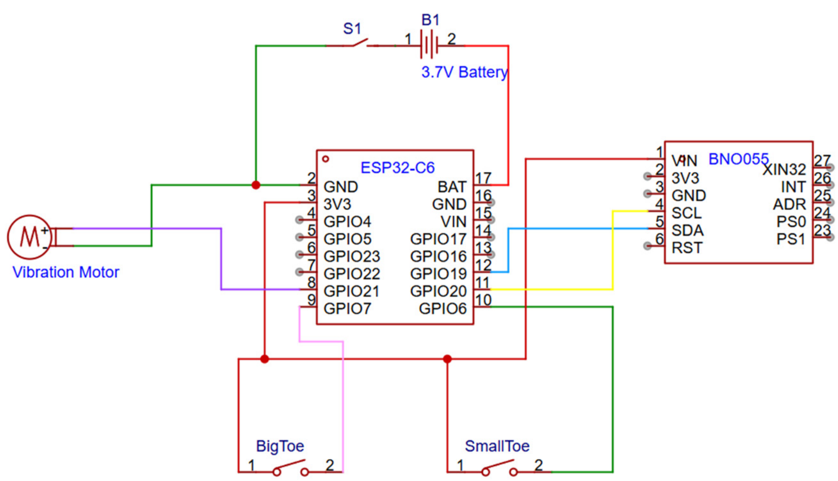


Figure 19: Foot Controller Circuit Diagram

Shown in **Figure *20*** is the prosthetic control circuit which bears no changes in comparison to last semester. The only changes that were made to the arm was changing the 7.4V battery to an 11.1V battery to accommodate the 150 kg-cm servo which requires a minimum 8.4V battery for actuation.

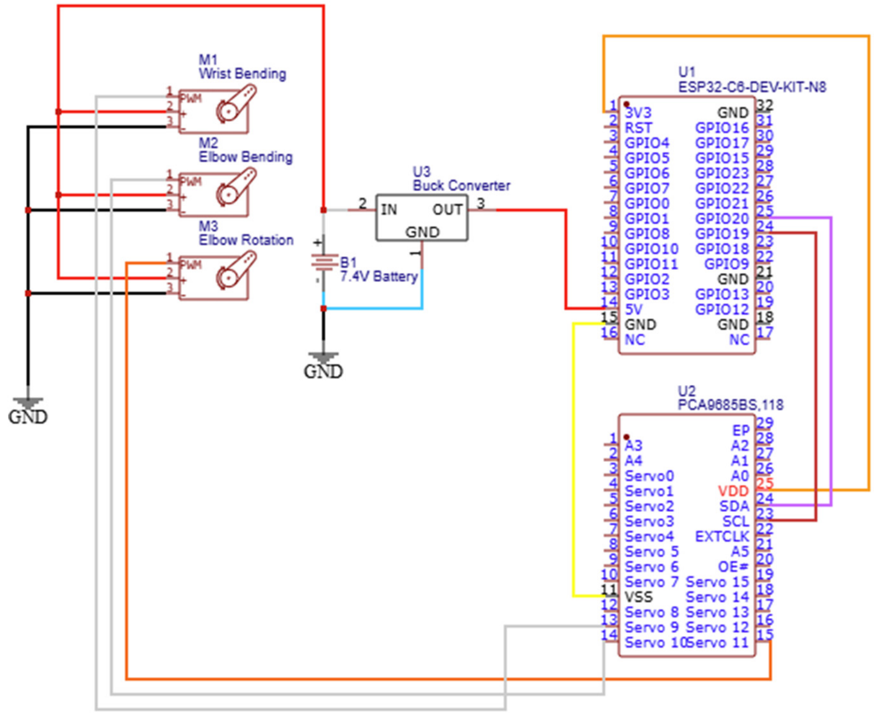


Figure 20: Prosthesis Control Circuit Diagram

2.2.4 Gesture Recognition & Control Approach

To finalize the gesture recognition model for the foot controller more gesture data needed to be collected. Gesture data for five different gestures was collected 25 times each for a total of 100 gesture samples. An overview of the available gestures and their corresponding outputs is shown in ***Figure 21***. The gesture data was passed through the TensorFlow machine learning API to acquire a TensorFlow lite model that could be used directly in Arduino using the consentium IOT API.

Figure 22 shows a breakdown of how the gesture recognition data was utilized to train the AI model. When passing the 20% testing data into the completed trained model it had an accuracy of 99% across all gestures. Further testing is still required to assess the accuracy of the model in real world gesture recognition situations, but we estimate an accuracy of 70-90%. Training data can be reviewed in ***Figure 23*** which showcases the model validation loss over a number of epochs.

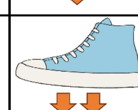
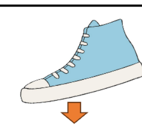
Index	Foot Gesture	Hand Action
1		**Switch Joints**
2		**Toggle On/Off**
3		**Thumbs Up** 
4		**Peace sign** 
5		**Point** 

Figure 21: Finalized Gestures List

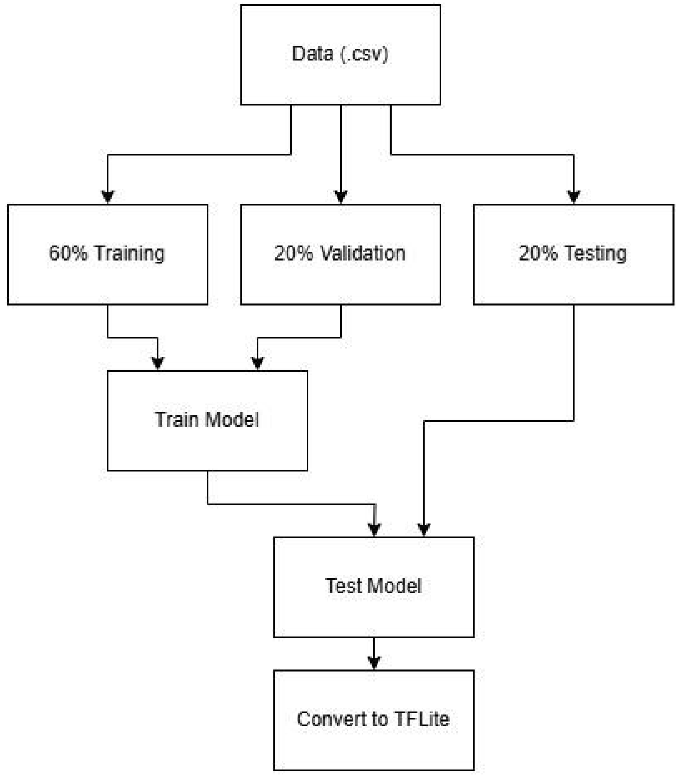


Figure 22: Model Training Process

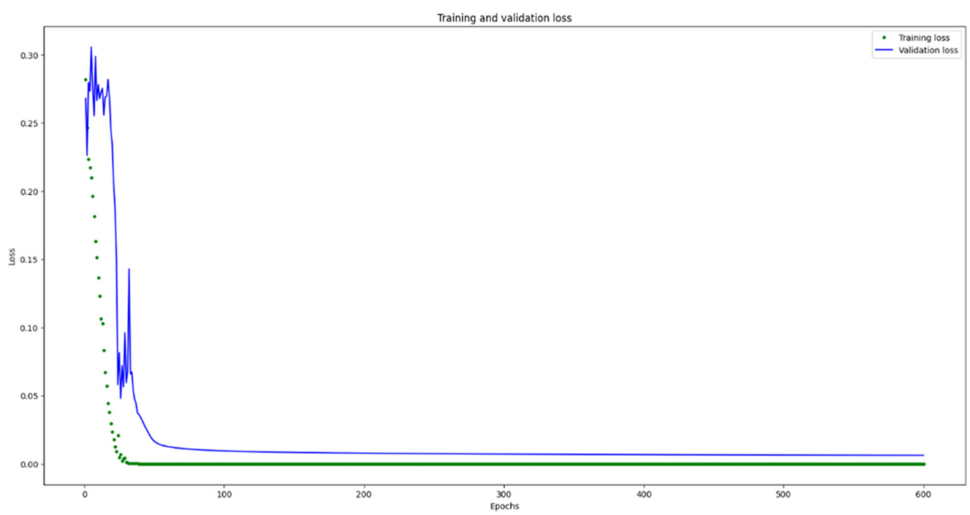


Figure 23: Training and Validation Loss

CONCLUSION AND FUTURE WORK

This work was conducted as a coordinated effort to address some of the common causes of prosthetic abandonment in upper extremity prosthesis. The device combines various innovative technologies and design strategies to develop innovative solutions to abandonment causes such as weight concerns, control issues, device fidelity, and dexterity. This paper serves as the primary conceptual design for an ambitious prosthetic titled Prometheus that cohesively pushes the envelope of prosthetic dexterity, biomimicry, and control. Future work should focus on increasing customizability of the device to multiple users, developing the actuation system for increasingly refined control, and increasing the actuation speed of the elbow mechanism.

References

[1] Toshimitsu Yasunori, Forrai Benedek, Cangan Barnabas Gavin, Steger Ulrich, Knecht, Manuel, Weirich Stefan and Katzschmann, Robert. "Getting the Ball Rolling: Learning a Dexterous Policy for a Biomimetic Tendon-Driven Hand with Rolling Contact Joints." arXiv preprint, 2023. doi: 10.48550/arXiv.2308.02453.

[2] Y. -J. Kim, J. Yoon and Y. -W. Sim, "Fluid Lubricated Dexterous Finger Mechanism for Human-Like Impact Absorbing Capability," in *IEEE Robotics and Automation Letters*, vol. 4, no. 4, pp. 3971-3978, Oct. 2019. doi: 10.1109/LRA.2019.2929988.

[3] H. Liu, K. Xu, B. Siciliano and F. Ficuciello, "The MERO Hand: A Mechanically Robust Anthropomorphic Prosthetic Hand using Novel Compliant Rolling Contact Joint," in *2019 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM)*, Hong Kong, China, 2019, pp. 126-132. doi: 10.1109/AIM.2019.8868520.

[4] S. Kim, E. Sung and J. Park, "ARC Joint: Anthropomorphic Rolling Contact Joint With Kinematically Variable Torsional Stiffness," in *IEEE Robotics and Automation Letters*, vol. 8, no. 3, pp. 1810-1817, March 2023. doi: 10.1109/LRA.2023.3243439.

[5] Marinelli, Andrea, et al. "Active upper limb prostheses: A review on current state and upcoming breakthroughs." *Progress in Biomedical Engineering*, vol. 5, no. 012001, 2023. doi: 10.1088/2516-1091/acac57.

[6] Ingram, James N., et al. "The Statistics of Natural Hand Movements." *Experimental Brain Research*, vol. 188, pp. 223–236, 2008. doi: 10.1007/s00221-008-1355-3.

[7] Franzke, A.W., et al. "Users' and therapists' perceptions of myoelectric multi-function upper limb prostheses with conventional and pattern recognition control." *PLOS ONE*, vol. 14, no. 8, p. e0220899, 2019.

[8] Salminger, S., et al. "Current rates of prosthetic usage in upper-limb amputees – have innovations had an impact on device acceptance?" *Disability and Rehabilitation*, vol. 44, pp. 3708–3713, 2020. doi: 10.1080/09638288.2020.1866684

[9] Bishay, P.L., et al. "Controlling a Below-the-Elbow Prosthetic Arm Using the Infinity Foot Controller." *Prosthesis*, vol. 5, no. 4, pp. 1206–1231, 2023. doi: 10.3390/prosthesis5040084.