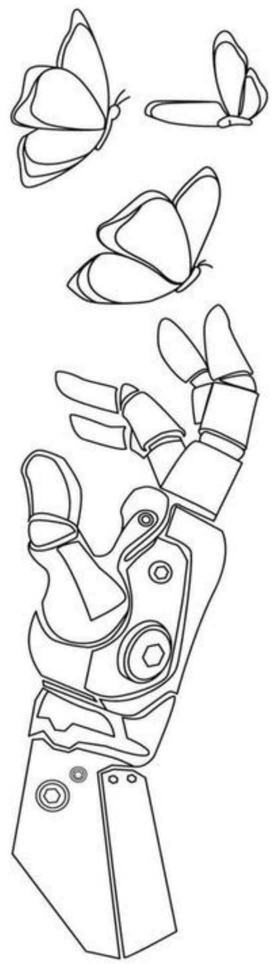
REPORT TITLE:	**Technical Development of the R.E.A.C.H. Prosthetic Device**
COURSE:	**BMED 450: Upper-Limb Prosthesis Control and Sense Perception**
Institution:	**California Polytechnic State University – San Luis Obispo**	**REV**	**A**



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Revision History

Rev	Description of Change
01	Draft Submission
A	Final Submission; completed sections 5- 11 in compliance with rubric and professor feedback.

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1 Purpose

This document aims to outline the design input criteria driving the development and performance of the EMG-controlled *R.E.A.C.H. Prosthetic Gripper* in the accomplishment of simple, day-to-day tasks.

2 Scope

The R.E.A.C.H. is a low-fidelity myoelectric gripper that utilizes an EMG sensor to interpret user input and translate those signals into mechanically driven movements. Furthermore, the hand will relay variable vibrotactile haptic feedback to the user to communicate active contact with an object in the grasp of the device.

3 Definitions and Acronyms

Table 1: Term Definitions and Abbreviations

Term / Acronym	Definition
Analog	A signal that is continuously variable and is often represented within a range of values. (i.e. 0-255, or 0-1023)
BBT	Box and Blocks Test
Body-Powered Prosthetic	A body powered or conventional upper extremity prosthetic device often operated by a body-harness system. The harness system is controlled by specific body movements to perform day-to-day tasks.
C.A.I.R.	An acronym describing the four foundational pillars of user-centered prosthetic design: Comfortable, Affordable, Intuitive, and Reliable.
Comprehensive Healing	The process of addressing and improving all aspects of an individual's physical, emotional, and psychological well-being. In the context of a robotic prosthetic arm, comprehensive healing involves not only restoring physical functionality but also supporting the individual's overall health and promoting their holistic recovery. This may include rehabilitation, pain management, psychological support, and ensuring a smooth transition to using the prosthetic arm in daily activities.

Term / Acronym	Definition
Congenital Amputation	A limb difference discovered at birth, originating from incomplete development during pregnancy as opposed to limb-loss due to an injury or surgery after birth.
EMG Sensor	An Electromyography Sensor is a device that measures activity in the muscles via the electrical signals that are produced during a contraction.
FSR	Force Sensitive Resistor
Haptic Feedback	The implementation of mechanical, vibrational, or electrical devices to a system with the intent of providing a user with a sense of tactile feedback based on an external component's interaction with the user's environment.
I/O	"Input/Output", referring to the communication between an information processing system, such as a microcontroller, and the outside world.
LED	Light emitting diode
Microcontroller	A microcontroller is a compact, single integrated circuit that functions as a small, self-contained computer designed to monitor and control specific tasks within an embedded system
Myoelectric Prosthetic	A myoelectric upper extremity prosthetic device is powered by a battery system and is often controlled by electromyography (EMG) signals generated during muscle contractions received through electrodes mounted in the socket. These signals are sent to a motor in the prosthetic elbow and/or wrist. A myoelectric elbow may then bend or straighten, a wrist can flex, and a hand can open or close based on user-input.
Passive Prosthetic	A passive functional or cosmetic upper extremity prosthetic device is similar in appearance to the non-affected arm or hand and provides simple aid in balancing and carrying items.
R.E.A.C.H.	Robotic Enhanced Arm for Comprehensive Healing
Vibrotactile Feedback	A form of haptic feedback that relies on vibration-based sensations to convey a sense of "touch" to the prosthetic user.

4 Associated Documents

Table 2 – Reference Documents

Reference Number	Title	Source
1	*Amputee Coalition Introduction*	*Amputee Coalition, Beginning Your New Journey. Amputee Coalition, Nov. 22, 2025.*
2	*The Promise of Assistive Technology to Enhance Activity and Work Participation*	*National Academies of Sciences, Engineering, and Medicine, The Promise of Assistive Technology to Enhance Activity and Work Participation. Washington, DC: The National Academies Press, 2017.*
3	*Clinical Reality of Measuring Upper-Limb Ability in Neurologic Conditions: A Systematic Review*	*L. A. Connell and S. F. Tyson, "Clinical reality of measuring upper-limb ability in neurologic conditions: A systematic review," Archives of Physical Medicine and Rehabilitation, vol. 93, no. 2, pp. 221–228, 2012.*
4	*The Bionic Chef: Cooking With or Without Hands.*	*C. Douglass, The Bionic Chef: Cooking With or Without Hands. Kindle eBook, Feb. 8, 2015.*

5 Background

Over 2 million people live with some sort of limb loss with upper-limb amputees accounting for 35% of the amputee community [1]. For hundreds of years, prosthetic devices have been created to *restore* some sort of function to either a congenital or acquired limb difference. Upper-limb prosthetics specifically are needed in society as the majority of our environment and day-to-day world we live in was designed either intentionally, or unintentionally to be interacted with through a two-hand medium. For people living with a limb difference, the world around them is increasingly more frustrating to work with than it is for the majority of people living with two hands. Furthermore, for amputees with an acquired limb difference, the known loss of one's ability with a natural hand in regard to sensory feedback and dexterity. Continued iteration and development Early prosthetic devices were purely passive devices, often carved from wood and were more for aesthetic purposes than functional. Technological advancements in both upper and lower limb prosthetics have been made to meet the day-to-day functional needs of their users through both body-powered and myoelectric limbs, especially in the lower-limb prosthetics realm. Due to the higher complexity, degrees of freedom, and dexterity of the human hand in comparison to the leg, current upper-limb prosthetic abandonment rates are significantly higher with lower satisfaction rates driven by high device weight, limited functionality, and poor user control.

Currently, EMG-controlled myoelectric prosthetics have allowed for upper-limb amputees to begin to bridge the gap between more natural muscle-based input and prosthesis control. Compared to body-powered prostheses, myoelectric allows for more precise control of the hand, increasing overall coordination and day-to-day ability. Although, myoelectric devices vary in function and structure, ranging from motorized hook designs that emulated a body-powered prosthetic, to full hands with multi-articulated fingers and gripping patterns. While these devices are all far from perfect, they are more desirable to most amputees than body-powered devices as the user-input is closer to how a natural hand is controlled.

Existing industry companies like PSYONIC, Taska, Open Bionics, and Covvi are working to develop high dexterity, myoelectric prosthetic devices that are intuitive to use and a step up from the typical "claw" that is commonly used by body-powered and some myoelectric prosthetics. However, the aforementioned companies all face one critical issue: high resolution user-control and sense perception. While some of these products have up to 20 degrees of freedom, individual finger control, and even haptic feedback, existing products lean more into technological feats and impressive achievement rather than a user-focused design. There is no existing technology that currently allows us to replicate the pin-point accurate tactile aspects of sensory feedback from a mechanical system and relay that to a human user. In order to dramatically decrease abandonment rates in prosthetic users, this core issue must be addressed by prosthetic devices.

If individuals using an upper-limb prosthesis were able to genuinely feel what they were touching through accurate, high-resolution tactile sensory feedback, the impact on their day-to-day lives would be profound. Sensory perception would restore a critical component of natural hand function that current prostheses cannot replicate, allowing users to appropriately modulate grip force and prevent accidental drops or damage to objects. This level of feedback would reduce the heavy cognitive load associated with relying solely on visual cues, enabling more fluid and efficient execution of everyday tasks. Users could perform fine motor activities such as handling small tools, fastening clothing, or interacting with textured or fragile objects with significantly greater confidence. Psychologically, the reinstatement of tactile sensation would help reestablish a sense of embodiment and connection to the prosthetic limb, which many amputees describe as missing. This enhancement would likely increase device satisfaction and reduce abandonment rates, transforming the prosthesis from a functional tool into a more integrated extension of the user's body.

5.1 Designing for C.A.I.R. in Prosthetic Devices

As mentioned in the prior section, existing prosthetic technologies fail to properly address the user, leading to high abandonment rates. A successful prosthetic device, upper or lower limb, can be defined as one that properly addresses the C.A.I.R. acronym: Comfortable, Affordable, Intuitive, and Reliable.

5.1.1 Comfort

Comfort in prosthetic design refers to how well the device integrates with the user’s body without causing pain, irritation, or excessive fatigue. A comfortable prosthesis distributes pressure evenly across contact surfaces, minimizing high-stress points that can lead to skin breakdown or soreness. Material choice also impacts comfort, as soft interfaces, breathable liners, and lightweight components reduce thermal buildup and enhance wearability. Fit is critical, and even small misalignments can drastically affect overall comfort and long-term user compliance. Because residual limbs often change in volume throughout the day, accommodating adjustability is essential for maintaining comfort through dynamic conditions. Ultimately, a comfortable prosthesis encourages consistent daily use, which is key for functional success.

5.1.2 Affordable

Affordability in prosthetic development concerns not only the initial cost of the device but also its long-term maintenance and accessibility. For many users, expensive materials, complex electronics, or custom fabrication can make high-end prosthetics unattainable. A low-fidelity or low-cost design must balance performance with manufacturing constraints, often leveraging readily available materials or simplified mechanisms. Designers must also consider repairability, as devices that require specialized tools or proprietary components can increase lifetime costs. Affordability extends to the healthcare system as well; more economical devices improve accessibility for underserved communities and global populations. Ultimately, an affordable prosthetic should provide meaningful function without imposing financial barriers to sustained use.

5.1.3 Intuitive

Intuitive device use reflects how naturally and easily a user can operate the prosthesis without needing extensive training or cognitive effort. An intuitive prosthetic aligns with expected human movement patterns, making the device feel like an extension of the user rather than a tool they must consciously manage. Mechanically, this can involve simple, predictable gripper actions or controls that respond directly to user inputs such as body motion, cable actuation, or basic EMG signals. Intuitiveness also depends on feedback, commonly visual, tactile, or mechanical, that helps the user gauge grip force, position, or device state. Reducing unnecessary complexity in the user interface lowers frustration and shortens the learning curve. When a device is intuitive to operate, users are more likely to integrate it into everyday tasks effectively and consistently.

5.1.4 Reliable

Reliability refers to the prosthetic's ability to perform consistently under typical daily loads, environmental conditions, and repeated use. A reliable device maintains stable functionality without frequent adjustments, failures, or degradation of performance over time. Mechanical durability is crucial, particularly for low-fidelity designs that may use simple materials but still need to withstand repetitive forces. Designers must also consider failure modes, ensuring that even if components wear down, they do so safely and predictably rather than catastrophically. Environmental robustness such as, resistance to moisture, dirt, and temperature variation further contributes to reliability, especially for users with active lifestyles. Ultimately, a reliable prosthesis builds user trust, allowing them to confidently depend on the device for essential tasks.

5.2 Case Study: Cheryl Douglass

Cheryl Douglass is an American quadruple amputee who lost both of her arms below the elbows and both legs below the knees after developing a severe group A streptococcal infection in 2008 that progressed into toxic shock and gangrene [4]. Before her illness, she led an active life, often playing tennis, and following her amputations, prosthetic limbs played a central role in restoring her independence and functional ability. With her lower-limb prostheses, she regained the ability to walk, move independently, and resume daily activities that were impossible during rehabilitation. Upper-limb prosthetics enabled her to return to cooking, which was an immense passion of hers, eventually authoring *The Bionic Chef, a* cookbook designed for individuals with prosthetic limbs [4]. These devices also supported her psychological recovery, helping her rebuild a sense of agency, normalcy, and confidence in navigating daily tasks. As she regained function, she became a certified mentor for other amputees, using her experience and mobility with prosthetics to offer encouragement, serve as a role model, and demonstrate what is achievable after limb loss. Today, her prosthetics allow her to remain active in cooking, traveling, and supporting others, illustrating their significant influence on her quality of life and personal accomplishments. During an in-class interview with Cheryl, she shared that her biggest improvement she would make to her prosthetics was a sense of touch, so she could feel her granddaughter and hold her.

5.3 Prior Work

The work that has been done is far from over, as the development of this device is a continuously iterative process, as more people are interviewed and feedback is incorporated. The work completed in this class has created a strong foundation for continued development of a low-cost, day-to-day prosthetic device. The current state of the device addresses core issues such as intuitive control, haptic feedback, and functional task performance which is faced by most individuals with an upper-limb difference. Integrating an EMG sensor as the primary control input for the prosthetic aims to address the difficulty many amputees experience when trying to operate devices that rely on unnatural or non-intuitive movements. The EMG-based control system allows users to activate the device through muscle signals that more closely resemble how a natural hand is used, improving usability and reliability. To further address the absence of tactile sensation, a major barrier to effective prosthetic use, a low-cost vibrotactile feedback motor driven by the analog output of a FSR was implemented, giving the user a simple but meaningful indication of grip force. Additionally, by designing the device in compliance with the Box and Blocks Test and conducting extensive performance testing, it was ensured that the prosthetic was evaluated using a standardized metric commonly used in clinical assessments of upper-limb function. Together, these design choices allowed the device to engage directly with the real-world limitations of current prosthetic technology and contribute toward solutions that enhance control, feedback, and functional capability for upper-limb prosthesis users. Furthermore, while this low-fidelity prototype is nowhere near industry-level, on the market devices, there now exists a strong foundation to iterate a more functional and effective device in the long term.

6 Goals

The overall goal of this project is to develop a prosthesis that can perform everyday tasks, while providing device users with a means of interacting with their environment with greater definition in tactile and haptic experiences.

In order to meet these overall goals, this project contains several subprojects:

- Development of different, toggleable control strategies for increased user-control.
- Incorporate a clinical scale, in this case, the box and blocks test will be the primary scale used to evaluate the performance and efficacy of the design.
- Mechanically driven "gripper" that allows for the grasp of objects with varying size and geometry
- Incorporate sensory feedback via a vibrotactile motor output from the microcontroller.
- An incorporated LED board to visually relay which control scheme the user is currently in, as well.

7 Product Design and Implementation Methods

At its core, the R.E.A.C.H. Prosthetic is foundationally structured in a similar manner to industry-level devices. The structure in reference is the overall I/O system that is used to provide users with a "full circle" experience, i.e., user gives a specific input, and the device reacts accordingly. The driving question for most of the device's development was, how can this be done in a cheap and effective way where people could build and modify it at home? Naturally, that question was applied first to the microcontroller system as that would somewhat dictate what input and output devices were compatible for the rest of the build. The most logical choice for this was Arduino's *Nano Every* microcontroller. Arduino boards are famously user-friendly and easy to pick-up alongside endless online resources for troubleshooting, which made the device not only easy to work with on a development end, but also on a user's end if they chose to change something for themselves. All major circuit components are shown below in **Table 3.**

For user input, an EMG sensor was chosen based on versatility and consistency with the control of myoelectric prosthetic devices. Placing an EMG sensor is a highly customizable process that often requires the device user to be worked with to determine the most anatomically optimal location for obtaining clean electrical readings. For additional input, an FSR was chosen to relay pressure-based data at the distal end of the gripper to the user. The FSR acts as the driving analog data behind the variable haptic feedback provided by the device.

For device output, a single microservo was chosen to drive the mechanical linkage system that grabs objects and allows the user to interact with their environment. The original "gripper" design that the course followed that used two rigid popsicle sticks proved problematic. Issues often arose when attempting to grab larger objects as the rotating beams had minimal contact area with the object and would often fail in picking up the target. For output of haptic feedback to the user, a vibrational motor was used to provide the user with a variable tactile sensation. The motor's vibrational intensity varied by the amount of resistance measured in the analog FSR. Additionally, an LED was ran between the D2 output pin driving the motor, and power for the motor, providing the user with a visual indicator of the contact strength with an object. Variation in LED brightness had a direct correlation with the force input recorded by the FSR.

Table 3: Circuit Components

Component	Model Name
Microcontroller	Arduino Nano Every
EMG	Gravity Analog EMG Sensor
FSR	Interlink Electronics Mode 402 FSR
Vibration Motor	Adafruit Vibrating Mini Motor Disc
Microservo Motor	MG90S Metal Gear RC Micro Analog Servo

The microcontroller selected for this device was the *Arduino Nano Every*, a beginner-friendly, compact microcontroller that can be directly mounted onto a breadboard for quick integration. The schematic shown below in **Figure 1** shows the layout of the pins and their purpose. Analog pins A0 and A3, along side digital pins D9, and D2 were the primary pins utilized for device I/O.

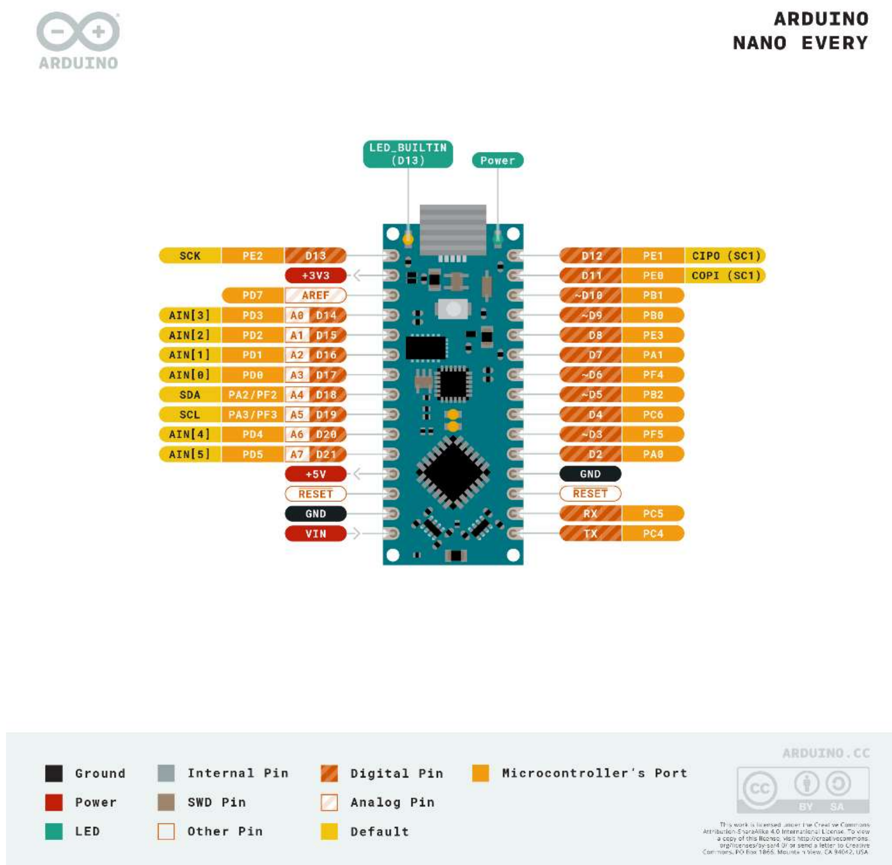

Figure 1: Arduino Nano Every Schematic

7.1 Full Assembly

The fully assembled device mounts to the user's forearm with a custom-fit arm rigid brace and three adjustable hook and loop straps. The first strap is wrapped around the mechanical gripper placing point, in the case of the layout shown below in **Figure 2**, the user's thumb and palm, to mount the servo-driven gripper onto the user. The second strap is ran through the bottom of the battery pack and around the mid-forearm. The final strap is ran around the forearm at the back end of the aluminum frame and adjusted for a snug fit.

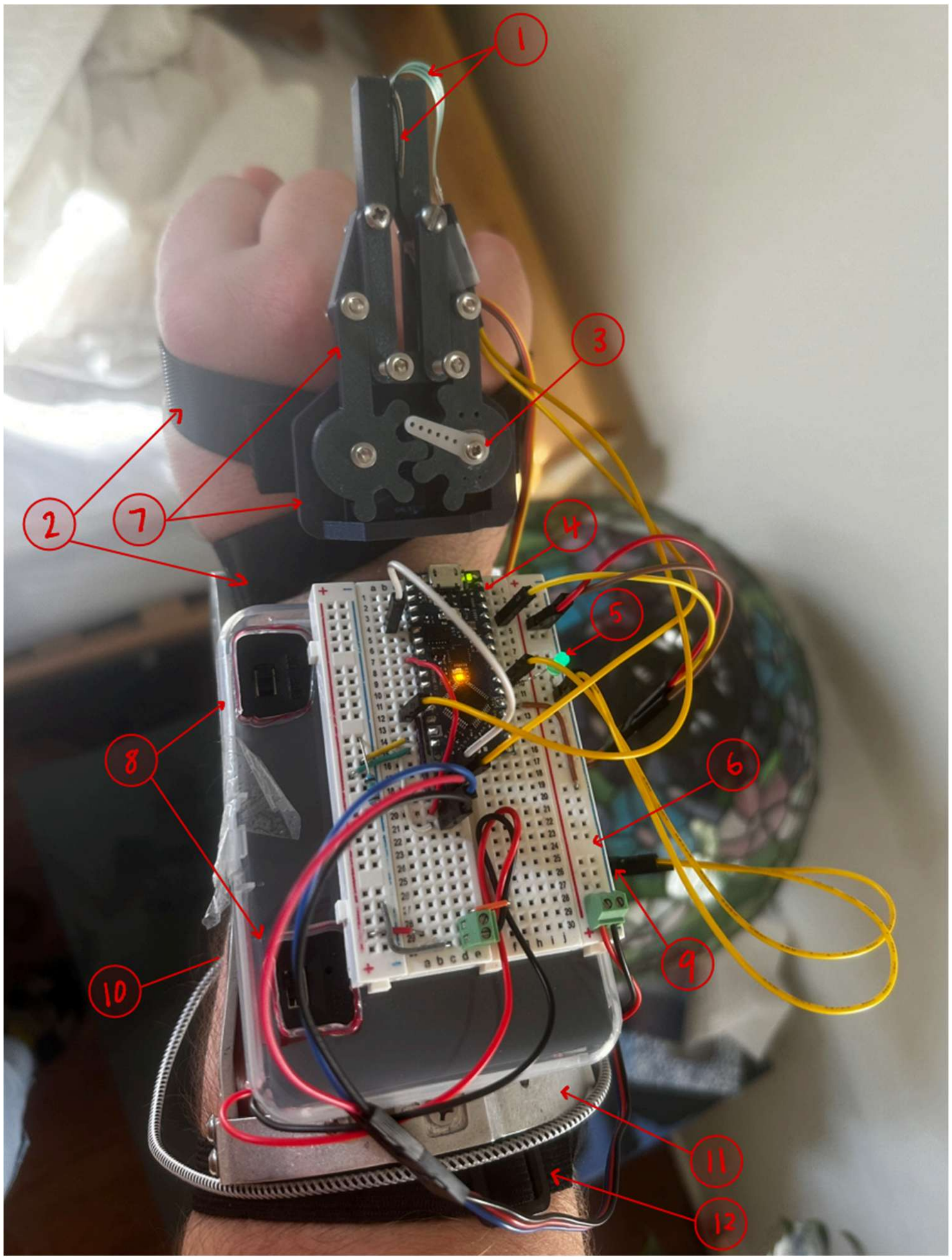

Figure 2: Full Assembly Mounted and Annotated

A comprehensive summary of the full assembly components shown above and their respective functions are outlined in **Table 4** below.

Table 4: Assembly Components

Annotation Number	Component	Description
1	FSR	A force-sensitive resistor that interprets varying forces and converts those to analog values within a range. Acts as the driving force behind the intensity of the vibrotactile feedback.
2	Hand Strap	Used to secure the gripping apparatus to the hand.
3	Microservo Motor	The mechanical driving force behind the linkage-based gripper mechanism.
4	Arduino Nano Every Microcontroller	The brain of the device, reading inputs from the EMG and FSR, and translating that to appropriate mechanical, vibrotactile, and electrical outputs in the prosthetic.
5	LED	A light emitting diode used to visually communicate the force read by the FSR.
6	Breadboard	A board where each row behaves as a single “node” and allows circuits to be built without the need for solder.
7	3D-Printer Gripper Mechanism	The linkage-based gripper mechanism allows objects of different sizes to be grabbed as the opposing surfaces approach objects in a parallel manner. This is opposed to the radial approach of the original design.
8	Battery Pack	The battery pack contains two battery units, a 9v battery that directly powers the Arduino Nano, and a 5v battery that directly powers the servo motor.
9	Vibration Motor	A DC component with an off-axis weight, that creates a vibration when powered. This component provides the vibrotactile haptic feedback of the system.

Annotation Number	Component	Description
10	EMG Sensor	Placed on the flexor digitorum superficialis and records muscle data used to drive gripper behavior.
11	Aluminum Frame	A custom-fit lightweight frame that prevents the device from rotating about the forearm while providing an elevated mounting surface for the batteries, circuit, and vibrotactile feedback system. The modular build allows for future device iteration and component placement.
12	EMG Support Strap	Ensures the EMG sensor is properly held against the skin to ensure a high resolution read of electrical activity.

When it comes to device installation and use, it takes about three to five minutes to properly set everything up, with EMG placement and strap adjustments taking most of the time to get right. While it is more than possible to place the prosthetic on one's forearm with a single hand, having a second person assist with tightening down the straps and inspecting overall security would make the process go faster. As adjustments continue to be made on the device, this will be a major focus so ensure that total setup time can be decreased, allowing users to go about their day faster.

7.2 Circuit Electrical Schematic

The circuit schematic for the R.E.A.C.H. Prosthetic is shown below in **Figure 3,** and outlines electrical I/O for the entire system. Conveniently the device inputs, the FSR and EMG, are placed on the left side of the microprocessor while the outputs, the servo, LED, and vibrotactile motor, are shown on the right. Additionally, both the 9V and 5V batteries are illustrated providing power to the board and servo motor and are labeled "Bat 1" and "Bat 2", respectively.

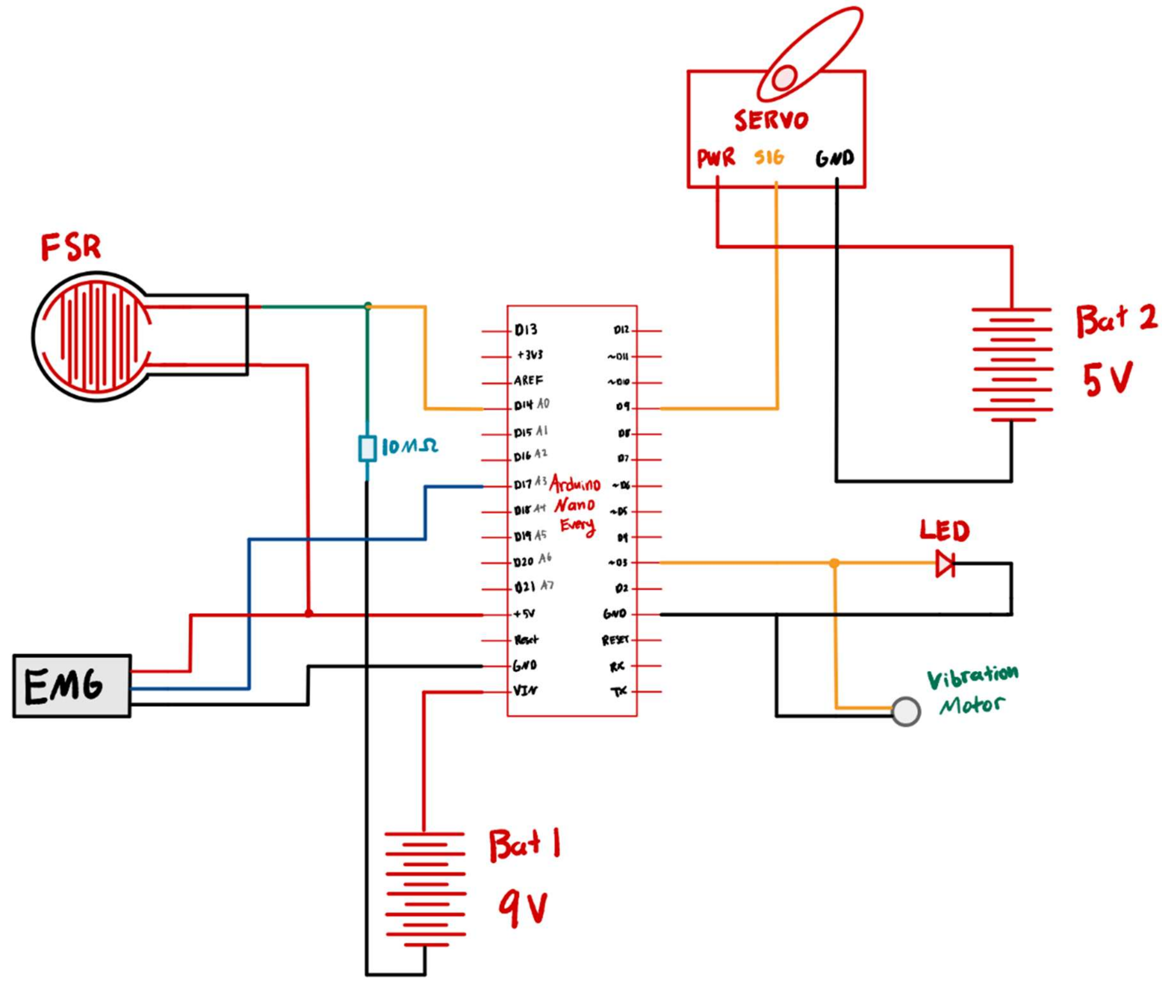

Figure 3: Full Electrical System Schematic

7.3 EMG Signal Acquisition

Proper EMG signal acquisition is a process that will require the user to spend time determining where their signal is the clearest. Signal clarity depends on how close the muscle is to the surface of the skin, presence of oils and debris on the skin and sensor, and flex strength. The EMG sensor is placed on the flexor digitorum superficialis shown below in **Figure 4.** This location was discovered by placing the EMG electrodes in different locations of the forearm and analyzing overall reading strength and curve resolution. As mentioned before, EMG sensor placement is a delicate and considerate process as placement sites vary user-to-user.

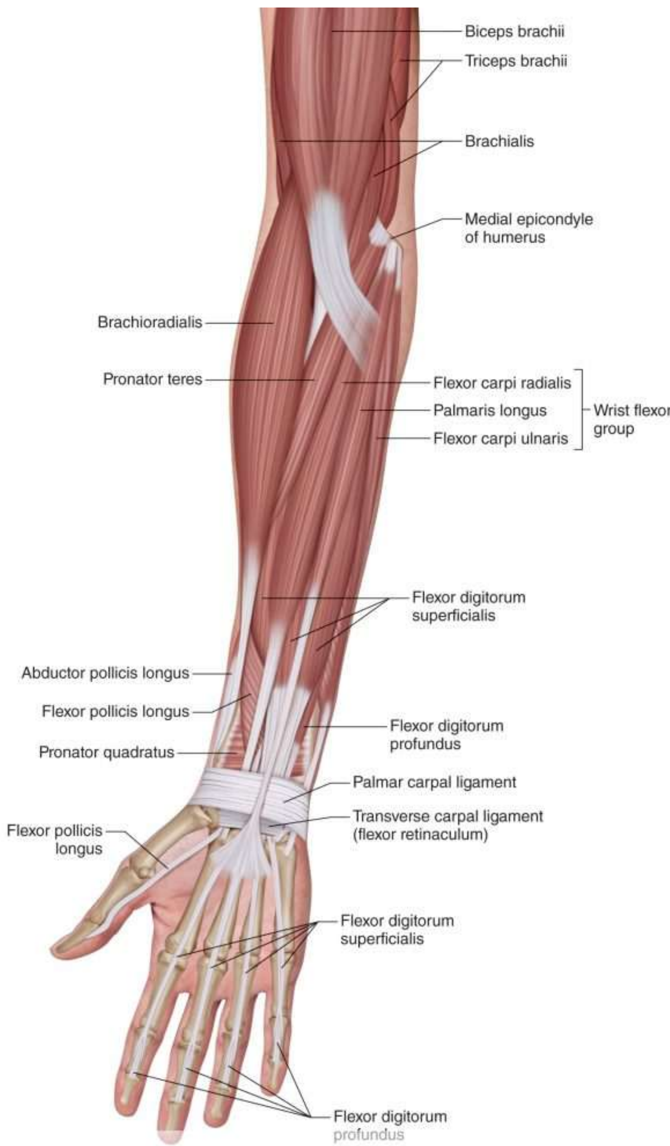

Figure 4: Forearm Anatomy

For users choosing to utilize this device, the EMG signal is processed and rectified in the program being run on the microcontroller, so they simply need to put on the electrode and let the program do the rest. This is a multistep process that involves taking the raw EMG signal, obtaining a baseline, and centering that at a reference point, in the case of this program, that reference point is “0” on the serial plotter. Following that, the absolute value of the signal is taken to ensure all EMG values are positive and increasingly positive based on flex intensity. Throughout the development of this device, it was found that the EMG needs some time to initially warm-up before accurately reading contractions. This warm-up period presents itself in the form of excessive noise in the serial plotter and rapid open-close gestures from the gripper. The user should allow up to five minutes for the sensor to properly warm up prior to using the gripper. Once the EMG sensor was warmed up, opening and closing the device was extremely accurate, with occasional misfire occurring after extended use of the device. The baseline had some residual noise, likely due to the servos drawing power in the system, but this never exceeded the threshold for device control. The cause of the misfire from long term use was determined to be caused sweat and oil excreted from the skin needing to be cleaned off of the electrodes with an alcohol wipe. Once this was done, the prosthetic returned to behaving normally with control issues.

7.4 Control Strategies

Four distinct control strategies were written throughout the early development phase of the device: A simple open/close with the gripper defaulting to closed, a toggleable open/close scheme, an incremental closing scheme with an EMG-based reset, and an EMG-based moving average. As improvements to the device continue to be made, a planner addition will utilize a potentiometer and an LED board to allow the user to change between control schemes on the device. The four individual schemes are discussed in detail below.

7.4.1 Control Scheme 1: Simple Open/Close

The first control method was a simple open/close command triggered by exceeding the threshold of the rectified EMG signal. When the signal exceeded a preset amplitude, the servo was commanded to fully open the gripper; when the signal remained below the threshold, the gripper returned to a fully closed position. The scheme required minimal computation and relied entirely on a binary interpretation of muscle activation.

This approach was chosen as a baseline because it provided immediate, predictable behavior and allowed rapid verification of the EMG hardware, filtering, and signal routing. Its simplicity made it useful for early debugging, but its usability was limited as opening the gripper for extend periods of time required active flexion which was often straining. There was noted difficulty in modulating grip force, and the lack of intermediate positions made the gripper unsuitable for tasks requiring gentle or precise manipulation. Furthermore, involuntary spikes in EMG activity occasionally caused the gripper to unintentionally open, reducing the user’s control and the scheme’s overall reliability.

7.4.2 Control Scheme 2: Toggle Open/Close

The second strategy introduced state-based control by using the EMG threshold crossing as a toggle input rather than a direct command. A brief, deliberate muscle contraction toggled the gripper between fully open and fully closed states. The program maintained a boolean "flexactive" variable that flipped each time a rising-edge event was detected in the EMG signal alongside a "flex" variable that was equated to the current value of the EMG signal.

This scheme improved usability by reducing the physical effort required to maintain a position, since the user no longer needed to continuously contract to hold the gripper open. It also reduced accidental reactivation because the system ignored sustained or noisy EMG activity and responded only to distinct contractions. However, the user still lacked control over intermediate positions or grip strength, and toggling could feel unintuitive when rapid changes were needed. Despite these limitations, this strategy served as an important intermediate step in separating activation events from continuous control.

7.4.3 Control Scheme 3: Incremental Closing with EMG-Based Reset

The third strategy introduced proportional control in the form of incremental positional changes. A threshold-exceeding EMG contraction caused the system to close in the gripper's position by a fixed angular increment, effectively "ratcheting" the linkages closed. This allowed the user to approach a desired grip force gradually instead of moving directly to a fully open or closed position. To prevent the hand from continuing to close indefinitely, a secondary EMG event based on a larger contraction that exceeded a secondary threshold was used as a reset command that returned the gripper to the fully open position.

This approach gave users significantly more control during grasping tasks, enabling fine adjustments with relatively simple signal processing. It also allowed the system to remain responsive without requiring continuously smooth EMG input, which is often difficult for new users to generate. The main drawback was cognitive load since users had to remember that small contractions increased grip and larger ones opened it, which sometimes led to confusion. Overall, this design had a higher learning curve and was less favorable while being more open in terms of control. Additionally, the incremental scheme required careful tuning of step size and reset thresholds to avoid overshooting or accidental resets. However, this method represented an important step toward analog, user-modifiable control.

7.4.4 Control Scheme 4: EMG-Based Moving Average

The final strategy used a moving-average filter on the rectified EMG signal to generate a smoother, more continuous control input. Instead of relying on binary threshold crossings or discrete increments, the filtered EMG magnitude was mapped to a corresponding servo position. Higher sustained activation levels resulted in a more closed gripper, while relaxation opened it. The moving average window was tuned to suppress transient spikes and reduce jitter, making the servo response noticeably more stable.

This scheme provided the most natural proportional control of the four approaches. Users could intuitively vary grip force by modulating muscle activation, and the servo responded in a continuous, predictable manner. However, it was more likely to cause muscle fatigue in the users, rendering it less friendly for longer use sessions. Despite these challenges, the moving-average method delivered the closest approximation to traditional proportional myoelectric control and is likely the most versatile for an open-source prosthetic platform. Further work will have to be done to determine how to reduce muscle fatigue over longer periods of time.

7.5 FSR Driven Vibrotactile Haptic Feedback

The feedback subsystem utilizes a force-sensitive resistor embedded in the distal region of the gripper to measure contact force from grabbing an object and relay it back to the user. The FSR operates as a variable resistor with an effectively infinite resistance when no object is touching the gripper and decreases as compressive load increases. To convert this resistance change into a measurable electrical signal, the FSR is wired in a voltage-divider configuration with a fixed resistor shown below in **Figure 5**, allowing the Arduino Nano Every to read the resulting analog voltage ranging from 0-1023 through an analog input pin. A low voltage corresponds to an uncompressed FSR, while increased pressure raises the voltage proportionally.

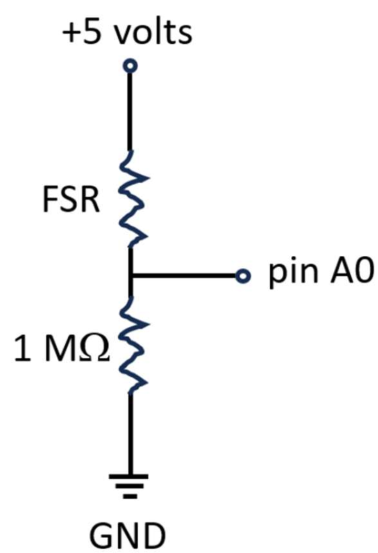

Figure 5: FSR Voltage Divider Circuit

The Arduino uses this voltage to modulate the haptic output signal. A small vibratory motor, mounted on the aluminum frame, contacting the user's forearm provides vibrotactile feedback. As the sensed force increases, the Arduino outputs a higher-duty-cycle PWM signal to the motor driver, resulting in a stronger vibration. This creates a fairly intuitive sensation with gentle vibration for light contact and stronger vibration for a firmer grip. An LED placed in series with the motor output provides a redundant visual cue, brightening proportionally with the applied force and allowing users to gauge grip strength even when not wearing the device.

To enhance system sensitivity, the resistor value in the voltage divider was tuned to maximize resolution in the expected range of gripping forces. This feedback system significantly improves gripper performance, enabling users to reliably distinguish between no contact, light contact, and firm gripping without looking at the hand. In practice, this allowed users to avoid crushing delicate objects and improved overall confidence during different object-interaction tasks.

8 Test Description – Box and Blocks Test

The Box and Blocks Test (BBT) is a standardized clinical assessment used to measure gross manual dexterity by counting how many blocks a participant can transfer from one compartment of a box to the other across a partition within 60 seconds. Clinically, it serves as a reliable and repeatable method for evaluating upper-limb function across a wide range of populations, including individuals recovering from neurological injury and those using prosthetic devices. The test is valued for its simplicity, ease of administration, and strong normative datasets, which allow clinicians and researchers to compare performance across age groups, sexes, and functional levels. In the context of prosthetics, the BBT provides an objective measure of how effectively a user can perform repetitive grasp-and-release tasks, one of the most fundamental motions required for daily activities. Because prosthetic users often struggle with limited grip reliability, slow actuation, or poor sensory feedback, the BBT has become a crucial benchmark in evaluating how well a device supports rapid, consistent manipulation and mind-muscle-device connection. Justifying its use in prosthetic development, the BBT allows designers to quantify improvements, validate design choices, and assess whether a prosthesis meets the functional standards necessary to succeed in real-world use. As a result, it remains one of the most widely adopted tests for demonstrating practical upper-limb prosthetic capability.

The BBT was performed with the natural hand as well as the full device assembly in each of the four control schemes discussed in **Section 7.4.** Ten small wooden blocks and six large foam cubes were provided for two versions of the test and a textbook was used as a partition as shown below in **Figure 6** and **Figure 7**. The test was then ran three times for both cube types, and for each control scheme for a total 36 tests, 18 for each cube type, and 6 for each control scheme. The results of the BBT are discussed in **Section** Error! Reference source not found. and displayed quantitatively in **Table 5**, with Intuitive and reliability rankings shown in **Table 6**.

Figure 6: Box and Blocks Test Setup, Small Wooden Blocks

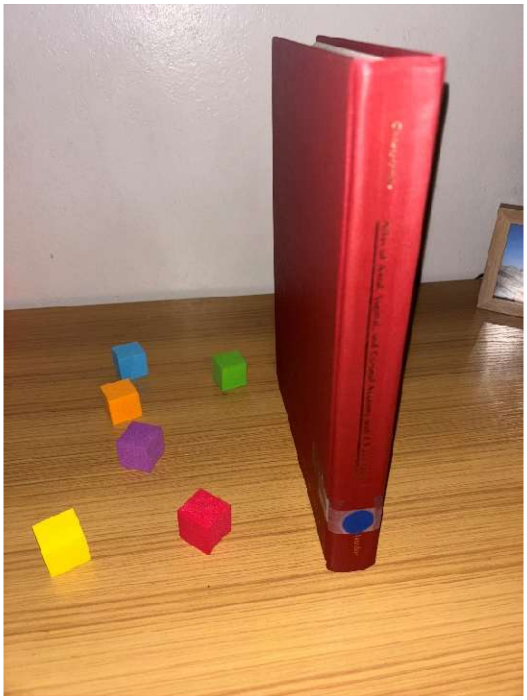

Figure 7: Box and Blocks Test Setup, Large Foam Blocks

9 Box and Blocks Test Results and Reflection of Test Efficacy

This section explores the results of the modified Box and Blocks Test described above in **Section 8** and also reflects upon overall effectiveness of the BBT in comparison to real-world prosthetic applications.

9.1 Data Analysis and Discussion of Test Results

As mentioned before, three trials were recorded for each combination of control strategy and object type, allowing calculation of both average performance and trial-to-trial standard deviation. **Table 5** summarizes the results and highlights the differences in speed, consistency, and overall usability across all five control strategies, and the natural-hand baseline.

Table 5: Box and Blocks Test Results

Table 1: Box and Blocks Test of Performance											
Control Strategy	Small Wooden Cubes						Large Foam Cubes				
	1	2	3	Avg	Std		1	2	3	Avg	Std
1) Natural Hand	44	56	62	54.0	9.2		47	63	67	59.0	10.58301
2) briefly open (default closed)	12	18	23	17.7	5.5		25	31	29	28.3	3.05505
3) toggle b/t open and closed	42	37	45	41.3	4.0		51	56	58	55.0	3.605551
4) incremental closing (with EMG reset)	38	35	40	37.7	2.5		44	51	53	49.3	4.725816
5) Moving Average (sensory feedback OFF)	29	27	31	29.0	2.0		38	41	40	39.7	1.527525
6) Same as (5) but with sensory feedback ON	30	26	33	29.7	3.5		32	37	40	36.3	4.041452

In comparison to the natural hand baseline, the *toggle b/t open and closed* scheme proved to be the highest performing scheme for the box and blocks test with the strongest performance, averaging 41.3 blocks/min with wooden cubes and 55.0 blocks/min with the foam cubes. Its success is likely due to its simplicity and responsiveness as the user only needs a brief EMG activation to change states, allowing for the user to enact fast, predictable movements without the need for continuous contraction and induced muscle fatigue.

The lowest-performing schemes were the *briefly-open (default-closed)* strategy and the *incremental closing scheme*. Strategy 2 requires frequent muscle activation to reopen the gripper, slowing the overall pace of the task and increasing cognitive effort. Strategy 4 demands fine timing of EMG contractions to avoid overshooting target grip positions, introducing delays and reducing the user and device's efficiency. The moving-average proportional control, Strategies 5 and 6, showed decent results, with averages near 29–30 blocks/min for wooden cubes and 36–40 blocks/min for foam cubes. These schemes offered smoother control but required sustained EMG modulation, which can quickly fatigue the user and reduce the total during a timed task like the BBT. Overall, the results suggest that schemes that require fewer

EMG activations per object transfer, like the toggle open/close, outperforms schemes that rely on continuous modulation or precise timing from the user.

While the Box and Blocks Test helps quantify the overall performance of each control scheme, subjective usability is also critical for prosthetic control. Device control and usability preference are two major factors that contribute to a user's overall enjoyment and willingness to continue using their prosthetic. To capture the user's perception of ease-of-use and reliability, each control strategy was scored using an Intuitive and Reliable (IR) rating system. The "Intuitive" score reflects how natural or mentally demanding the control scheme felt during use, while the "Reliable" score evaluates consistency of performance across object types. Both scores ranges from 0-2 with 0 equating to non-functional, and 2 equating to high ease of control. The "reliable" score was averaged across small wooden cubes and foam cubes to compute a single reliability rating for each strategy. Table 2 presents these IR scores, offering a complementary perspective to the performance data and helping contextualize which control approaches are not only effective but also user-friendly.

Table 6: Intuitive and Reliability Scores

Table 2: Intuitive and Reliable (IR) Scores

Control Strategy	1. Intuitive (I) Score	2. Reliable (R) Score			3. IR ($I + R_{avg}$) Score
		Small Wooden Cubes	Large Foam Cubes	Avg R Score (R_{avg})	
1) Natural Hand	2	2	2	2	4
2) briefly open (default closed)	1	1	1	1	2
3) toggle b/t open and closed	2	1	2	1.5	3.5
4) incremental closing (with EMG reset)	0	0	1	0.5	0.5
5) Moving Average (sensory feedback OFF)	1	0	1	0.5	1.5
6) Same as (5) but with sensory feedback ON	1	1	1	1	2

The highest intuitive score (2) was assigned to both the Natural Hand and the toggle open/close control strategy (Strategy 3). These approaches felt most natural to use, requiring minimal cognitive effort and offering predictable responses. The natural hand felt the most natural to control, with the toggle scheme following slightly behind.

The lowest intuitive score (0) occurred for incremental closing with EMG reset (Strategy 4). This strategy is less intuitive as it requires the user to remember two EMG activation types, short activations for incremental closing and long activations for resetting the gripper, making it cognitively demanding.

In terms of reliability, both the Natural Hand and toggle control again performed best, each maintaining consistent results across wooden and foam cubes. These schemes offered clear state transitions and provided stable performance independent of the type of object. The worst reliability scores (0.5) occurred for the incremental closing (Strategy 4) and moving average with sensory feedback OFF (Strategy 5). These approaches are more sensitive to EMG noise, fatigue, and timing errors, resulting in greater trial-to-trial variability. The combined IR score identifies the most user-friendly and dependable control methods. The toggle scheme (IR = 3.5) once again ranked the highest amongst all the control schemes. The lowest IR score (0.5) belongs to the incremental closing scheme, indicating that both its intuitiveness and reliability are problematic for the user when it comes to the timing limitations of the BBT.

There is a clear correlation between the Intuitive and Reliability scores. Strategies that were easier to understand and operate tended to also produce more consistent performances. The two highest-scoring schemes in intuitiveness also ranked highest in reliability, those being the Natural Hand baseline and toggle control. Similarly, the least intuitive strategy, the incremental closing scheme, also showed the lowest reliability. However, the correlation is entirely consistent. For example, the moving average scheme scored moderately for intuitiveness, but low for reliability, demonstrating that a scheme can *feel* understandable but still produce inconsistent results due to excessive noise or muscle fatigue. On the other hand, it is unlikely for a scheme to be highly reliable while also being unintuitive, as non-intuitive control schemes typically increase cognitive load and introduce user-based errors. Overall, the data from the BBT suggests that an intuitive control scheme tends to promote a more reliable performance.

9.2 Reflection

The Box and Blocks Test provides a useful quantitative baseline for assessing how quickly and consistently the gripper can grasp, lift, and release small objects. However, its relevance to real-world operation is somewhat limited. The task is highly repetitive, uses uniform objects, and does not capture challenges such as irregular shapes, varying textures, unexpected slippage, or the need for delicate manipulation. In terms of daily use, the gripper must be able to handle objects with very different geometries such as bottles, utensils, and clothing. These realistic interactions place more importance on control intuitiveness, stability, and force modulation than on raw repetition rate. Therefore, while a high Box and Blocks score suggests good mechanical responsiveness and decent control mapping, it does not fully predict real-world functionality.

The Intuitive and Reliable (IR) score is likely more aligned with real-world effectiveness. Real-life tasks require the user to quickly understand how the device responds to user-input while producing repeatable, predictable results. A control strategy that feels natural to operate reduces cognitive load and allows the user to focus on the task at hand rather than managing the device. Additionally, reliability is crucial in daily use because inconsistent control can lead to objects being dropped or user frustration. In this manner, the IR score captures elements of human–device interaction that the Box and Blocks score simply cannot measure, providing insight into long-term usability and user satisfaction.

A noticeable pattern is that strategies that scored high on Box and Blocks performance also tended to receive high IR scores such as the toggle control. Alternatively, the incrementally closing scheme performed poorly in both metrics. This suggests that intuitiveness and reliability strongly influence the usability of the device, with the more natural a control method feels, the easier it is for the user to move objects quickly and accurately. One noticeable anomaly is the Moving Average scheme. It produced moderate Box and Blocks scores but only modest IR ratings. This indicates that a strategy can achieve reasonable performance in a controlled, repetitive test while still feeling inconsistent or mentally demanding to the user. Factors such as EMG signal drift, long-term muscle fatigue, or the need for sustained muscle contraction offers a strong explanation for why its reliability rating did not match its measurable performance.

From the Box and Blocks results, sensory feedback produced only a small improvement in object transfer rate. This is expected as the Box and Blocks task emphasizes speed over subtle force adjustment from the user. The haptic feedback did not meaningfully accelerate task performance as the objects were lightweight and required a fairly low grip force. From an IR perspective, sensory feedback provided a slight benefit in perceived intuitiveness but did not dramatically enhance reliability. Users may feel more connected to the device with feedback, but the signal did not significantly reduce task variability because EMG control noise still dominated the behavior of the gripper. Overall, sensory feedback offered more subjective benefit than measurable performance gain. Additionally, sensory feedback may offer more noticeable benefit in different tasks, the BBT is one of many clinical evaluations that relies more on speed and mind-muscle-device coordination than haptics and perceived contact quality.

9.2.1 Assessment of Compliance with C.A.I.R.

When it comes to comfort, the addition of a vibratory motor introduces a new form of sensory stimulation, but because the vibration is localized and of fairly low-intensity, it does not noticeably decrease comfort. The motor’s placement away from the EMG electrodes prevents interference, and its activation pattern is brief and proportional. Overall, sensory feedback has a neutral-to-slightly-positive effect on comfort by helping the user feel more connected to the device without adding physical strain.

In terms of affordability, the sensory-feedback system maintains strong alignment with affordability goals. Using a low-cost FSR and common hobby-grade vibration motor, the components are cheap and easy for users to replace or integrate. The simplicity of the circuitry ensures that the cost of adding feedback remains negligible relative to overall device cost. Thus, sensory feedback enhances functionality without compromising the affordability pillar.

Sensory feedback has its greatest impact on the intuitive component. Although the Box and Blocks performance did not dramatically improve, vibrotactile feedback helps a prosthetic user understand when contact occurs and how firmly they are gripping an object. This reduces cognitive effort during general use, even if it does not directly increase speed or accuracy in repetitive test conditions. For everyday tasks, this increased situational awareness makes the device feel more natural and less mentally demanding.

From a strictly performance-based perspective, haptic feedback offered only minor gains in reliability. While it improved the user's perception of griping events, the dominant source of variability, EMG activation noise and fatigue remained unaffected by the change. The feedback signal itself is stable and dependable, but it does not significantly increase the system's overall consistency in high-speed tasks like the Box and Blocks test. In real-world contexts, however, it may help reduce accidental object drops by giving the user more immediate awareness of contact.

9.2.2 Alternative Assessments for IR and Sensory Feedback

While the BBT provides a standardized measure of repetitive object transfer speed, and the IR score reflects subjective intuitiveness and reliability, both metrics overlook important aspects of real-world prosthetic use. Everyday tasks involve objects of varying shapes, sizes, weights, and textures, which require adaptive grip strategies that aren't effectively captured in a uniform block-lifting task. Additional tests such as functional object manipulation tests, grip-force precision testing, error-rate analysis, and multi-object or bimanual tasks would provide a more complete understanding of the gripper's performance. These approaches would reveal how well each control scheme handles complex dexterity tasks, fine motor control, and unexpected conditions, all of which are critical for practical daily-living activities.

The benefits of sensory feedback extend beyond what the Box and Blocks and IR scores can measure, primarily because those metrics emphasize speed and subjective impressions rather than force-awareness or situational sensitivity. More targeted assessments like fragile-object handling, slippage detection tasks, force-matching trials, and cognitive load evaluations would be much more tuned for capturing the value of the implemented haptic feedback system. These tests would highlight whether feedback genuinely helps the user control grip strength more accurately, detect contact earlier, react to changing object conditions, or operate the device with less mental effort. Measures like these are crucial for determining how sensory feedback contributes to safer, more controlled, and more confident prosthetic use in real-world scenarios.

10 Conclusions

Provided the context of the prosthetics low-fidelity means of development, this was a successful project that met all the initial goals and subgoals that were set out in **Section 6.** It is never possible for this project to have completely met its initial goal given the current state of extremely advanced prosthetic devices. However, the foundation that has been built through this project is stable for long-term iteration and development, which is the current plan following the submission of this report.

The most challenging aspect of developing the *R.E.A.C.H. Prosthetic* was maintaining a mindful approach to creating the strong foundation that now exists within this build. It was very easy to become hyper-fixated on a specific subsystem and start deviating from the original structure that was planned. While I often backed myself into a programming corner, I was able to come out of it and maintain the overall structure I set out for myself to complete.

If I were to do this project again, I would honestly take the same approach I did with this project. I can't express how proud and happy I am with the current result of this design. I have invested countless hours, and immeasurable amounts of energy into this project to get it to where it is now. In terms of different designs, I would have implemented my anatomical model design that I have been working on in parallel to this; however, it is not in a state where it can be successfully implemented. One of the most successful aspects of this project was the user-friendliness and ease of control that the *Arduino Nano Every* provided. I have taken Assembly-based mechatronics courses in the past and that is its own, fairly-outdated beast. While my current code is not perfect, it is extremely functional and successful overall.

Through this project, I learned so much about surveying user needs and developing design aspects around catering to those general needs in a manner that is still modular for the individual user whose needs and preferences might differ from another. While I had a fair mechatronics and Arduino understanding, I never had the time and dedicated space to develop a myoelectric prosthetic, which was a dream project of mine that I knew I needed to complete during my time at Cal Poly. This project solidified my knowledge of high-level language code structure and how to go about optimally building my program to be memory, power, and hardware efficient.

As this document comes to a close, I'd like to note my next steps. Going forward, I plan to implement the aforementioned anatomical model that has been in development and implement an on-board potentiometer to switch between control schemes on the gripper, relayed to the user via a a four-color LED board. After that, I want to make a socket-like gauntlet that maintains the placement of the EMG at the exact location on my forearm, similar to an actual socket, while supporting the circuit and electrical components. Finally, further down the line I want to create a PCB that will use the minimal amount of space and allow for a much more compact design overall.

Thank you to Dr. Iian Black for mentoring me throughout this project and my close friend Christopher Macartney, for motivating me and pushing me to do better, and take advantage of this project to grow in the direction I have always wanted to.

11 Appendices

11.1 Appendix A – Current Code

```
#include <Servo.h>

// Pin definitions
const int forcePin = A0;
const int emgPin = A3;
const int ledPin = 3;
const int servoSinglePin = 9;

// EMG and servo variables
int emgRaw = 0;
int emgCent = 0;
int emgRect = 0;
int threshold = 30;
int baseline = 0;
bool gripperClosed = true;
bool flexActive = false;

// Force Sensor Variables

int forceRaw = 0;
int brightness = 0;

// Servo objects
Servo single;

void setup() {
  pinMode(emgPin, INPUT);
  pinMode(ledPin, OUTPUT);
  single.attach(servoSinglePin);
  Serial.begin(9600);
```

```
  // Get initial EMG baseline
  baseline = analogRead(emgPin);

  // Start gripper in closed state
  single.write(15);
  digitalWrite(ledPin, LOW);
}

void loop() {
  // Read and process EMG
  emgRaw = analogRead(emgPin);
  emgCent = baseline - emgRaw;
  emgRect = abs(emgCent);
  int flex = emgRect - threshold;

  // Check for rising edge of flex
  if (flex > 0 && !flexActive) {
    toggleGripper();      // Toggle state
    flexActive = true;    // Mark flex as active
    delay(500);           // Debounce delay to avoid rapid toggling
  }

  // Reset flexActive when EMG drops back below threshold
  if (flex <= 0) {
    flexActive = false;
  }

 forceRaw = analogRead(forcePin);
  brightness = map(forceRaw, 0, 1023, 0, 255);

  analogWrite(ledPin, brightness);
  Serial.println(forceRaw);

  // Serial plot output
  Serial.print(threshold);
```

```
  Serial.print(",");
  Serial.print(emgRect);
  Serial.print(",");
  Serial.print(0);
  Serial.println();

  delay(10); // Slight delay for stability
}

void toggleGripper() {
  if (gripperClosed) {
    // Open gripper
    single.write(15);
    digitalWrite(ledPin, HIGH);
    gripperClosed = false;
  } else {
    // Close gripper
    single.write(125);
    digitalWrite(ledPin, LOW);
    gripperClosed = true;
  }
}
```