High Level Design:

ARM (<u>A</u>ctuation via <u>R</u>eal-Time <u>M</u>yoelectric Signals) ProsthEEsis

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Table of Contents

1 Introduction

e-NABLE is a global network of volunteers committed to combating the medical device inaccessibility gap by providing functional 3D-printed prosthetic devices at no charge to users. Over the last decade, this community has democratized access to low-cost, scalable, and customizable prosthetic devices through the development of open-source, 3D-printed prosthesis designs. The University of Notre Dame chapter of this network, e-NABLE ND, has laid a strong foundation for this work here on campus, focusing mainly on manufacturing scaled versions of existing, mechanical prosthesis designs and creating devices specific to certain users or tasks.

The ARM ProsthEEsis project seeks to build on e-NABLE ND's past projects by addressing specific challenges in the design and desired functionality of these devices, pushing beyond existing designs through the implementation of advanced features such as myoelectric control. In addition to myoelectric integration, we intend to improve the overall actuation design to better accommodate typical functionalities while minimizing the weight and cost of the device. The ultimate goal of the project is to provide e-NABLE ND, and potentially the greater e-NABLE community, with a myoelectric prosthesis design which can be replicated and adapted to different users with a maximum degree of functionality at a minimal production cost.

2 Problem Statement and Proposed Solution

For children in search of prosthetic devices, the current market presents several challenges. Traditional prostheses are costly and require frequent replacement as children grow. e-NABLE ND, an organization on campus dedicated to creating affordable, 3D-printed prosthetics, provides a solution to this problem. However, their designs are predominantly mechanical, which limits functionality for users who require more advanced, ergonomic solutions. These devices rely on body-powered mechanisms, which can require substantial effort to actuate. For example, elbow-actuated designs require the user to bend their arm to create a fist, limiting their ability to reach or grasp objects naturally. Additionally, the effort needed to keep a fist closed can lead to discomfort and fatigue, making daily tasks cumbersome and reducing the overall functionality of the prosthetic.

A promising alternative is the development of a myoelectric prosthesis that uses electromyography (EMG) sensors to detect muscle signals, interpret them, and use these to control the hand position.

The input will use single-use adhesive electrodes that are commonly found in clinics for EKG and EMG studies. Another benefit of this sensing method is the ability to use the response of a single muscle, which can be chosen to be independent of elbow flexion. This allows more intuitive functionality with less effort for the user, in addition to a level of customization based on the chosen muscle. Electrodes will be attached to the user on either side of the center of the designated control muscle parallel to the muscle fibers. A reference electrode will be placed on a nearby bony area that should have little to no electrical signaling. The exposed snaps on the outside of the electrodes will allow snap wire connection to the processing center. Another input will be a switch or push button that activates a locking mechanism. This additional function will minimize user fatigue in holding the same hand position for an extended period of time, allowing longer and more frequent use of the device.

The processing center will be a microcontroller. There are many microcontrollers readily available that could efficiently process these signals and generate an output. Key factors for this project include the developer's familiarity with the microcontroller and the microcontroller's ability to run Arduino code. It is crucial that the microcontroller can understand Arduino because of the availability of open source code available to begin interpreting the EMG signals. This code will be analyzed and refined to adapt to the specific needs of this device. On top of hand actuation, the device will need to be able to adapt to the strength of the user at each time of use. A calibration function may be necessary for the processor to confirm threshold values when the device is powered on. This will ensure that the device properly responds to user input despite changes in the user's muscles over time.

Lastly, for the output, the microcontroller will interface with either a servo motor or linear actuator. e-NABLE has successfully used servo motors to change string tension to alter position of a 3-D printed hand. These motors are readily available and can be relatively small. So, when one is placed close to the end of the residual limb, it will not significantly impact functionality. The hand will be 3-D printed using the EIH and done as per the specifications typically utilized by e-NABLE.

Overall, this device will be more accessible and more intuitively operated than existing prostheses. This device will be battery-powered, allowing the user to go about their day without interference, ideally for approximately 8 hours.

3 System Requirements

1. **Device integrity: The prosthesis will be strong enough to pick up objects up to 2.5 lbs.**

   The weight requirement has been chosen to be in line with the goal to be able to pick up everyday items that one may encounter in their household (i.e. water bottle, grocery items, etc.). Although a focus on lifting/grasping heavier items could be a possible future addition to our design, this would likely require a device designed more specifically for this goal.

2. **EMG sensor-based hand actuation: EMG sensors will be used to detect electrical signals from a muscle. Flexion of a target muscle will make the hand open or close.**

   The device should be able to obtain meaningful readings via the EMG sensors, conduct appropriate processing of this signal, and actuate the device, with an appropriate duration of delay, when the user intends to do so.

3. **Locking mechanism: The prosthetic hand will have a switch to “lock” it in a position, minimizing the user’s muscle fatigue.**

   Since the design seeks to minimize the effort required for use in comparison to the existing elbow or wrist actuated devices, the hand should not require continuous ‘flexing’ or muscle movement in order to stay closed. At minimum, a ‘lock’ button should be added in order to provide an improved user-experience. Additional buttons or an alternative user interface for ‘settings’ may be added in order to further improve the user experience.

4. **Calibration: A simple, user-friendly calibration process will allow users to successfully use the device based on their strength at the time of use.**

   An early task in our design process will be to determine the requirements of calibration by observing how signal readings differ from person to person. Based on preliminary research, the use of myoelectric technology appears to typically require some level of calibration, particularly adjusting signal thresholds for actuation. Regardless, the signal obtained from the EMG should be meaningful and should trigger actuation of the device when appropriate. The chosen calibration procedure should facilitate this outcome.

5. **Battery power: The prosthetic device will operate solely on battery power.**

   The device should be designed for daily use, and as such should involve means of power which allows use for an extended period of time, independent from a power cable.

   > **Rechargeable vs non-rechargeable:** At this stage, we are deciding between rechargeable and non-rechargeable batteries. If we opt for rechargeable batteries, there should be a means of recharging device batteries. If we opt for non-rechargeable batteries, the battery pack should be easily accessible by the user. Rechargeable batteries will be more convenient for the user as they can simply plug the prosthetic in at night to recharge. However, recharging batteries takes time. The user may not be able to wait for a recharge if their battery runs out in the middle of the day. Using non-rechargeable batteries gives the advantage of being able to carry extra batteries and quickly switch them out if there is no time to recharge or no outlet available. Choosing a rechargeable battery with long battery life will mitigate these issues, but using non-rechargeable batteries is a more surefire solution to recharging speed and availability.

4 System Block Diagram

4.1 Overall System:

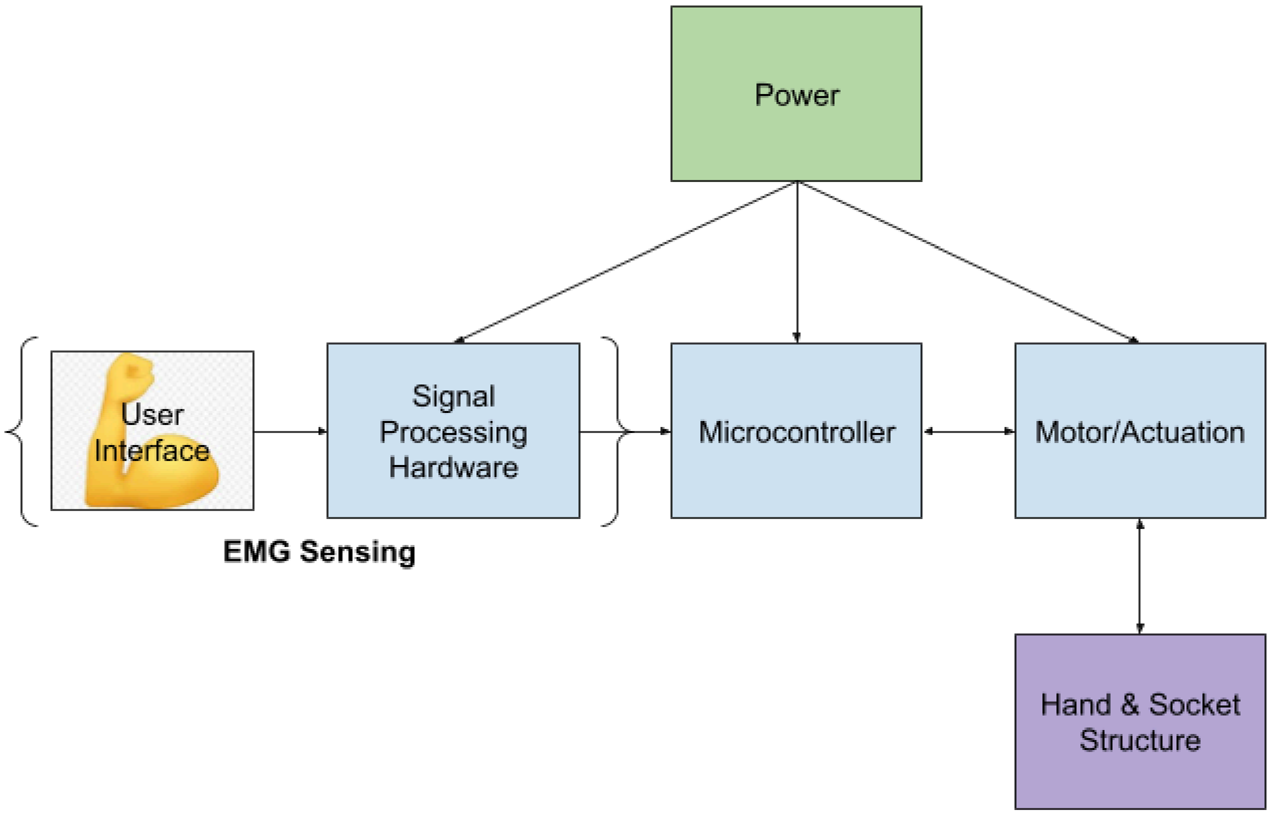

Figure 1. Overall System Block Diagram

4.2 EMG Sensing Description and Interface Requirements:

The EMG sensing subsystem will read EMG signals from the user's arm, and convert those signals into a format usable by the microcontroller. The subsystem will consist of:

1. EMG sensors placed on the user's arm
2. Wired connections from the sensor to a processing board
3. Hardware processing components
4. Software processing

The primary major interfaces are described below:

1. **Sensor-User Interface:** The user will be placing the sensors themselves, so a placement guide will be provided to the user. The intricacies of the user interface will be handled by the calibration subsystem.
    a. **Calibration Interface:** The calibration subsystem relies on the hardware components of the EMG Sensing subsystem, with

separate software. The EMG readings input to the microcontroller must be usable by the calibration software.

2. **Sensor - Microcontroller Interface (Hardware Processing):** The interface between the EMG sensors and the microcontroller will be managed by the hardware processing circuit, which will convert signals from the sensors into usable information for the microcontroller. The goal is to detect whether the user is flexing their muscle (signal is present) or not (signal is absent), which can be simplified to a threshold detection. The signal input to the ADC pins of the microcontroller must be between 0 and 3V3, with a frequency of less than 2 MHz (assuming WiFi is not running). Hardware processing will consist of the following components:
    a. **Amplification:** Typical EMG signals are less than 10 mV, so amplification is necessary to fully utilize the 0 to 3V3 range of the ADC pins.[1]
    b. **Filter:** EMG signals are typically between 0-400 Hz, so we will implement a low pass filter to reduce the noise in our readings. Using a high pass filter to remove frequencies below 20 Hz will limit hardware interference.[2]
    c. **Rectification:** Remove negative components of the circuit
    d. **Offset Removal:** Center the signal at 0V
    e. **Smoothing** (optional)**:** Smooth the signal with envelope detection or root-mean-square (RMS) to make it easier to perform threshold detection

4.3 Motors and Actuation

The hand actuation will be driven by tension applied to the strings of the finger joints. These strings will be attached to the shaft of the servo motor(s), which will turn when activated by a command signal from the microcontroller. This subsystem will consist of the following:

1. String or Fishing Line
2. Servo Motor(s)
3. Command Signal from Microcontroller
4. Feedback from Motor

Considerations for the design of this subsystem include determining the torque, size, and weight requirements of the servo motor. The initial design will incorporate a single motor to actuate the closing of all five fingers, although an additional motor could be added to allow for multiple grip positions. Additionally, programming will be required to write command signals to the motor at the appropriate times, as well as to monitor feedback from the motor to ensure precise angle control. The angle necessary to turn in order to fully close the hand will need to be measured and/or calculated. It is also of the utmost importance to

[1] https://pmc.ncbi.nlm.nih.gov/articles/PMC1455479/
[2] https://www.bu.edu/nmrc/files/2010/06/103.pdf

select a durable string, so that wear from the turning of the motor shaft does not deteriorate the string and cause breakage or snapping.

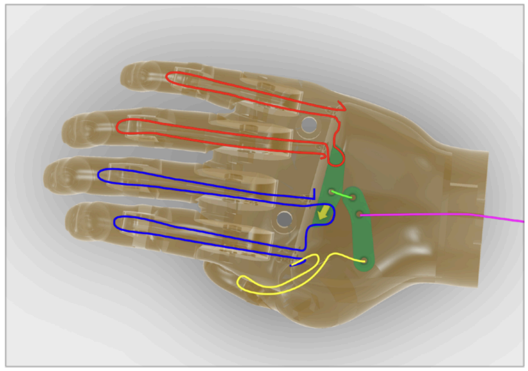

Figure 2. Diagram of String through Prosthetic Hand

4.4 Power

The overall system has three general tasks that require power: signal amplification, microcontroller operation, and actuation. To provide the necessary power for operation, we plan to use a removable rechargeable LiPo battery. We are opting for a removable design so that the user will have a quick way to swap empty batteries for fully charged ones if the charge runs out in the middle of the day. To indicate to the user the charge of the battery, we can use an LED that illuminates or changes color when the battery is low. Also, using rechargeable batteries ensures that the user does not have to repeatedly buy batteries to power the arm. When selecting a battery, we aim to select a battery that can power the arm for about 8 hours. Additionally, the battery needs to be able to supply the proper voltage and current to the servo, microcontroller, and amplifiers. When interfacing with the servo, we will need to design a circuit that protects the rest of the system from any large back EMFs that might be generated.

A key task for using a LiPo battery will be properly charging and discharging the battery to ensure safe operation and preserve battery health. Using a removable design allows us to use a manufacturer provided charger that is external to the arm. This charging strategy decreases the likelihood that the battery is improperly charged. While using the arm, we also need to have some monitoring and/or limiting circuit that ensures that the battery does not over discharge or provide too much current, scenarios which could endanger the battery health or the user respectively.

4.5 Hand and Socket Design (CAD)

The hand and socket of the prosthesis will be 3D-printed, and CAD will be used to design spaces for integrating the circuitry components. The international e-NABLE network provides a catalog of open-source hand and sockets designs[3] which can act as a basis for our system. Considerations will include determining a sufficient amount of space for electronic parts, while also minimizing the 'bulkiness' of the hand. Decisions on placement of heavier parts will also affect the user experience. Ideally, this design will be easily scalable for a variety of users. The joints for the fingers of the hand will require more flexible material, potentially via resin printing.

4.6 User Interface: Locking Mechanism, Calibration

Our requirements include features which allow the user to interface with the performance of their device. This includes enabling a 'calibration mode' via holding down a button for a predetermined duration (i.e. 3 seconds). Once 'calibration mode' is enabled, the user will be guided through a short calibration process via instructions on a small OLED display. These instructions will inform the user when to contract versus relax the relevant muscles, so that signal data can be recorded for the calibration process (i.e. setting thresholds).

The design will also include a switch to put the device into a 'Locked Position' mode. This feature will improve the user experience by allowing the user to avoid the possibility of accidentally changing the hand position from closed to open and vice versa. This switch will restrict the command signal writing to the servo motors so that the current hand state is unchanged. Exiting this mode will be achieved via the same button or switch.

4.7 Future Enhancement Requirements

Future iterations of this design could focus on providing multiple grip positions through the integration of more motors. These additional hand positions could be triggered via more precise sensing of different muscles being contracted or via additional 'modes' activated via additional buttons. Activating different positions via different muscles contracting would likely require increased sophistication within the EMG processing subsystem.

Another potential improvement focus would be prioritizing the functionality to hold items of significant weight. This task would likely consist of more mechanical challenges in terms of the material durability of the strings and joints, as well as selection and integration of a motor with greater torque.

[3] e-NABLE Devices Catalog: https://hub.e-nable.org/s/e-nable-devices/wiki/overview/list-categories

5 High Level Design Decisions

EMG Sensing

1. Sensor - User Interface

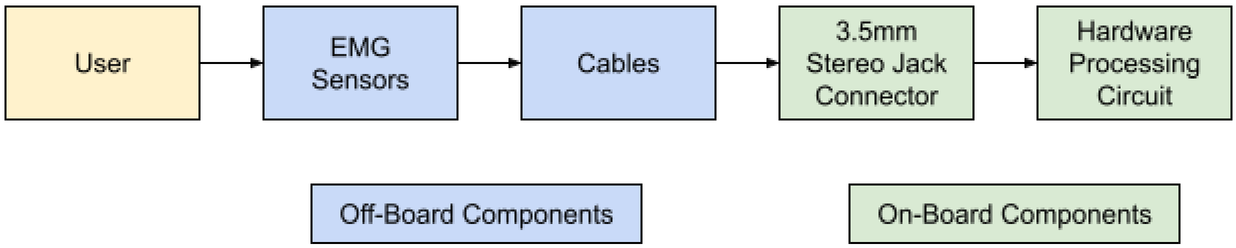

Figure 3. Sensor-User Interface

EMG sensors are fairly standard in design, with slight variations in size. They all require the same snap-on connector, and typically connect to a cable with a 3.5mm audio jack on the other end. The board would require a matching 3.5mm female connector to interface with the audio jack. Because the parts are all fairly standard, the exact parts can be selected based on availability and price.

2. Sensor - Microcontroller Interface

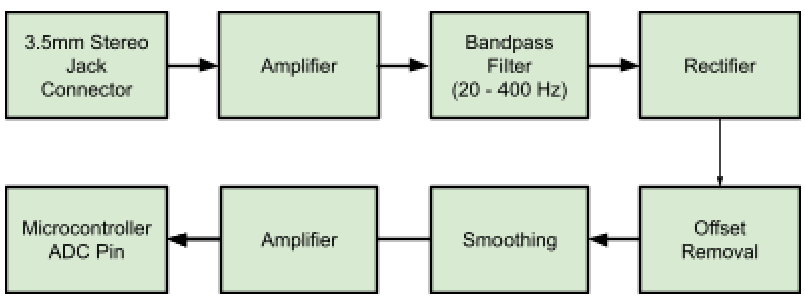

Figure 4. Hardware Processing Circuit for EMG Signals

We are basing our initial hardware processing on the Myoware 2.0 Ecosystem Circuit, which processes EMG signals prior to ADC conversion,[4] but the exact order of steps may change as we learn more. The intended design of each step is described below:

- **First Amplifier:** The expected magnitude of EMG signals is less than 10 mV, so the signal should be amplified before it is processed. We want the signal in a range of 0-3V3, so we should amplify the signal 200-300x.This amplifier will also amplify noise because it occurs before the filter, and can be implemented using an op-amp.

[4] https://learn.sparkfun.com/tutorials/getting-started-with-the-myoware-20-muscle-sensor-ecosystem/myoware-20-muscle-sensor

- **Filter:** The bandpass filter can be implemented using passive components to achieve our desired frequency range of 20-400 Hz, or could be combined with the op-amp as an active bandpass filter.
- **Rectifier:** To preserve the power of our input signal, we will use a full-wave rectifier to make the negative voltage components positive. A full-wave rectifier can be implemented using diodes. The diodes will be selected based on the expected power of the signal after the first amplifier.
- **Offset Removal:** Depending on the output from the sensors, this portion of the processing circuit may be unnecessary. DC offset can be removed using op-amps combined with passive components.
- **Smoothing:** There are two methods of smoothing the signal: envelope detection and RMS calculation. Envelope detection is a simpler circuit, primarily requiring passive components, while the RMS calculation would require additional op-amps. We are trying to simplify signal detection into a binary decision: either the signal is present (muscle is contracted) or it isn’t. With this requirement in mind, we plan to use envelope detection because it is easier to implement and should be sufficient for our design.
- **Second Amplifier:** The previous hardware processing steps will reduce the power of the EMG signal, so we plan to amplify the signal right before the ADC pin of the microcontroller to ensure we get adequate ADC resolution. We expect this to be a smaller amplifier, around 2x gain.

Motor and Actuation

The decision to include motors as means of actuating the opening and closing of the hand is based on the tension-based design of the existing e-NABLE devices. A typical stringing application is shown in **Figure 2**. For a typical, mechanical e-NABLE design, applying tension on the string forces the finger joints to bend, thus closing the hand. Our design will build on this mechanism by creating string tension via a servo motor. When the servo motor shaft turns, the end of the string will wrap around the shaft, creating the tension needed to close the hand.

We have considered using a linear actuator as an alternative to the servo, but have concluded that weight and size could potentially introduce negative effects on the overall socket design and user experience. Additionally, there is some precedent for using servo motors in existing e-NABLE demos for pressure sensor devices and other intermediate tests made towards myoelectric design.

Choosing a servo motor will involve considerations including size, weight, torque, and power requirements. We will also need to consider a design for a hub on the servo shaft which will allow the string to “wrap” around as necessary. For this aspect of the design, we will need to consider how to avoid wear on the string and servo hub, without introducing significantly higher costs (extremely durable string/fishing line) or weight (metal servo hub).

Power

As previously mentioned, we are planning to use a LiPo battery for its size, removability, and chargeability. It will be easy to fit the battery into the prosthesis since it is small and relatively lightweight. Since it is removable, it will be simpler to ensure safe charging with an external charger, and the prosthesis can continue to be used with an additional battery in the meantime. The battery will need to power the EMG sensors, the processor, the servo motor, indicator LEDs, and an OLED display. Ideally, the battery will power the device for around 8 hours, allowing more convenient use of the prosthesis.

Additional considerations include servo integration and charging and discharging regulation. With powering the motor, there must be precautions in place to prevent negative effects of opposing voltage generated by the motor. To ensure safety, the LiPo battery needs regulated charging and discharging. Charging will be handled with an external charger that has the necessary limitations included. For discharging, we will have an indicator light for low battery and a failsafe limiting circuit that will power off the device to prevent damage to the battery and the user.

Hand and Socket CAD Design

The physical design of the prosthesis will use existing e-NABLE elbow-actuated designs as a basis. The decision to build off of elbow-actuated devices is due to the increased space for circuitry on a device with a longer socket component. The hand component of the physical design should not require extensive redesign, although space must be reserved for the servo motors to be housed. Additionally, as with typical e-NABLE device design, the finger components will need to be hollow to allow string to be passed through. Flexible material will likely be required for the joints of the fingers, and so we will likely use resin 3D-printing material.

The socket will need to house the PCB, OLED display, and battery pack. Weight considerations will need to be taken into account as locations for components are determined, as creating a “top-heavy” (i.e. the majority of weight being concentrated closer to the hand) device could make the device difficult to use, especially for users who may not be accustomed to using muscles in their residual limb. Currently, we plan to make the battery pack easily-accessible so that batteries can quickly be replaced, allowing the user to maximize their use of the device. The OLED, as well as any push-buttons used for locking the device or enabling different “modes,” will also need to be accessible by the user.

User Interface

One role of the user interface is to convey any necessary information or directions to the user. Information that we need to convey to the user includes battery level, the state of the locking mechanism, and the calibration status. The battery level, lock state, and calibration status are very simple information so it will be sufficient to communicate them with LEDs. However, we expect the directions for calibration to be more involved. The arm may need to autonomously prompt the user to contract or relax their muscle in order to gather data about what a user's EMG signals look like. Having an OLED screen to prompt the user or to convey error messages etc. will be required. Additionally, while the LEDs can provide basic, but quick access to information, the OLED can also be used to display more detailed information about battery level etc.. To activate the lock and to initiate calibration, a push button will be sufficient. If we designate a single press as the toggle lock command and a press and hold as the initiate calibration command, then a single push button will suffice for the UI.

The other role of the user interface is to read EMG signals from the user. The literature does not definitively describe the best way to monitor EMG signals, but we anticipate needing up to three electrodes which the user can stick to their above specified monitoring points. To do this, standard EMG equipment exists including electrodes and snap connector cords. EMG readings will eventually determine when the hand will be open or closed.

Microcontroller Selection
Based on the requirements of our subsystems, our microcontroller must have 1-3 ADC input pins for EMG sensing, 1 PWM output pin for servo motor or linear actuator control, low power consumption to maximize battery life, and enough processing power to handle EMG sensing and hand actuation concurrently. We do not intend to use WiFi or Bluetooth in our design, so those features are not a factor in our microcontroller selection.

We are considering the ESP32-S3 for our project because it has Successive Approximation Register (SAR) ADC pins, which can operate more efficiently with lower power consumption than the standard ADC pins on the ESP32. In selecting our ADC resolution, we will need to balance power consumption with precision, as SAR ADC pins consume more power at high resolutions. The ESP32-S3 also meets our other listed requirements.

6 Known Unknowns

EMG Processing

The expected output of the EMG sensors is a significant unknown. Research into similar projects gives us an idea of the frequency and amplitude to expect, but it will likely vary depending on the muscle and sensors we pick. Because we don't fully know what the signals will look like, we are not entirely sure which components are necessary in the hardware processing circuit. From our initial research, most EMG processing includes a filter, rectifier, and some kind of smoothing (envelope detector or RMS). Some processing circuits also include an amplifier and offset removal, and they all vary in the order of steps.

We are planning to measure EMG signals on an oscilloscope to better understand the output of the sensors. We can also prototype some of the hardware processing, like the filter and rectifier, using a breadboard and passive components, and view the output on an oscilloscope to analyze the effect of the processing on the signal.

Calibration Procedure

It is known that the device will have to be properly calibrated to the specific user to ensure that an effective opening and closing motion occurs upon voluntary muscle contraction. Unique biological factors in each person force the need to make sure the device can work on any user. Our primary focus is making sure that we are able to effectively read and process the EMG signals produced by the user, and while we aren't exactly sure what it will look like, we anticipate a need to adjust the threshold of what "qualifies" for a prompt to change the hand position from open or close. It is unknown how we will change the software, user-by-user, to accomplish this.

Selection of Muscle to Sense

Every muscle in the body is controlled by nerves, so every muscle gives off myoelectric signals when flexion or contraction occurs. Thus, we have a multitude of muscles to conduct EMG sensing on. We anticipate utilizing the biceps brachii muscles, as previous research suggests a strong signal from bicep muscle contraction.[5] However, part of our engineering process will involve experimentation to decide on the best muscle that allows for best EMG sensing and user interface.

An important consideration in this selection is ensuring that accidental actuation of the device doesn't occur upon other, unrelated movements. We don't know which muscles best accomplish this, but will experiment in order to make sure the muscle(s) that we choose provide an upgrade over mechanical prosthesis that have this issue.

7 Major Component Costs

Part	Required Specs	Selection Options	Average Cost
EMG electrode	• snap connection • foam pad for comfort[6]	• BioMedical • OpenBCI • Amazon	$20 for 50 pack
EMG cable	• snap connection • audio	• DigiKey • DigiKey • TME	$6-12

[5] Analysis of the Biceps Brachii Muscle by Varying the Arm Movement Level and Load Resistance Band - PMC
[6] Danlee Medical - What Are the Electrodes Used for ECG Measurement?

	connector		
Microcontroller	• dual core • analog pins (sensors) • PWM pins (servo)	• DigiKey • DigiKey option 2	~$7
Servo	• Full 180 degree range • ~5V operation • Stall torque: 3-8 kg/cm*	• DigiKey • goBilda	$20-30
3D printing	• Resin printing may be required for joints	EIH Printing	$0
PCB	• 2-Layer • Size should accommodate microcontroller, test points, potentially an LDO (if multiple power levels needed)	• TBD	TBD
Myoware Kitboard (experimentation)		• Adafruit • Mouser • DigiKey	$45

* Estimation made based on e-NABLE past purchases for similar applications - Measurements will need to be made before actual determination.

8 Conclusions

The future is electronic, not mechanical. While the e-NABLE community is certainly doing amazing work with their current prosthesis solutions, we aim to take the next step in this great work by leveraging EMG sensors to create a myoelectric prosthesis. Though it will require more advanced signal processing and power supply considerations, the benefits for users will be rather substantial. Controls for their prosthesis will be much easier and more intuitive, which in the end means that the device can better serve the important needs of the user. While still very feasible to create in terms of design and fabrication, the ARM ProsthEEsis will be impactful not only from an engineering perspective, but from a human perspective as well. With a cost-effective design built to be replicated and adapted for real customers by other e-NABLE chapters, there is truly no limit to the reach that our project could have.

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