Project Proposal:

ARM (Actuation via Real-Time Myoelectric Signals) prosthEEsis

K Blouch, Cassidy Chappuis, Owen Nettles, Madeline Prugh, Andrew Sovinski

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 Description

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.

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3 Proposed Solution

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.

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4 Demonstrated Features

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

    a. 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.

    a. 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.

    a. 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.

    a. 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.

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a. 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.

b. 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.

5 Available Technologies

This section should have sufficient information to convince me you will be able to do what you are proposing. ***Remember that parts availability is still a very big issue.***

- **EMG sensors** will detect the electrical signals in a muscle, generating the input signal for the device. Sensors on multiple muscles may allow for additional hand positions.
  - Available: e-NABLE ND has a few EMG sensors we can use to start the project. Additional sensors can be purchased from multiple websites: DigiKey, Amazon, and Bio-Medical Instruments.
  - Affordable: The electrodes are <$1 each (and <50¢ in bulk). Associated cables and connectors can be purchased for <$10 total.
  - Accessible: Advancer Electronics has an Arduino-compatible EMG sensor ecosystem targeted to students and hobbyists. Though we do not plan to use the available boards, the existing Arduino support for this type of signal will help make coding the system much easier.
- **Servo motors** will pull on strings in the device to actuate the closing of the fist.
  - Available: Very common devices with many different sizes & specs are available for purchase on many websites: Adafruit, Digikey, and many more.

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    - Affordable: Price ranges from $3 - $30, which is well within budget.
    - Accessible: e-NABLE ND typically uses servo motors including this one, which has a weight and operating voltage that is fitting for our application.
    - ***Potential Alternative:* Linear Actuator**
        - Possible Advantages: A linear motion might simplify the design of the circuitry versus having to calculate the torque needed from the servo motors. Additionally, linear actuators might offer physical dimensions that are easier to integrate on the final device.
        - Possible Disadvantages: Weight may be a concern. Need to do more research on the torque, size, speed options available.
- A **microcontroller** will take in and process the EMG sensor input as well as create an output signal that will control the servo motors, moving the hand.
    - Available: Very common devices (ESP32 and similar) are widely available online.
    - Affordable: Many are available for under $30.
    - Accessible: We already have experience using Arduino, Raspberry Pi, and Espressif devices, which would all be sufficient for our project
- A **rechargeable battery** is needed to power the electrical components. Li-Po batteries have great energy density, but we plan to explore safer alternatives. If we do not find a suitable alternative, we will implement multiple safeguards to ensure user safety.
    - Li-Po risk factors:
        - Overcharging: not likely to happen while attached to human
        - Overheating: Body heat + warm temperatures could be problematic?
        - Physical damage: could be problematic, battery should be protected
    - Li-Po alternatives:
        - Non-rechargeable AA batteries (see battery comments above)
        - Nickel-metal hydride DigiKey
        - lithium iron phosphate DigiKey
    - Available: Very common devices are available with a variety of specs: Adafruit, Amazon, and more.
    - Affordable: It will depend on what type of battery we choose to be the optimal solution, but the majority cost below $20.
    - Accessible: Our motors, sensors, and microcontroller all can operate on 5V or less, so they can use batteries typical of Arduino and other hobbyist designs. There are many existing examples of charging circuits that we can reference to incorporate a rechargeable battery.

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6 Engineering Content

We divide our product into the following functional blocks, which can be developed concurrently.

I. EMG Sensing

Developing functional EMG sensing requires experimentation with our selected EMG sensors. We must determine how many sensors to use, and where to place them for the best readings. Initial research suggests using three sensors, two on the muscle, and one placed near a bone to act as a ground; if we use multiple sensors, we will need to determine how to effectively utilize all three signals. Additionally, we will implement a signal processing circuit and software, using the existing Arduino-compatible EMG ecosystem as a reference. The hardware workflow of the existing ecosystem is shown in **Figure 1**.

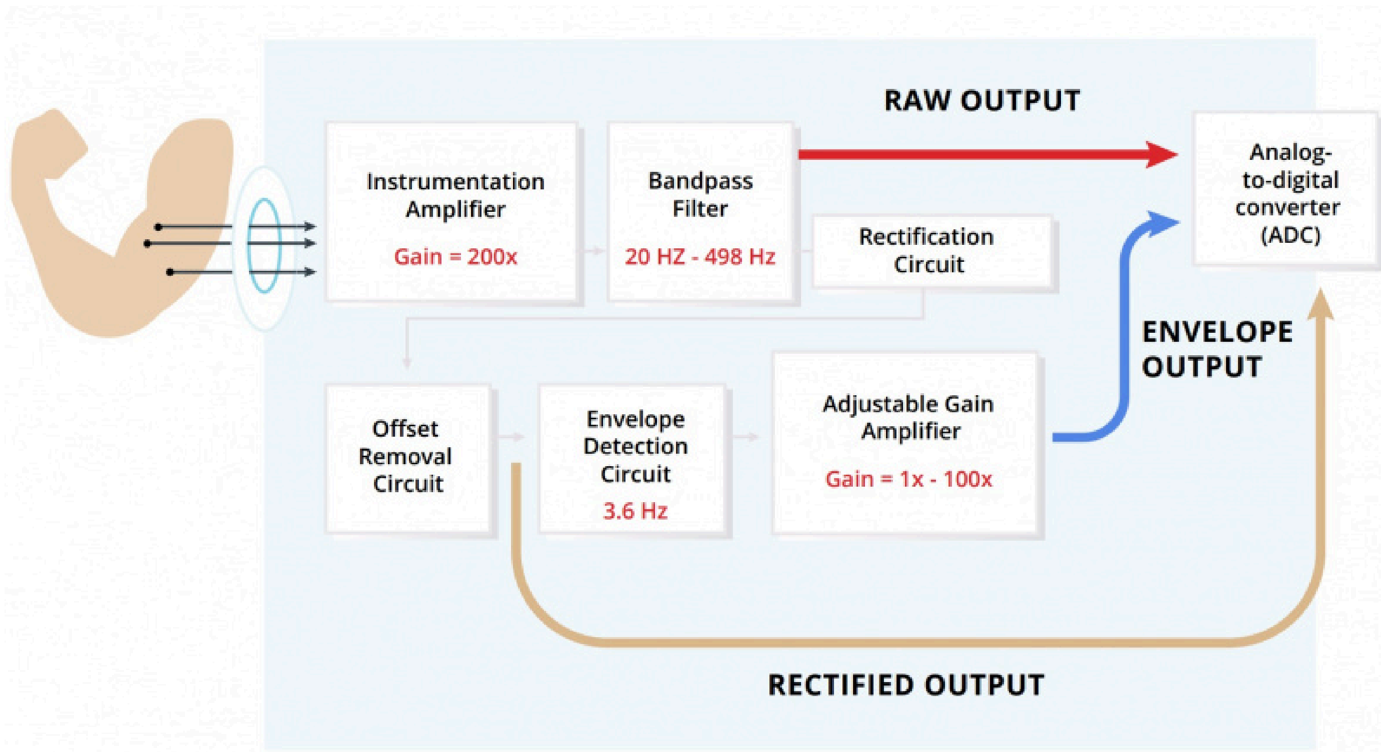

Figure 1. Myoware 2.0 Ecosystem Circuit Workflow

In the following subsections, we analyze each component of the circuit.

Filter:

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Rectification, Offset Removal, and Amplification: We will need to ensure that the input signal is within the range of the analog inputs pins on our microcontroller (0-3.3V), which requires offset removal and rectification circuits. We also will likely need to amplify the signal to ensure we have high ADC resolution.

Envelope Detection Circuit: The ESP32 ADC can reach a sampling rate of 1 kHz with Wi-Fi on, and 2 MHz with Wi-Fi off, but it's recommended to use a smaller sampling rate. Depending on the frequency of the input signal from our EMG sensors, we may need to implement an envelope detection circuit to improve the ADC conversion of the signal.

II. Calibration Process

The prosthesis will have to be tuned to each individual user, as each person will have slightly different EMG signals. Furthermore, variation in EMG sensor placement may necessitate calibration each time the user puts on the device. The user must be able to complete calibration independently within a reasonable amount of time, else the device will be too inconvenient to actually use. The high level overview of the calibration process is outlined below:

1. Collect EMG readings when user is at rest
2. Collect EMG readings when user is flexing the designated muscle
3. Use the readings to update signal thresholds for hand actuation

We will design an interface for the user to initiate and interact with the calibration process. In its simplest form, this interface could consist of a button and an LED on the outside of the prosthetic's casing, with a corresponding guide on what the LED blinking pattern is indicating. A more complicated version could involve multiple buttons, an LCD screen, and/or a wireless connection to an external device running a calibration program. The final calibration design will be primarily driven by two factors: ease of use and power consumption.

III. Hand Actuation

The prosthetic hand must be strong enough to pick up objects up to 2.5 lbs, with low latency (< 1s) . The hand should be able to successfully grip different sized objects without using so much force that the object breaks. The force with which the hand closes will need to be designed through iterative testing to ensure it meets our requirements. The simplest version of hand actuation is to use a single servo motor to pull on strings in order to close the fist. A more complex design involves different servo motors or each finger, allowing for a wider variety of hand positions. We are additionally considering a normally closed design. In this

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design a spring will hold the hand shut and a servo or linear actuator will retract the fingers when muscle activity is detected.

IV. Power and Charging Circuit

Our product must operate solely on rechargeable batteries, with an easily accessible charging port. We will implement a charging circuit to regulate battery charging. Our main power considerations are safety and operating time. The product should operate for a few hours between each charge, and the expected lifetime of the battery should be at least a year. The batteries must be able to tolerate impacts without risk of short-circuiting.

V. Physical Design

Enable currently uses 3D printing to create their final products. For this project we will also 3D print the prosthetic arm.

Our product should be reasonably comfortable to use for sustained periods of time. To ensure that the prosthetic is comfortable for sustained use, it should be light enough that it does not fatigue the upper arm. Based on Bruno et al., a human forearm and hand make up for approximately 3.4% of the full bodyweight. If the users are children weighing less than 125 lbs, the arm should be at most 4.25 lbs, with the goal of being even lighter to accommodate younger users. Placing heavier elements closer to the attachment point will ensure that the moment of inertia is small.

Also, incorporating a locking mechanism can reduce user fatigue if they need to grasp an object for a sustained period of time. The locking mechanism could be accessed by the user via a button press or with a specific muscle activation pattern detected by EMG sensing. We are concerned however, that using a locking mechanism will cause safety issues if the user needs to let go of an item quickly (eg. releasing something very hot or letting go of a bike handlebar to brace themselves). The normally closed hand design solves this issue as the user will not have to activate or deactivate a locking mechanism, simply flexing the target muscle will disengage the grip. Another benefit of this design is that the spring used to hold the hand shut will provide constant pressure over time on the grasped object across a variety of positions. A spring mechanism is more well suited to do this than a servo.

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7 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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