Closing the Loop - Haptic Feedback for EMG-Controlled Prosthetics

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This project investigates the design and development of a prosthetic hand controlled using Electromyogram (EMG) signals of the forearm with haptic feedback provided to the arm based on pressure sensors on the prosthetic fingertips. As part of Rose Ridder's Culminating Exercise in Engineering, this system was designed to connect control and feedback mechanisms and integrate four years of engineering study at Swarthmore College. In this project, a simple EMG-controlled, 3D printed prosthetic that provides fingertip pressure-based feedback to the user is prototyped and successfully demonstrates a functional device with a material cost of less than $100.

Contents

Background 1

Introduction 1
- Muscle Groups . . . 2
- Haptics . . . 2

Design 2
- Electromyogram, EMG . . . 2
- Prosthetic . . . 3
- Haptic Feedback . . . 4

Results 4
- EMG Waveform . . . 4
- Prosthetic Actuation . . . 4
- Pressure Sensitive Curve . . . 5
- Connected EMG Haptic Prosthetic . . . 5

Conclusions 5

Further Development Opportunities 5
- Acknowledgements . . . 5

Appendix 6
- Haptics Research Thesis . . . 6
- Associated Documents and Presentations . . . 6
- EMG Full Wire Diagram . . . 6
- Level Shifting Methods . . . 6
- System Materials List . . . 6
- EMG Materials List . . . 6
- Prosthetic Materials List . . . 7
- Haptic Materials List . . . 7

Background

According to the World Health Organization, over 40 million people worldwide are in need of a prosthetic device due to amputation. That number is expected to double by 2050[1]. This rising population of people who need prosthetics is even more concerning when considering that only about 5% of those who need them have access to a prosthetic, and these prosthetics are expensive and often limited in their functionality[1].

With the rise in maker-culture, prosthetics have been one arena in which cheap fabrication and development is often highlighted. Stories of people making 3D printed limbs are readily available with a simple Google Search, but their performance is limited. Moreover, even the most expensive and complex prosthetics can be limited in their adoption by users. Studies reveal prosthetics are worn only 27% - 56% of the time for upper limb amputees with 43% not using a prosthetic at all[2]. Reasons for this are not well studied, but often relate to issues of function and comfort. Functionality is the most cited reason for reduced prosthetic usage with 33% of respondents citing that as their primary concern. This is followed by issues of fit, cosmetic beauty, and maintenance each at 20% of the respondent pool[3]. Lack of tactile sensation specifically is also one of the key rejection reasons for prosthetics [4]. Therefore, research in prosthetics, functions, and feedback is critical to develop better and cheaper solutions for amputees around the world.

Introduction

This project is targeted to encompass four years of Engineering Education at Swarthmore College with a focus on electronics, robotics, and biomedical engineering fields. It aims to address the very real problem of developing a cheap, functional, and dynamic prosthetic limb to improve prosthetic adoption and accessibility for amputees. By developing a three-module device (as seen in Figures 2-4 that includes an Electromyogram (EMG) signal acquisition circuit, a prosthetic hand, and a haptic feedback system, this project requires electrical circuitry development, 3D printing technologies, robotic prosthesis actuation, and integrated system pressure-sensitive button development for generating meaningful signals for haptic vibrotactile feedback. These technologies may be further developed into a single prosthetic device that uses muscle signaling to dynamically control the prosthetic and provide real-time touch simulation feedback to the user.

Muscle Groups

Electromyograms (EMGs) measure the voltage potential across muscles associated with muscle flexing and relaxing. In this project, the focus is upon forearm flexion to control a prosthetic, so that is the target muscle groups location for signal acquisition. Each finger of a hand is controlled by individual and multiple muscle contractions which are expressed electrically by a higher voltage potential across the muscles. By measuring the voltage at the center of the muscle and near one end, a voltage difference across the muscle may be measured and processed to control a prosthetic.

Because EMG electrodes are positioned upon the surface of the skin, it is important to select muscles that are superficial rather than deep, and that have a detectable voltage difference across the muscle. Figure 1 displays the muscles in the left forearm.

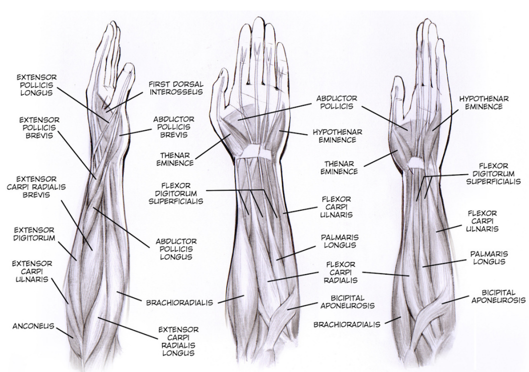

Figure 1. Forearm Muscle Diagram

A contrast-sketch of forearm muscles with the left hand displayed with the palm facing rightward, forward, and leftward[5].

By measuring different muscles around the forearm, EMG acquisition was focused on the Extensor Digitorum and the Flexor Carpi Ulnaris, which gave the most observable EMG signals for full-hand and individual finger flexing.

Haptics

Haptics, or the simulation of touch sensations, is a growing field of study as an additional sensory method for perceiving the world around us. Typing on your phone, 4D IMAX movies, and virtual reality are some of the most well-known uses of haptics in today's market. Harnessing the power of tactile sensory mechanisms provides a unique opportunity to enhance user experience and feedback about a person's environment beyond the other senses of vision, audition, smell, and taste [6]. In this design, haptics provide feedback to a user, replacing lost sensation in the prosthetic limb.

Design

The project design is comprised of three modules - an EMG for muscle contraction detection, a prosthetic controlled the EMG, and a haptic band to provide feedback to the user based on pressure devices measuring contact made by the prosthetic fingertips.

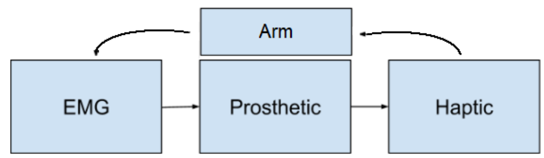

Figure 2. Block Diagram of 3 Modules

A block diagram of the three modules of this project - the EMG circuit, prosthetic hand, and haptic array, receiving signal from and providing it to the user's arm.

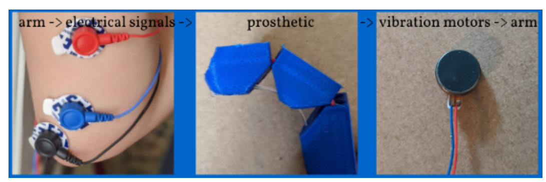

Figure 3. Simple Design Diagram of 3 Modules

Images of the three modules of this project - the EMG circuit, prosthetic hand, and haptic array as implemented.

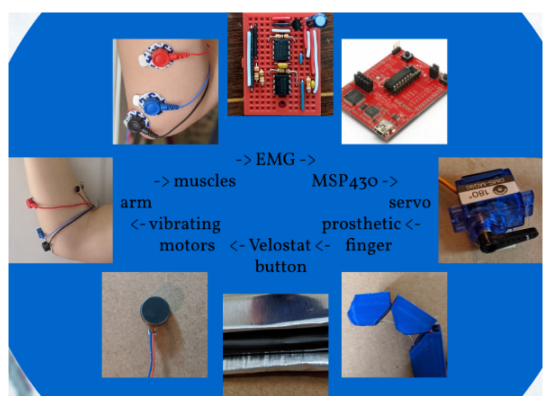

Figure 4. Complex Design Diagram of 3 Modules

Images of the critical components of the three modules of this project - the EMG circuit, prosthetic hand, and haptic array, as implemented, with intermediate devices included.

Electromyogram, EMG

The Electromyogram (EMG) module consists of a circuit designed to measure voltage potential across the target muscle. By attaching conductive EMG electrodes to the skin, electrical potential may be measured between the electrodes to detect whether the muscle is flexed of relaxed. This signal is then fed to a circuit composed first of an instrumentation amplifier (INA114) to amplify the voltage difference between two points of the muscle. This amplified signal is then filtered by an active high pass filter followed by an active low pass filter, creating a band of frequencies that remain in the final signal between 16Hz and 482Hz[7]. These filters are implemented as active filters using a TLV2772 dual op amp in order to amplify the signal as they are processed such that through the circuit, the input EMG difference potential has a gain of 30 from the instrumentation amplifier, 6.6 from the high pass filter, and 3.3 from the low pass filter. The circuit may be seen in Figures 5 and 6, with a more in-depth implementation diagram in Appendix Figure 15. The full equipment list may be seen in Appendix Table 2.

The EMG is powered using a 3.6V MSP430 voltage pin as V_{cc}. There is also a voltage splitter within the circuit to create a virtual ground of $\frac{V_{cc}}{2} = 1.8V$ which is used to allow all active filters to "invert" the signal around the 1.8V reference point.

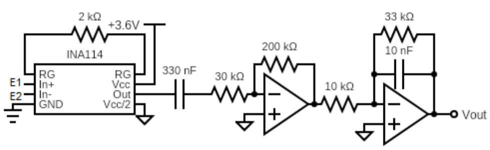

Figure 5. EMG Circuit Schematic

EMG Circuit consisting first of a voltage splitter, an instrumentation amplifier (INA114) and two operational amplifiers LFV2772 for active filtering of an EMG signal between the frequencies of 16Hz and 482Hz. E1 and E2 indicated leads to Electrodes 1 and 2 placed in the middle of the muscle and at the end of the muscle.

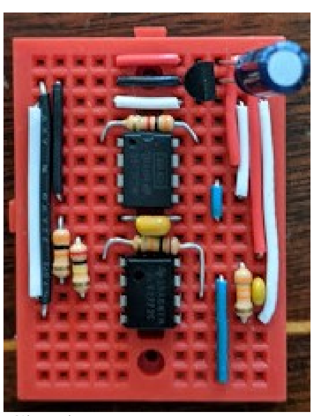

Figure 6. EMG Circuit Image

The built circuit of the EMG signal acquisition and filters.

The output of the circuit is passed to an Arduino Circuit Playground for 60Hz filtering and thresholding*[1]. Based on the EMG testing results, the threshold voltage to identify a muscle flex was set at 0.1V which was translated to a digital Circuit Playground Pin output. The MSP430 measured this pin and had a threshold of 660 units (on an ADC scale of 1024) to activate the servo motors.

Prosthetic

The second module of the project design consists of a prosthetic device. This device is a 4-fingered hand-inspired device made of rigid PLA 3D-printed material. Each finger consists of 3 independent rigid sections, resulting in 2 bending joints. Each section of each finger has two large-diameter holes in the exterior side of the finger and one smaller-diameter hole in the interior side of the finger. The 3D print was designed by "grossrc" on Thingiverse [8] as seen in Figure 7.

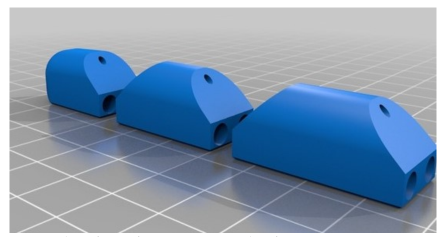

Figure 7. Prosthetic Finger Rendering

Prosthetic Finger Rendering displaying the two larger-diameter holes on the outer finger and the one smaller hole on the inner section.

Through the larger diameter hole are laced two wires connecting a pressure-sensitive fingertip button. Through the smaller diameter hole is a nylon microfilament connected to a servo motor horn that allows full compression of the finger joints such that the finger is closed into as tight a circle as the stiff PLA angles allow. By removing the tension on the nylon microfilament, the finger is released toward straight.

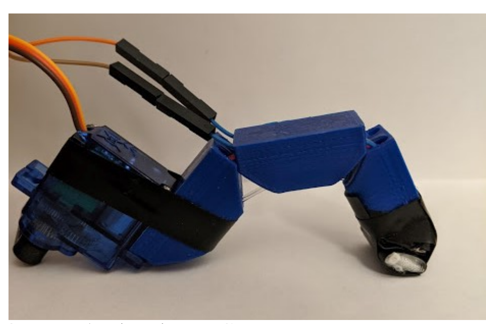

Figure 8. Prosthetic Finger Setup

The built prosthetic finger with wiring and nylon microfilament connections.

[1]Ideally, the full system would employ only an MSP430, but due to filtering issues, the Circuit Playground was used

The full finger is controlled with one servo motor signalled by the MSP430. An array of fingers may be made to be actuated simultaneously or individual based on the specificity of the EMG differentiation algorithm. In this design deployment, two fingers are activated at once based on the simplicity of the 0.1V thresholding algorithm.

In order to provide appropriate voltage to the servo motor, a level shifter is used to shift the signal from the MSP430 up from 3.6V to 5V for servo motor activation. This circuit incorporated a CD40109B Level Shifter and may be seen in Appendix Section . The signal itself is a PWM signal from the MSP430 with a base frequency of 50Hz. Adjusting the duty between approximately 5% and 10% controls the servo motor angle spanning 180°.

At the tip of each finger is a pressure-sensitive velostat button. Velostat is a conductive fabric allowing it flexibility and mobility for many uses. Here, the button consists of two squares of aluminum tape, a highly conductive adhesive, each attached to one of the wires that runs through the larger diameter holes of the finger segments. These aluminum squares are separated by the velostat so that they do not conduct electricity in their resting position, as seen in Figure 9. When pressure is applied to the velostat, the aluminum squares make more complete contact with the velostat sheet which results in a lowered resistance. The resistance of the velostat pressure element can vary between greater than 1MΩ and less than 80Ω, allowing more power to reach the next module in the device - the haptic motors (module 3). An example force/resistance relationship can be seen in the results section in Figure. 13

Figure 9. Velostat Button Design
Design of the three-layer velostat button used for fingertip pressure sensing consisting of two external layers of aluminum tape sandwiching a piece of conductive velostat. Pressure reduces the resistance of the system, allowing more current to reach the haptic micro motors in module 3.

Haptic Feedback

The haptic feedback module consists of an array of micro motors that simulate touch feedback from the fingertips and provide it on the forearm as seen in Figure 10. Based on the pressure measured via resistance on the velostat fingertip buttons, the corresponding micro motors will vibrate with variable intensity. This allows the user of the prosthetic to sense when enough pressure is applied to perform tasks such as pressing a doorbell, grasping an egg, or closing the fingers together.

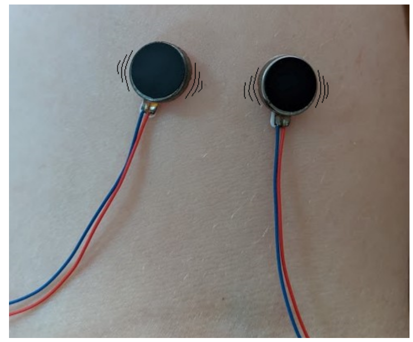

Figure 10. Haptic Micro Motor Array
The wearable array of micro motors corresponding to the two fingertip velostat buttons on prosthetic module 2.

Results

EMG Waveform

After signal filtering in the EMG circuit, the signal is passed to theArduino Circuit Playground for processing. Figure 11 displays a filtered muscle contraction that exceeds the flex threshold (signal>.1V) at which point the prosthetic finger is triggered (by the MSP430 after the signal is passed there).

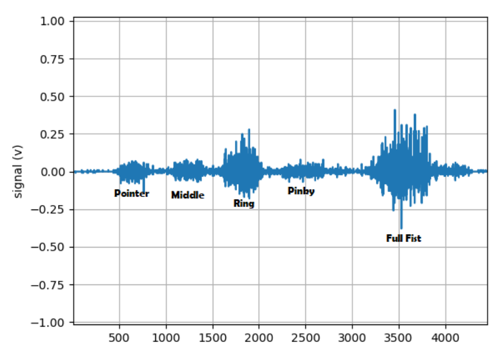

Figure 11. MSP430 Processing Diagram
The filtered signal from electrodes placed on the Flexor Carpi Ulnaris and recorded by the Arduino Circuit Playground.

Prosthetic Actuation

The MSP430 provides a signal to the appropriate finger's servo motor to close slowly. When the muscle flexion is halted, the servo motor is halted.

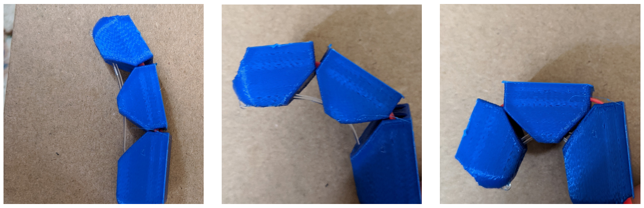

Figure 12. Prosthetic Finger Actuation
Three images of the varying degrees of contraction of the prosthetic finger actuated using a servo motor.

Pressure Sensitive Curve

The velostat button upon the tip of each prosthetic finger is used to detect pressure on the fingertip. Using this velostat button as a resistor in a circuit, the haptic motors are activated to provide simulated sensory feedback of touch. The resistance curve of the velostat button is plotted against applied weight in Figure 13

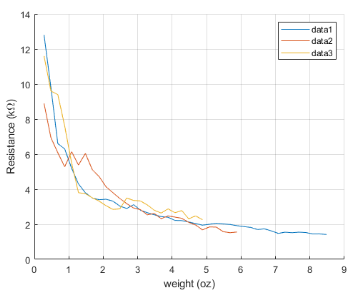

Figure 13. Velostat Button Pressure Response
Plotted relationship between weight on the velostat button and resistance of the button.

Connected EMG Haptic Prosthetic

Two videos displaying the activation of the EMG and the full system with feedback are available at

- `https://www.youtube.com/watch?v=FYtTcfgnoBk`
- `https://www.youtube.com/watch?v=OA-Bv2iPrC8`

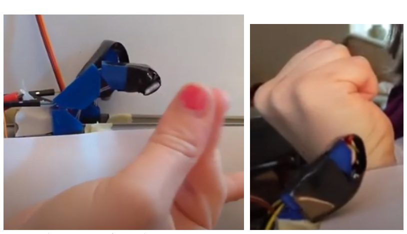

Figure 14. Product Display
Images representing the body-based action that induces actuation of the prosthetic fingers. Upon making contact with the pictured surface, the haptic motor representation of the corresponding finger vibrates, alerting the user that contact has been made.

Conclusions

This project displays the successful implementation of a cost-efficient, functional, feedback-driven prosthetic. The EMG circuit is successful in detecting muscle flex differences across a single muscle, the Circuit Playground and MSP430 filter and threshold flexing signals appropriately, the prosthetic contracts, velostat button resistance decreases with pressure, and the haptic motors convey fingertip pressure information back to the user. All of this was done with a minimal budget, and all supplies used in this design (with both the Arduino Circuit Playground and MSP430) total $98.73.

Further Development Opportunities

Further developing this design could be especially rewarding to improve its functionality and cost-efficiency. Particular development opportunities include:

- fully implement design on MSP430
- Better single-muscle flex-detection algorithm
- multiple EMG electrode array
- individual finger flex detection
- individual prosthetic finger activation
- improved prosthetic finger design:
- including better stabilizing mechanism between fingers, rounded corners, fingertip customization for pressure buttons such as flatter tip or better connection mechanism to avoid bumping from nylon cord knots
- full hand and wrist implementation
- algorithmic fingertip pressure recording
- variable haptic motor activation

 For questions or inquiries, please contact Rose Ridder at rosecridder@gmail.com.

Acknowledgements

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Appendix

Haptics Research Thesis

The background and interest in haptics for this project was inspired by Rose Ridder's Cognitive Science Thesis on the use of haptics for learning and education which may be found in the Swarthmore College Archives.

Associated Documents and Presentations

- Project Proposal, Google Drive
- Mid-Semester Presentation
- Final Presentation, Prezi
- Haptics Thesis available on the Swarthmore College Library Thesis Archive.
- Arduino Circuit Playground Code, Google Drive
- MSP430 Code, Google Drive
- LaTeX. Final Paper Code, Overleaf

EMG Full Wire Diagram

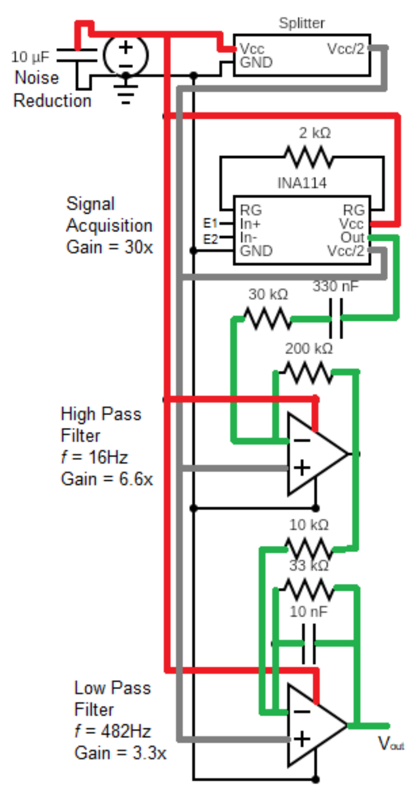

Figure 15. EMG Full Wire Colored Diagram
Color Coded EMG circuit diagram for assembly purposes. E1 and E2 indicate electrodes 1 and 2.

Level Shifting Methods

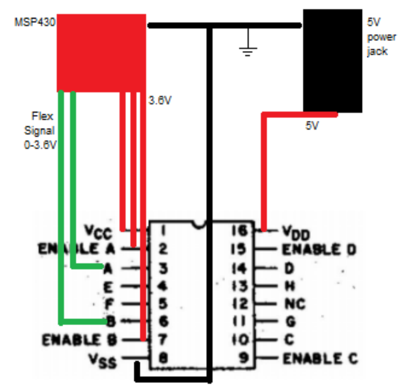

Figure 16. Level Shifting Circuit Diagram
The diagram for level shifting the MSP430's 3.6V signal to 5V for servo motor activation. The integrated circuit is a CD40109B Level Shifter. Pins A and B are shifted up to 5V and the outputs are E and F for servo motor activation.

System Materials List

Item	Quantity	Unit Price	Total Price
MSP430G2553	1	$11.79	$11.79
Circuit Playground	1	$17.50	$17.50
M/F Jumper Wires	1	$1.95	$1.95
M/M Jumper Wires	1	$1.95	$1.95
F/F Jumper Wires	1	$1.95	$1.95
Total			$35.14

Table 1
Materials used throughout the design and across modules. Each item is linked to its purchase location

EMG Materials List

Item	Quantity	Unit Price	Total Price
EMG Leads	1	$5.00	$5.00
.01 μF Capacitor	1	$.30	$.30
.33 μF Capacitor	1	$.32	$.32
10 μF Capacitor	1	$.84	$.84
33 KΩ Resistor	1	$.10	$.10
10 KΩ Resistor	1	$.10	$.10
TLV2772 Op Amp	1	$2.74	$2.74
Mini Breadboard	1	$2.15	$2.15
Voltage Splitter	1	$2.66	$2.66
INA114	1	$11.56	$11.56
EMG Electrodes	3	$15.56/100	$.47
Total			$26.24

Table 2
Materials used for the EMG circuit. Each item is linked to its purchase location.

Prosthetic Materials List .

Item	Quantity	Unit Price	Total Price
PLA 3D print material	< 100g	$.06	$6.00
Aluminum Tape	<1yrd	$5.00/10yds	$.50
1mm Nylon Cord	25in	$.50	$.50
Electrical Tape	20in	$.50	$.50
Velostat	1	$4.95	$4.95
5V Power Supply	1	$7.54	$7.54
Power Jack Connector	1	$.77	$.77
Level Shifter	1	$.55	$.55
Mini Breadboard	1	$2.15	$2.15
Servo Motor	2	$5.96/finger	$11.92
Total			$35.85

Table 3
Materials for the servo-actuated prosthetic finger with pressure-sensitive velostat buttons on the fingertip. Each non-bulk item is linked to its purchase location.

Haptic Materials List

Item	Quantity	Unit Price	Total Price
MiniMotors	2	$0.75	$1.50
Total			$1.50

Table 4
Haptic module materials consisted only of the micromotors. The item is linked to its purchase location.

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