ACKNOS PROSTHETICS

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1.0 Background and Motivation

Prostheses allow amputees (people with limb loss) to perform activities with fewer limitations. However, there are gaps between the functionalities of recent prostheses and biological limbs. Our client, Decisionics Lab, aims to bridge this gap and improve amputees' ability to carry out daily tasks.

The client identified a major limitation for prosthetic fingers (digits); the user cannot receive sensory pressure feedback, which is required for gripping objects of varying sizes, weights, and textures. To address this gap, the client wants to develop a prosthetic thumb to convey sensory pressure feedback to a partial hand amputee.

Prosthetic digits work as mechanical posts to restore length to a partial digit, sometimes enabling opposition between the finger and the thumb to stabilize and hold objects [1]. Existing solutions aid fine motor skills but have limitations as the device lacks tactile sensing capabilities [2]. Due to the lack of tactile sensing, it is difficult for amputees to control their prosthetic digits, resulting in poor performance in grasping objects [3].

Our design aims to fill the market gap by enhancing the performance of prosthetic thumbs by incorporating a sensing element to mimic the natural sense of touch [4]. Our team is designing a rigid thumb capable of tactile sensing. Tactile sensing involves mapping the contact mechanics between two objects. Our scope is simplified to sensing only the magnitude of pressure applied to various locations on the pad of the prosthetic thumb. This information is needed to relay to the user the intensity and location of contact between an object and the prosthetic thumb.

2.0 Project Requirements

2.1 Functions

1.Measure the intensity and location of pressure applied at the pad of the prosthetic thumb upon contact with an object.

a. Quantify the intensity of pressures between 0 and 340 kPa: The forces utilized in mundane activities range from 0 to 90 N [5]. The thumb surface area is estimated to be 2.64×10^{-3} m^2 using a rectangular model (47.6 mm by 55.5 mm) [6]. Assuming the maximum force is applied to a tenth of the area, the calculated maximum pressure is approximately 340 kPa.

b. Specify the pressure location from the thumb pad's top, middle or bottom.

2. Intuitively communicate the gathered data to the user, enhancing their tactile senses.

3. Allow radial movement of the prosthetic thumb controlled by the user's residual digit.

2.2 Objectives

Table 1 - Objectives for the design (Ordered by importance)

Objectives	Rationale	Metrics	Goal
Not impede the user's healthy range of motion	The device allows for everyday use and does not restrict normal wrist movement.	Degrees of wrist motion	5° flexion, 30° extension, 10° radial deviation, 10° ulnar deviation [7]
Be breathable	The prosthesis will contact the skin for a while. Perspiration during this should not lead to skin irritation.	Moisture Vapor Transmission Rate	450 g/m2/day [8]
Varying levels of intensity	The device should differentiate pressure levels into low, medium and high for easy user recognition.	Number of levels	Minimum of three levels
Last all-day	The design should be operational, without the need to recharge, for the duration of the user's working time.	Battery life	10 hours continuously [9]

Easy to wear and remove	The design should allow for easy and quick wearing and removal.	Time taken to wear and remove	~2 Minutes [10]
Lightweight	The user should be able to wear the device for long periods without physical discomfort.	Weight	Max 3 lb [11][12]
Feedback	The device should output readable signals to correspond to the different levels of pressure intensity	Varying vibration frequencies	One signal output per level of intensity

2.3 Constraints

Table 2 - Constraints for the design

Constraint	Rationale	Constraint Limit
Biocompatibility - Skin Irritation	Standards exist for materials used in biomedical applications to be considered non-irritant. For a material to be considered safe for clinical purposes, it must pass the in vivo and in vitro assessments [13]	Materials must be approved by the ISO 10993-10 tests.
Biocompatibility - Toxicity	Medical devices may adversely affect organ systems due to the absorption of leachates from the device into body parts. For a material to be considered non-toxic, it must adhere to the test standards [14]	Materials must be approved by the ISO 10993-11 tests.

3.0 Candidate Designs

The team had three rounds of feedback during the design process. In the first meeting, the user, client, supervisor and a board of advisory prosthetists from the Sunnybrooks prosthetics team aided in the selection of a candidate design, as well as iterations. In the second meeting, the client and supervisor provided feedback in a design review of the selected design. In the third meeting, the user tried the prototype of the device on their limb, and provided user-specific feedback.

The electrical design problem was divided into four sections: circuit, housing, script, and LCD code. The design was tested and iterated, and the final design is detailed in section 4.0. Appendix A shows the final circuit design.

Three candidate designs were presented to the user, client, supervisor and team from the Sunnybrooks prosthetics team. Their expertise was utilized to select one design, shown below. The other candidate designs are shown in Appendix B.

Figure 1. Candidate Design 3, selected candidate design [17]

The selected candidate design consists of a hollow thumb tip that houses the force sensitive resistors (FSRs) and wires, connected by metal rods to a wristband that houses the remaining electrical components. The initial design was attached to the hand via a socket that anchors to a joint in the residual limb, but was modified to be attached by a strap wrapping around the palm, based on the feedback.

The FSRs are slotted in the thumb tip, with the input voltage and sensor reading wires passing through the inside of the hollow thumb, coming out of a hole at the side of the digit and entering a housing on the wrist. The vibrotactile units are housed in a casing on the palm, with the applied voltage from the microcontroller and ground wires exiting the casing and entering the same housing on the wrist. The 16 wires exit the wrist housing and enter the electrical housing case through a hole in the housing. All external wires are sealed with heat shrink. The FSR input voltage wires, FSR output voltage wires, and the vibrotactile ground wires are soldered to the PCB. The input voltage to the vibrotactile is connected directly to the microcontroller using soldering.

4.0 Final Design

The final design integrates the final electrical and mechanical designs into one functional device. The model of the final design is shown below in Figure 2.

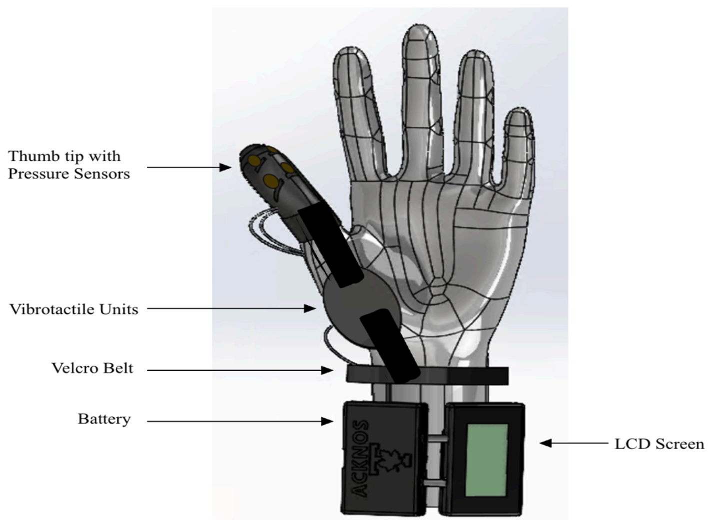


Figure 2. Final design

The electrical design was divided into 3 primary components (see Appendix C): PCB for voltage reduction, a microcontroller for data processing, and a battery for power supply (see dimensions in Appendix D). The PCB design consists of four voltage dividers to reduce the output voltage from the FSR and supply a voltage suitable for microcontrollers. The microcontroller (Arduino Uno) uses a code (see Appendix E) that sets three intensity levels, conveyed by the stratification of the levels of pressure visually sensed by the user. The low pressure level sensed for forces between 0-30N will have the LCD screen light in green. The screen will turn yellow for the medium level generated from forces 31-60 N. Beyond this pressure, the screen will display red (high). These levels are set based on the analog reading values from the microcontroller.

The mechanical design was divided into three primary components: the thumb, the socket and the vibrotactile feedback unit. The thumb is designed to have pressure sensors embedded within the extrusions (see Figure 3, dimensions in Appendix F). A small hole is located at the bottom of the tip (Figure 4) for the pressure sensors' wires to pass through. These wires will be heat-shrunk together, encasing them to reduce environmental exposure. The interface between the socket (within the thumb tip) and the user's skin was cushioned with silicone, protecting the user's skin from exposure to sharp 3D-printed edges (Figure 5). The vibrotactile units were sandwiched between two encasements (see Figure 6). Each half of the encasement had two extrusions for the velcro belts to loop through, holding the encasement together. The vibrotactile units were placed in cavities, with pathways present from which the wires can feed (see Figure 6, dimensions in Appendix F). The total cost to build this prototype is CAD 85.07 (see bill of materials in Appendix G).

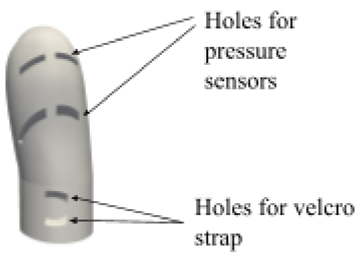


Figure 3. Digit with Extrusions housing pressure sensors and velcro strap

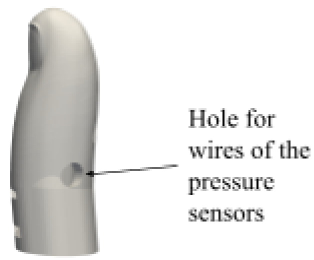


Figure 4. Extruded hole for Wires from Pressure Sensors

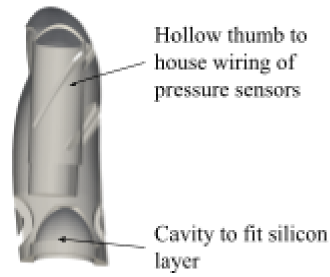


Figure 5. Silicone Socket Placement with Sectional view of Thumb Tip

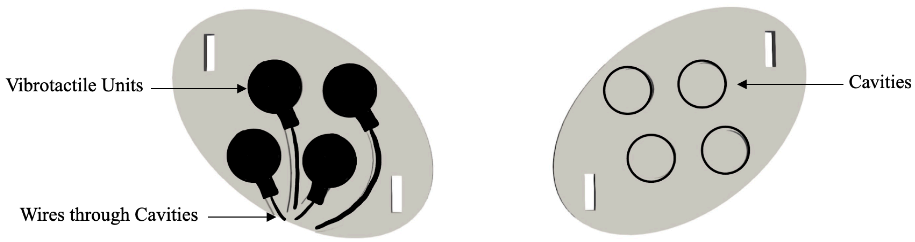


Figure 6. Vibrotactile unit encasements, including cavities for units and pathway for wires

Table 3 - Comparative analysis of design objectives achieved

Objectives	Metrics	Goal	Final Design
Not impede the user's healthy range of motion	Degrees of wrist motion:	5° flexion, 30° extension, 10° radial deviation, 10° ulnar deviation [7]	Maintains wrist and palm motions as no obstructing components reside in the area.
Be breathable	Moisture Vapor Transmission Rate	450 g/m2/day [8]	Silicone, TPU, and PLA are the primary materials and have been approved for medical use. Neoprene allows for breathability.
Varying levels of intensity	Number of levels	Minimum of three levels	Microcontroller reads a continuous range of applied pressure and quantifies them as low, medium, or high.
Last all-day	Battery life	10 hours continuously [9]	*Future improvement:* Lasts about 3 hours
Easy to wear and remove	Time taken to wear and remove	~2 Minutes [10]	Users can slip on the prosthesis like a glove. The velcro straps secure the device. Can be completed in under 2 minutes.
Lightweight	Weight	Max 3 lb [11][12]	Approximate weight of the design is 0.4 lb (180 g).
Feedback	Varying vibration frequencies	One signal output per level of intensity	PWM sets three varying levels of vibrations for the user. Validated with testing.

The following checklist details the design's ability to meet the design constraint as detailed in section 5.0.

- ☑ Compliance with ISO 10993-10 test for skin irritability:
  The materials that were used in the construction of the 3D printed parts are PLA, TPU and silicone, all of which pass the ISO's standards. The wristband consists of commercially available velcro straps, which also passes the ISO tests.
- ☑ Compliance with ISO 10993-11 test for toxicity:
  All the materials that were utilized in the construction of the prototype pass the ISO standards.

5.0 Testing and Validation

5.1 Goal 1: Comfort and Ergonomics

Markers of success in this category are minimal irritation to the skin via prolonged contact, compatibility with the user's current prosthesis, and minimal restriction in the flexibility and mobility of the user's hand. This was accomplished mainly via feedback integration with the user and the supervisor during meetings in which the various prototype iterations of the device were displayed and allowed for preliminary fitting.

5.2 Goal 2: Microcontroller Code Evaluation For Vibrotactile Feedback

The test was performed in the University of Toronto's Biomedical Teaching Lab and used a load cell that can apply a compressive load of a fixed force across a given area. The setup of the testing equipment is shown in Appendix H. An interface custom-designed to cover the area of the pressure sensor was utilized within the setup to ensure that the force generated from the load cell directly correlates to the pressure sensor. The experiment was as follows:

1. The pressure sensor was placed in between the compressive plates and covered with the thin casing used in the final design.
2. The custom cover was attached to the top metal pad. It is used to ensure that an even pressure over the entire area of the sensor.
3. Starting at 1N, the load cell was compressed and the sensor value was read from the ESP32 microcontroller using the serial monitor (gets values between 0-4096 bits). This value can be converted to voltage by dividing the reading by 4096 and multiplying by 5V.
4. The experiment was repeated 3 times and the average value was plotted.
5. The applied pressure was increased by 5N until 15N where it was increased by 10-20 each time.

The results of the experiment would be a graph of Force applied (N) vs Output Signal Strength, up to 90N, in compliance with the metrics as detailed by the objectives. The graph can be seen in Appendix H.

5.3 Goal 3: Optimal Vibration Frequency for Sensation

In the code, the vibration level for the vibrotactile units is set using a PWM output; the analog output is assigned a value between 0 and 255, which outputs a voltage between 2.5 and 3.3 volts. Increasing the voltage supplied across the units increased the intensity of the vibrations being felt. Therefore, the team must be selective about which PWM output value the vibrotactile units should vibrate at to ensure that the information is not lost to the user during the intended use or is not too large that it is uncomfortable for the user. A literature review and in-person testing of the capstone team members were done to find these levels.

6.0 Conclusion

This report covers the problem statement of designing a prosthetic thumb with sensory feedback, detailing the iterative scope and solution method. It outlines candidate designs, explaining steps in electrical and mechanical design refinement through meetings with stakeholders. The final design integrates mechanical and electrical components, followed by testing and validation.

Our project demonstrates technical excellence in mechanical engineering by featuring precision sensor integration, innovative feedback systems, and advanced materials for optimal comfort, and durability. Additionally, the compatibility of our device with the user's current prosthesis, emphasizes adaptability of our design to customized user needs. Development of 3D printable CAD models makes the design accessible and allows for future development of the device by making minor modifications to the CAD models. Our vibrotactile feedback system enhances user confidence, reflecting our commitment to empowerment and inclusion for individuals with disabilities worldwide.

References

[1] *Amputation: Prosthetic hand and fingers*. The Hand Society. (n.d.). https://www.assh.org/handcare/condition/amputation-prosthetic-hand-and-fingers (accessed Sep. 15, 2023).

[2] "I-digitsTM Quantum Myoelectric partial hand. Ossur.com," Össur. Life Without Limitations. https://media.ossur.com/ossur-dam/image/upload/pi-documents-global/iDigits_Quantum.pdf (accessed Sep. 15, 2023).

[3] Nerve-mimicking device gives 'feeling' to prosthetics - science, https://www.science.org/content/article/nerve-mimicking-device-gives-feeling-prosthetics (accessed Sep. 29, 2023).

[4] "Tactile Sensor & Tactile Sensing Technology explained," PPS, https://pressureprofile.com/about/tactile-sensing#:~:text=Definition%20of%20Tactile%20sensing,and%20other%20human%20body%20parts. (accessed Sep. 29, 2023).

[5] G. F. Shannon, "A comparison of alternative means of providing sensory feedback on upper limb prostheses - medical & biological engineering & computing," SpringerLink,

http://link.springer.com/10.1007/BF02478123 (accessed Sep. 29, 2023).

[6] S. Dosen, C. Prahm, S. Amsüss, I. Vujaklija, and D. Farina, "Prosthetic Feedback Systems," SpringerLink, https://link.springer.com/chapter/10.1007/978-3-030-60746-3_15 (accessed Sep. 29, 2023).

[7] C. Cipriani, F. Zaccone, S. Micera and M. C. Carrozza, "On the Shared Control of an EMG-Controlled Prosthetic Hand: Analysis of User–Prosthesis Interaction," in *IEEE Transactions on Robotics*, vol. 24, no. 1, pp. 170-184, Feb. 2008, doi: 10.1109/TRO.2007.910708.

[8] P. A. F. D. R;, "Functional wrist motion: A biomechanical study," The Journal of hand surgery, https://pubmed.ncbi.nlm.nih.gov/3968403/ (accessed Sep. 29, 2023).

[9] Richard BarkerRichard is Clarion's marketing executive and has over 15 years of experience in marketing for local and Richard is Clarion's marketing executive and has over 15 years of experience in marketing for local, "IP ratings explained: Ingress Protection Rating: IP Codes: Updated 2022," Clarion UK, https://clarionuk.com/resources/ip-ratings/ (accessed Sep. 29, 2023).

[10] A. Kapoor et al., "Breathability and safety testing of personal protective equipment: 'human-comfort' factor remains undefined," Indian journal of critical care medicine : peer-reviewed, official publication of Indian Society of Critical Care Medicine, https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7874299/ (accessed Sep. 29, 2023).

[11] R. M. C. M;, "Grip strengths and required forces in accessing everyday containers in a normal population," The American journal of occupational therapy : official publication of the American Occupational Therapy Association, https://pubmed.ncbi.nlm.nih.gov/9739394/ (accessed Sep. 29, 2023).

[12] Vaux JJ;Hugate RR;Hills JW;Grzybowski RF;Funk CK;, "Morphometrics of the human thumb metacarpal bone: Interest for developing an osseointegrated prosthesis," Surgical and radiologic anatomy : SRA, https://pubmed.ncbi.nlm.nih.gov/26228383/#:~:text=The%20average%20radius%20of%20curvature,%2C%2033%2D78.9%20mm) . (accessed Sep. 29, 2023).

[13] Body-driven digit prostheses naked prosthetics - steeper group, https://www.steepergroup.com/SteeperGroup/media/SteeperGroupMedia/Prosthetics/Upper%20Limb%20Prosthetics/Naked%20Prosthetics/Naked-Prosthetics-Brochure.pdf (accessed Sep. 29, 2023).

[14] "Point pivot product overview - 2023," Point Thumb overview,

https://9189610.fs1.hubspotusercontent-na1.net/hubfs/9189610/Point%20Pivot%20Product%20Overview.pdf (accessed Sep. 29, 2023).

[15] "An augmentation designer exploring the future body," Dani Clode design, https://www.daniclodedesign.com/thethirdthumb (accessed Jan. 3, 2024).

[16] J. O.- e-NABLE Volunteer, "Introducing the 'knick finger' • 3D printed partial Finger Replacement device," Enabling The Future, https://enablingthefuture.org/2016/05/02/knickfinger/ (accessed Mar. 22, 2024).

[17] "Thumbdriver," Naked Prosthetics, https://www.npdevices.com/devices/thumbdriver/ (accessed Mar. 22, 2024).

[18] DURAMIC 3D Filament 1.75mm Black 1KG Printing Filament Dimensional Accuracy +/- 0.02 mm, Amazon, 2021. [Online]. Available: https://www.amazon.ca/dp/B08XKH6HT7?psc=1&ref=ppx_yo2ov_dt_b_product_details (accessed Mar. 17, 2024).

[19] JS202011CQN, Digi-Key, 2021. [Online]. Available: https://www.digikey.ca/en/products/detail/c&k/JS202011CQN/1640097?utm_adgroup=&utm_source=google&utm_medium=cpc&utm_campaign=PMax%20Product_Low%20ROAS%20Categories&utm_term=&productid=1640097&utm_content=&utm_id=go_cmp-20291741422_adg-_ad-__dev-c_ext-_prd-1640097_sig-CjwKCAjwte-vBhBFEiwAQSv_xXuYoxjBqTpkiSCdYXFpzhaC4uBMjCqZrGumdJBZGCn4NrfjLAfGKRoC500QAvD_BwE&gad_source=1&gclid=CjwKCAjwte-vBhBFEiwAQSv_xXuYoxjBqTpkiSCdYXFpzhaC4uBMjCqZrGumdJBZGCn4NrfjLAfGKRoC500QAvD_BwE (accessed Mar. 17, 2024).

[20] "Akzytue ul 3.7V 1000mAh 703048 lipo battery rechargeable lithium polymer ion battery pack with JST connector," Amazon.ca: Electronics, https://www.amazon.ca/gp/product/B08R5DX97T/ref=sw_img_1?smid=A132D7PL1YID8X&psc=1 (accessed Mar. 21, 2024).

[21] YUNGUI Protoboard Stripboard Electronic Prototype Board 5x7 cm DIY, Amazon, 2021. [Online]. Available: https://www.amazon.ca/YUNGUI-Protoboard-Stripboard-Electronic-Experiment/dp/B07ZNZVDL6/ref=sr_1_26?crid=3KB52CC9E8YLS&dib=eyJ2IjoiMSJ9.8vk5bMRssmnEBjAAfzEFY3YcxzNXjKSXHdBVLrk3uYIJjvDFGzQxpTsiWmkjGG9E5hkA-Ag4PXZklxv6CmOlhgqltg7q8peV-m3LH2keu6mRvGz5SWBS7W2u1cwVFkS0TRdP-m2JKJOmtu6bXa1oP9N_6nGxPSQMLZOSKY3SVlNecxTpd7zNULZX7aVBYq-JJ6CWQh7xW_GDTQkFA2dU2zFrUpiAUfrC66zmNTAroLg6BF73rnTe8-ohLxcQwu4flHClZsa3pQs2StdtzArqulCDlxU25mcHeyUUC1Vu1P4.NdFY9sDtMA3O0kZyIaMZwmSPaArvR9aysV-iJYUvSos&dib_tag=se&key

words=protoboard&qid=1711062937&s=hi&sprefix=protoboard%2Ctools%2C63&sr=1-26 (accessed Mar. 17, 2024).

[22]]CFR200J100R, Digi-Key, 2021. [Online]. Available: https://www.digikey.ca/en/products/detail/te-connectivity-passive-product/CFR200J100R/3477580?utm_adgroup=&utm_source=google&utm_medium=cpc&utm_campaign=PMax%20Supplier_Focus%20Supplier&utm_term=&productid=3477580&utm_content=&utm_id=go_cmp-20282403582_adg-_ad-__dev-c_ext-_prd-3477580_sig-CjwKCAjwte-vBhBFEiwAQSv_xcUwoOrk_6X8oL0QhWeZn86V8QONf9sGRPNOFxydzb-8QT_kb5JHUBoCVXAQAvD_BwE&gad_source=1&gclid=CjwKCAjwte-vBhBFEiwAQSv_xcUwoOrk_6X8oL0QhWeZn86V8QONf9sGRPNOFxydzb-8QT_kb5JHUBoCVXAQAvD_BwE (accessed Mar. 17, 2024).

[23]44A0111-28-2, Digi-Key, 2021. [Online]. Available: https://www.digikey.ca/en/products/detail/te-connectivity-aerospace,-defense-and-marine/44A0111-28-2/7043727?utm_adgroup=&utm_source=google&utm_medium=cpc&utm_campaign=PMax%20Supplier_Focus%20Supplier&utm_term=&productid=7043727&utm_content=&utm_id=go_cmp-20282403582_adg-_ad-__dev-c_ext-_prd-7043727_sig-CjwKCAjwte-vBhBFEiwAQSv_xRp8GZHOaCqQsWgvHFKOKyIoRrxAOuxF3BhelJ2sUm27S928zx7tExoCrXkQAvD_BwE&gad_source=1&gclid=CjwKCAjwte-vBhBFEiwAQSv_x (accessed Mar. 17, 2024).

[24] DURAMIC 3D Filament Printing Dimensional, Amazon, 2021. [Online]. Available: https://www.amazon.ca/DURAMIC-3D-Filament-Printing-Dimensional/dp/B07TWDF866/ref=sr_1_2_sspa?crid=1KCNYFYSWA19F&dib=eyJ2IjoiMSJ9.w0wqadv1oHWB39Lnufjyy_-Xe2wACwhNuaH0s7sgnCet-cM1N6nyo4tcYT8UL_UcO8CKVcfr1WsSyZXWlWCffYGsR-EoJ7GQHBHJQodsiusQyRoKHUDrRx9ZbYqXhWdxlBv9O6OaJlXA3MFIP_W1cD0WwDMbzXgxxW3udeN2Am2h5L2PRgEprFK248ei1GPFlKtPrkyDyCSz4ashr70eEnmUR_C8gt1jMmSECIvI3GB_J3YbYTNx-Benpei4DCBwrfX3oAuUzxf87w0g6pRcpiy_i25kymPrIJueNyI_a3s.c_0kqc921w0o6ZZiCGLbxtSEQPbm8yAGW9De2wj3Yx8&dib_tag=se&keywords=PLA&qid=1711023288&sprefix=pla%2Caps%2C450&sr=8-2-spons&sp_csd=d2lkZ2V0TmFtZT1zcF9hdGY&th=1(accessed Mar. 17, 2024).

[25]Gorilla Glue Sealant Tube 82ml, Amazon, 2021. [Online]. Available: https://www.amazon.ca/Gorilla-Glue-Sealant-Tube-82ml/dp/B077TFTBT7/ref=asc_df_B077TFTBT7/?tag=googleshopc0c-20&linkCode=df0&hvadid=560416078525&hvpos=&hvnetw=g&hvrand=5741228604528556115&hvpone=&hvptwo=&hvqmt=&hvdev=c&hvdvcmdl=&hvlocint=&hvlocphy=9000945&hvtargid=pla-1365056717031&mcid=684178a393143e8abcd795e11270ddc3&th=1(accessed Mar. 17, 2024).

[26] T-Display S3, LILYGO, [Year]. [Online]. Available: https://www.lilygo.cc/en-ca/products/t-display-s3?variant=42351558590645 (accessed Mar. 17, 2024).

[27] McMaster Product 94510A611, McMaster, [Year]. [Online]. Available: https://www.mcmaster.com/94510A611/ (accessed Mar. 17, 2024).

[28] McMaster Product 91290A011, McMaster, [Year]. [Online]. Available: https://www.mcmaster.com/91290A011/ (accessed Mar. 17, 2024).

[29] 22AWG Hookup Wire White, Creatron Inc., [Year]. [Online]. Available: https://www.creatroninc.com/product/22awg-hookup-wire-white/ (accessed Mar. 17, 2024).

[30] FSR-X-400 Short, Interlink Electronics, [2024]. [Online]. Available: https://buyinterlinkelectronics.com/collections/x-ux-force-sensors/products/fsr-x-400-short (accessed Mar. 17, 2024).

[31] LET'S RESIN Silicone Making Non-Toxic, Amazon, 2021. [Online]. Available: https://www.amazon.ca/LETS-RESIN-Silicone-Making-Non-Toxic/dp/B07V5FFPWC/ref=sr_1_1_sspa?crid=1M2E3D3XZ4YUH&dib=eyJ2IjoiMSJ9.CLjOrk5lh05Vpk5GCWaAT9DKtgPIjEPOst-QxNrEIVEi0i2dPTLDpbJZ2WMIriCvePl0Ll_-PdVFiBVxqscRxe-pcH3KuJfJr4HFJa2QIev5QFZOGSElgmfLIU9ja2RrWsCfWRIAFlwJwFlcP8_01gEbku2rLXGMPznJr2t4jdHCAeg89Te0PhWNU7RbI5mnLh0xx3mcLuO5IGwqXiIRwx1fNtITB3kZZ_7-Rvd0j-jJQHs3HMYeR9IYXc5lJt3d2Az9TOCIrdFqBH5H_G7DQ5PdcPnCxGiSIOAu3r_cHM0.fw_jIoMVP5tuZlnT0c0Qdan0RHXNd-4JGmDiQBZydoY&dib_tag=se&keywords=silicone&qid=1711024782&sprefix=silicone%2Caps%2C168&sr=8-1-spons&sp_csd=d2lkZ2V0TmFtZT1zcF9hdGY&psc=1(accessed Mar. 17, 2024).

[32] VELCRO Brand Industrial Strength Indoor Outdoor Use Superior Holding Power on Smooth Surfaces Black 5 x 2 Roll, Walmart, [2024]. [Online]. Available: https://www.walmart.com/ip/VELCRO-Brand-Industrial-Strength-Indoor-Outdoor-Use-Superior-Holding-Power-on-Smooth-Surfaces-Black-5-x-2-Roll-90982/17190465?athbdg=L1102&from=/search (accessed Mar. 17, 2024).

[33] DURAMIC 3D Filament 1.75mm Black, Amazon, 2021. [Online]. Available: https://www.amazon.ca/DURAMIC-3D-Filament-1-75mm-Black-1/dp/B095HRG913/ref=sr_1_5?crid=2N28I2WQZTUZM&dib=eyJ2IjoiMSJ9.rOScaU6h-ZcvLTjGTuUZOdi0QfqqtID_3SGIUpyL50etH-df2iPB-Za1MKWtB4-x665xcbHbdEQEDydJ65ZT4konwqCx6iwJvTan8Yt33yckP0xtwS5IeqXPgYk-N9jYGlwzaHEYcRciqQqFyl7bNLjFFY0zKUvu4iQvHfuzjAZvjSI84H3O08U5l8i4fXLuHRhAbbce4N9M3ObebvTk440q9JJAOyC4-IzHXHjMN8fyPjolXY2-Ib-2XRsm1EOL6psMUSm1YqRkOgPByldDAngBzSCckAwuTZ9U1lIzvx8.VT_0a5jI_MM7Z7eElOYl6vXaBFu0TAzRM9-iAw2FZ-I&dib_tag=se&keywords=tpu%2Bfilament&qid=1711026265&sprefix=tpu%2Bfi%2Caps%2C134&sr=8-5&th=1(accessed Mar. 17, 2024).

[34] VYBRONICS. "Coin Vibration Motors - V-CLP1020B002L", [2024]. [Online]. Available: https://www.vybronics.com/coin-vibration-motors/with-brushes/v-clp1020b002l (accessed Mar. 17, 2024).

Appendix

Appendix A. Final Circuit Design

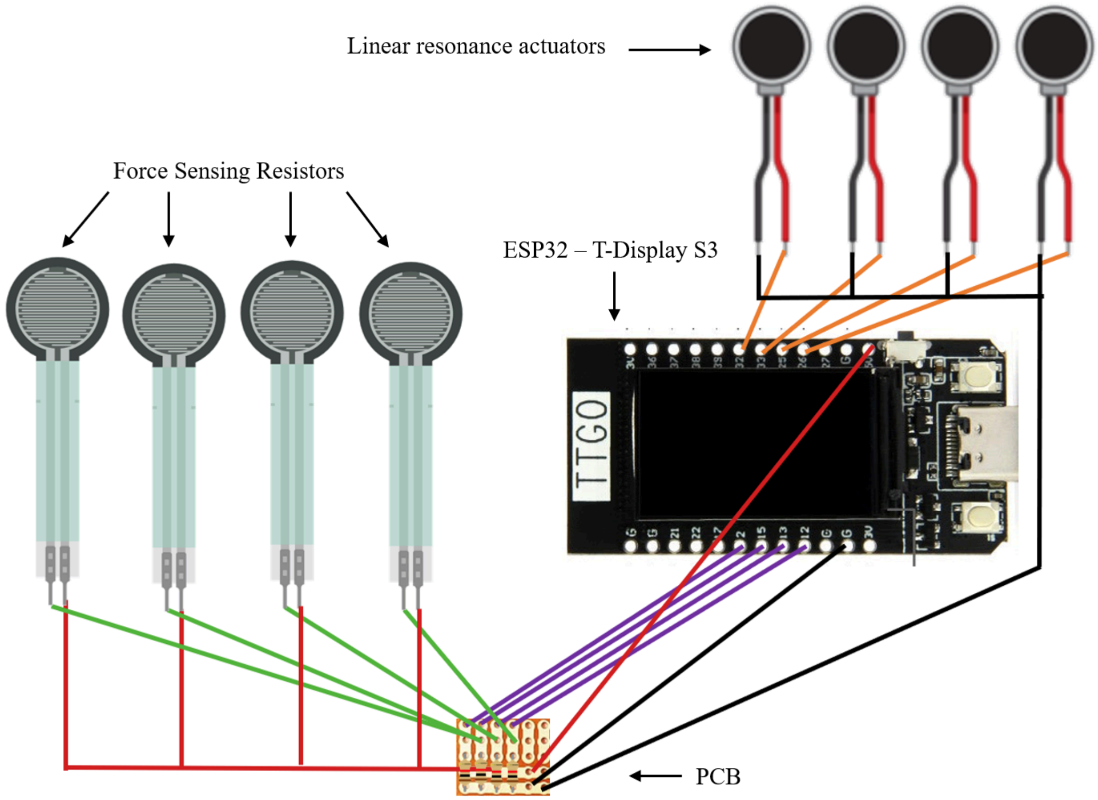
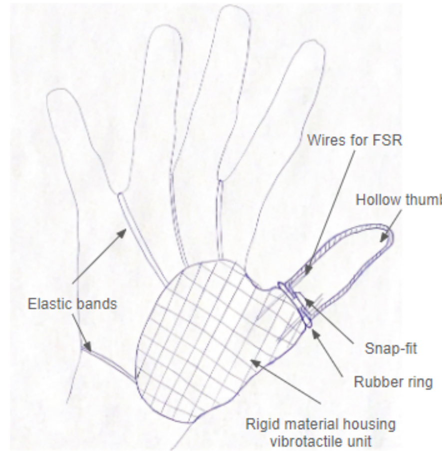


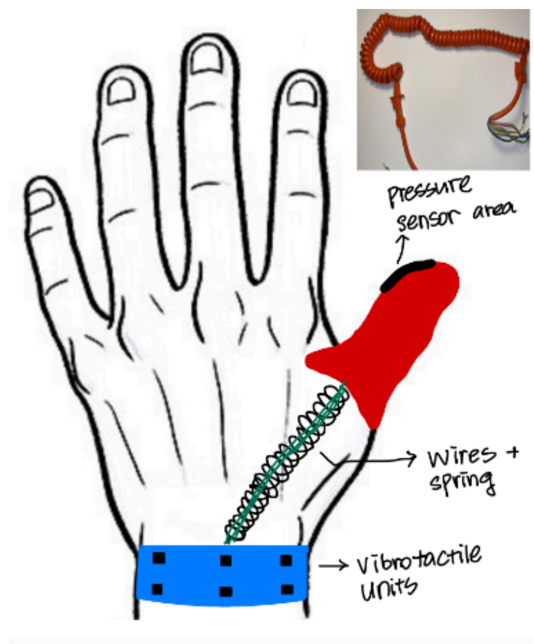
Figure 7. Final Circuit Design

Appendix B - Candidate Designs



(i) (ii)

Figure 8. Candidate Design 1 (i) Inspiration [15] (ii) Modifications



(i) (ii)

Figure 9. Candidate Design 2 (i) Inspiration [16] (ii) Modifications

Appendix C - Electrical Design Component List and Power Requirements

Components:	Mode	Power Usage (mAH)	Notes:
Microcontroller (ESP32)	Active Mode	240	Active Mode: Uses everything Including (Bluetooth, radio and Wifi)
Microcontroller (ESP32)	Modeum Sleep Mode	20	Modeum Sleep Mode: Uses everything except (Bluetooth, Radio and Wifi)
Microcontroller (ESP32)	Light Sleep Mode	0.8	Light Sleep Mode: Clock is turned off (Cannot Use PWM)
LED Screen	Regular Operation	100	Regular Operation (Note NOT Touch screen) Estimate
Pressure Sensor (Per Sensor)	Regular Operation	3	Estimated Using V=IR (Depends on circuit)
Vibrotactile Sensor (Per Sensor)	Always on at max Level	55	When in operation*
Vibrotactile Sensor (Per Sensor)	Always on at medium Level	27.5	
Total Power Usage (Max)	688		
Total Power Usage (Expected)	303		
Total when Idle	138		

Appendix D. Dimensions of Electrical Design Components

Table 4 - Major Electrical Component Selection

Component	Description	Part Selected
Microprocessor	- Created a list of candidates that met requirements, such as an Arduino Nano, ESP32, and Nucleo 32 - Selected ESP32: Able to charge the battery without additional circuitry	ESP32-S3 1.9 inch ST7789 LCD Display
Sensory Input	- Researched: Types of Force Sensing Resistors (AKA. FSR or Pressure Sensors) - Selected: Client recommended Sensor	FSR Model 400 Short
Sensory Output	- Researched: Vibrotactile (Linear resonant actuators), Electro-tactile, and Force-tactile sensors - Selected LRA: Best for comfort over time and overall integration.	VIBRATION ERM MTR 11000 RPM 5V
Battery	- Battery chosen based on expected power usage (Appendix A), rechargeability and size. Operation time 9.9 hrs (meets last all-day objective) - size: 50*34*10 mm^3	3.7V 3000mAh Lithium Rechargeable Battery
PCB	- Purpose: Reduce the voltage of the pressure sensor to read the voltages in a certain range, i.e. voltage divider circuit (Appendix A) - Simple, manufacture it by hand using a small, cut-down protoboard	RADIO SHAEK 2 - 276-15n

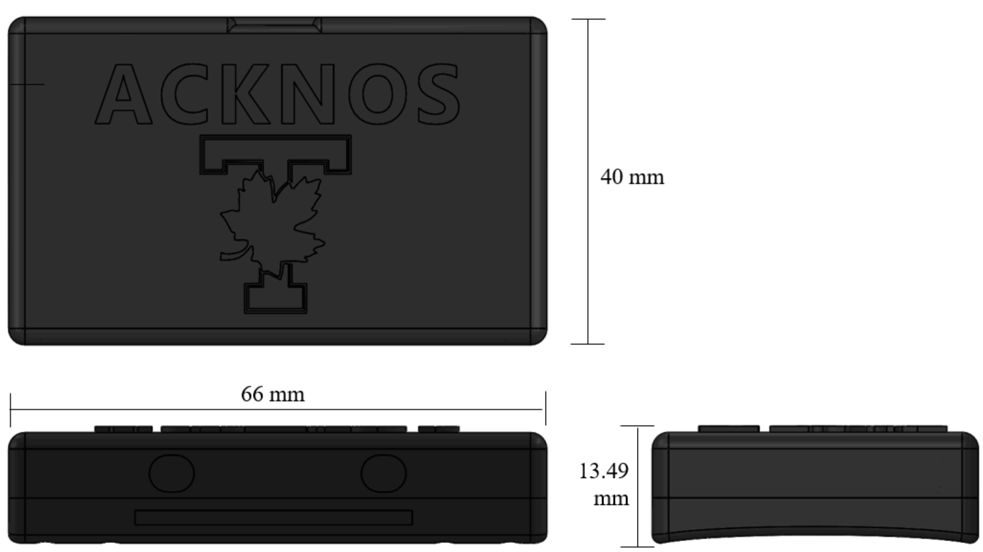


Figure 10. Dimensions of the battery housing design. Note that the LCD housing design dimensions are identical to the battery housing design.

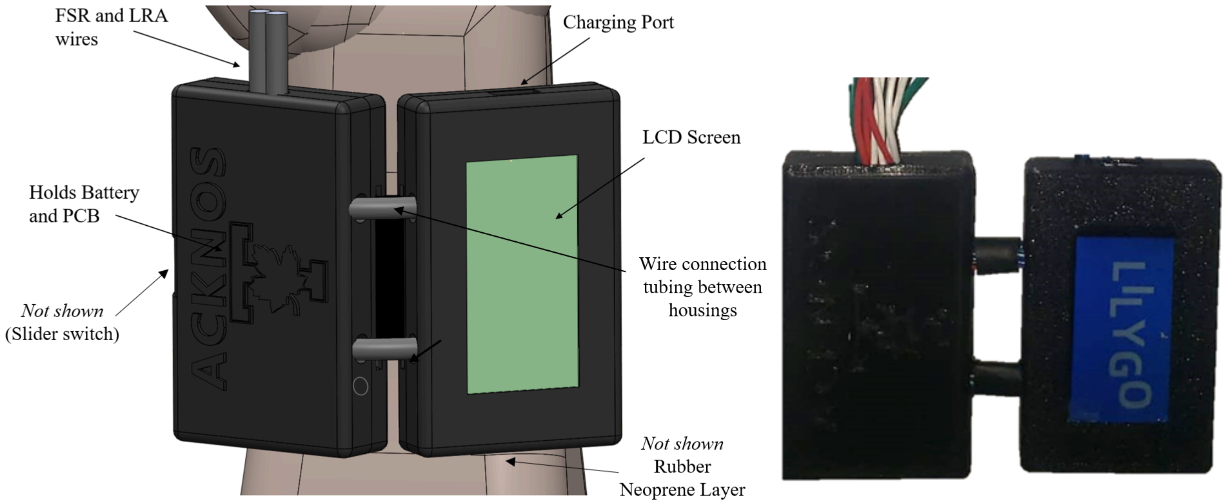


Figure 11. Final Electrical Housing Design (CAD model left, Physical right)

Appendix E - Arduino Code

```
void setup() {
  // put your setup code here, to run once:
  pinMode(A0,INPUT);
  pinMode(3,OUTPUT);
  Serial.begin(9600);
}

void loop() {
  // put your main code here, to run repeatedly:
  int sensorValue = analogRead(A0);
  Serial.print(sensorValue);
  Serial.print('\n');
  //double factor_division = 1023/5;
  //int Voltage = sensorValue/factor_division;
  //Serial.print(Voltage);
  if (sensorValue > 100 && sensorValue < 200) {
    analogWrite(3,70);
  }
  else if (sensorValue > 200) {
    analogWrite(3,70);
  }
  else
  {
    analogWrite(3,0);
  }
  delay(10);
```

Figure 12. Testing Code for Arduino Uno

```
void setup() {
  // Define Pins
  // Pressure Sensor 1
  pinMode(1,INPUT);
  // Pressure Sensor 2
  pinMode(2,INPUT);
    // Pressure Sensor 1
  pinMode(3,INPUT);
  // Pressure Sensor 2
  pinMode(10,INPUT);

  // Vibrotacile 1
  pinMode(11,OUTPUT);
  // Vibrotacile 2
  pinMode(12,OUTPUT);
  // Vibrotacile 3
  pinMode(13,OUTPUT);
  // Vibrotacile 4
  pinMode(21,OUTPUT);

  Serial.begin(115200);
}
```

```
void loop() {
  // put your main code here, to run repeatedly:

  // Read Pressure Sensor Data
  int sensorValue1 = analogRead(1);
  int sensorValue2 = analogRead(2);
  int sensorValue3 = analogRead(3);
  int sensorValue4 = analogRead(10);

  // Optional: Print Data
  Serial.print(Sensor 1: )
  Serial.print(sensorValue1);
  Serial.print('\n');
  Serial.print(Sensor 2: )
  Serial.print(sensorValue2);
  Serial.print('\n');
  Serial.print(Sensor 3: )
  Serial.print(sensorValue3);
  Serial.print('\n');
  Serial.print(Sensor 4: )
  Serial.print(sensorValue4);
  Serial.print('\n');

  // Cycles through each sensor and assigns vibrotacile output
  for(int x = 0; x < 4; x++) {
    if (x = 0){
      sensor = sensorValue1;
      output_pin = 11;
    }
    else if (x = 1){
      sensor = sensorValue2;
      output_pin = 12;
    }
    else if (x=2){
      sensor = sensorValue3;
      output_pin = 13;
    }
    else{
      sensor = sensorValue4;
      output_pin = 21;
```

```

    //Convert Analog bits to PWM output
    double factor_division = 1023/5;
    int outputValue = sensor/factor_division;

    //Low intensity (1.36V)
    if (sensor > 100 && sensor < 200) {
      analogWrite(output_pin, 70);
    }
    //Medium intensity (2.14V)
    else if (sensorValue > 100 && sensorValue < 200) {
      analogWrite(output_pin, 100);
    }
    //High intensity (2.93V)
    else if (sensorValue > 200) {
      analogWrite(output_pin, 150);
    }
    //Off Mode
    else
    {
      analogWrite(3,0);

    }
    delay(100);
  }
}
```

Figure 13. Second Revision of Testing Code

```
void loop() {
// Example: Assume analog input value (0-1023) representing PWM signal level
int pwmValue = analogRead(A0) / 4; // Scale 0-1023 to 0-255

// Update PWM duty cycle for each color LED
ledcWrite(0, pwmValue); // Green LED
ledcWrite(1, pwmValue); // Yellow LED
ledcWrite(2, pwmValue); // Red LED

// Update TFT display color based on PWM value
uint16_t color;
if (pwmValue < 85) {
  color = ILI9341_GREEN;
} else if (pwmValue < 170) {
  color = ILI9341_YELLOW;
} else {
  color = ILI9341_RED;
}
tft.fillRect(0, 0, tft.width(), tft.height(), color); // Fill screen with selected color

delay(100); // Delay for smoother display update, adjust as needed
}
```

Figure 14. LCD behavior code

Appendix F: Dimensions of Mechanical Design Components

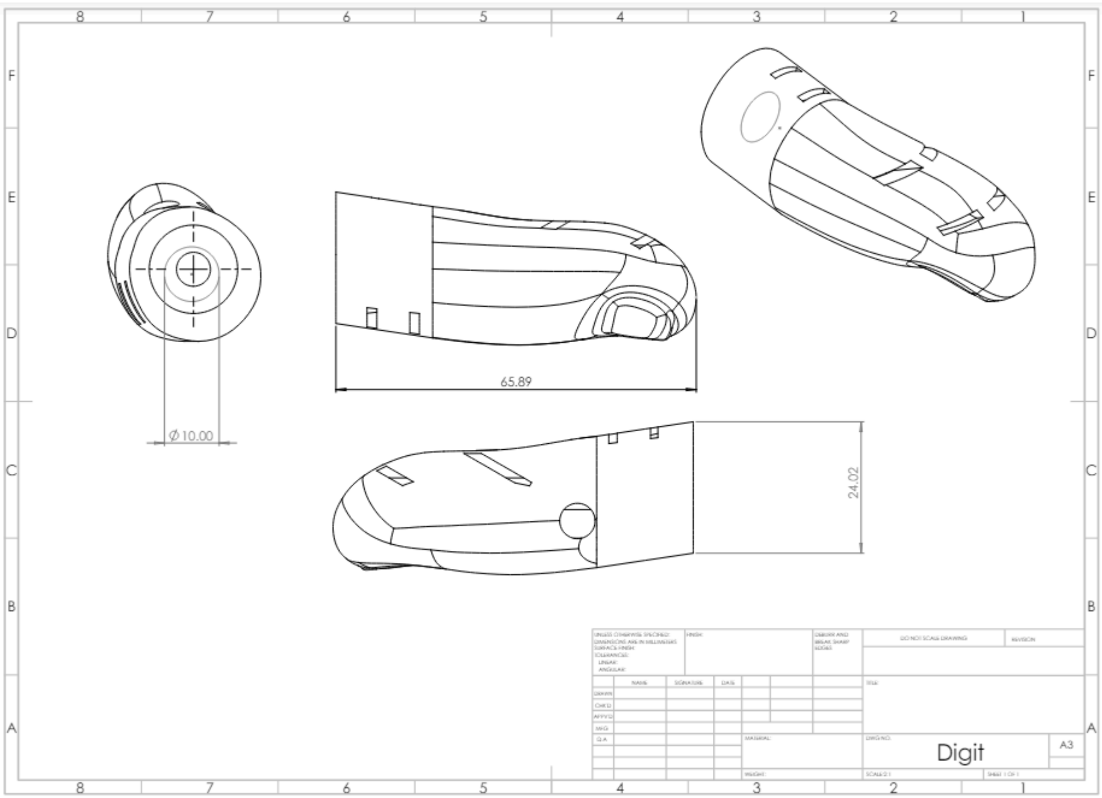


Figure 15. Engineering Drawings of Thumb tip Protrusion

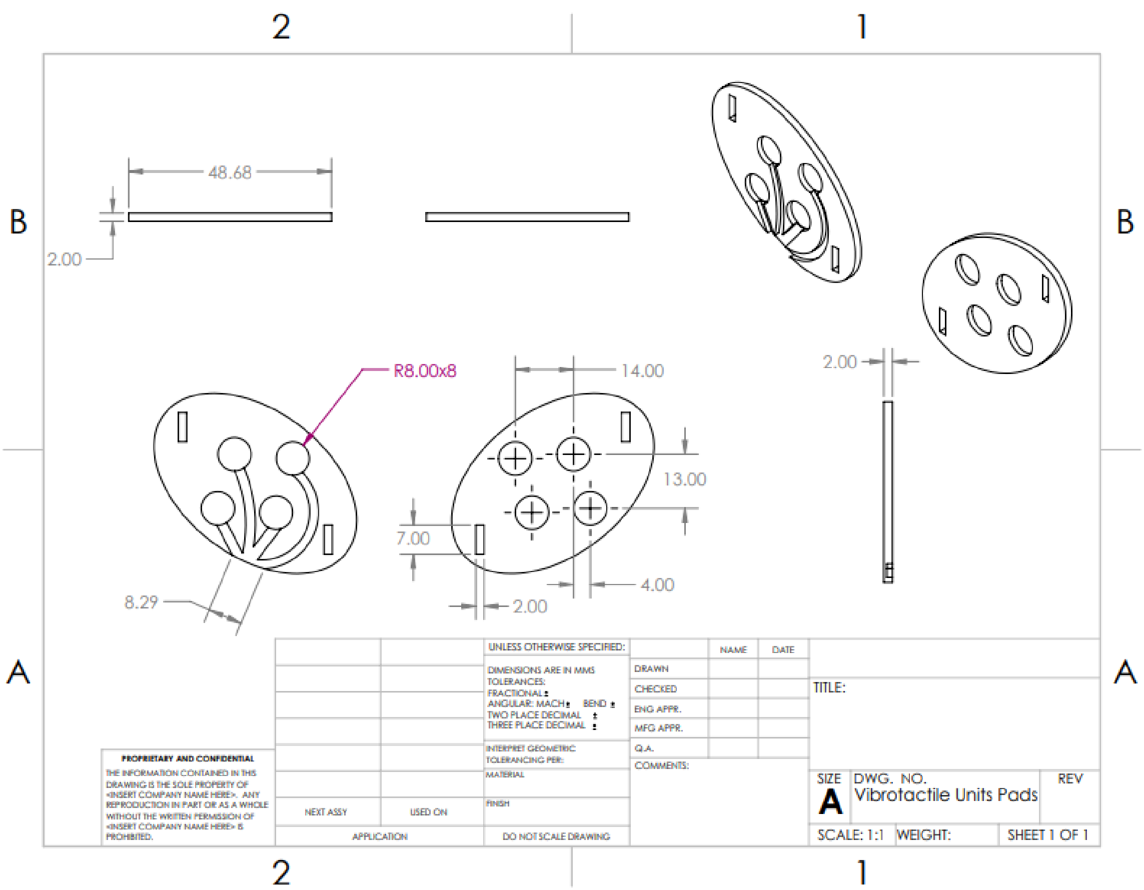


Figure 16. Engineering Drawing of Vibrotactile Units Pads

Appendix G - Table 5. Prototype Bill of Materials (BOM)

	Parts	Market Price (CAD)	Purchased Quantity	Quantity Required	Prototype Cost (CAD)
	Acrylic Sheet [18]	$10.95	5	1	$2.19
	Switch [19]	$1.00	1	1	$1.00
	Battery [20]	$11.56	1	1	$11.56
	PCB Board [21]	$16.59	15	1	$2.21
	Resistors [22]	$2.40	16	4	$0.60
	Wire [23]	$0.50	2 feet	1	$1.00
	Bottom Enclosure [24]	$25.99	1kg	0.015kg	$0.35
	Top Enclosure [24]	$25.99	1kg	0.015kg	$0.35
	Silicone to Seal [25]	$12.99	1	5%	$0.65
	ESP32 Board [26]	$23.98	1	1	$23.98
	Threaded Inserts [27]	$8.30	20	16	$13.28
Electrical	M2 Screws [28]	$22.42	100	16	$3.59
	Thumb Tip Protrusion (PLA Filament) [24]	$25.99	1kg	0.025kg	$0.65
	Wiring [29]	$5.00	7.62m	0.5m	$0.33
	Pressure Sensors [30]	$3.49	-	4	$13.96
	Silicone Socket [31]	$28.70	0.58kg	0.015kg	$0.74
	Velcro Belt [32]	$8.47	1.5m	0.25m	$1.41
	Vibrotactile Pads [33]	$26.99	1kg	0.0078kg	$0.21
Mechanical	Vibrotactile Units [34]	$7.00	4	4	$7.00
TOTAL					**$85.07**

Appendix H: Applied Pressure Calibration and Testing Setup

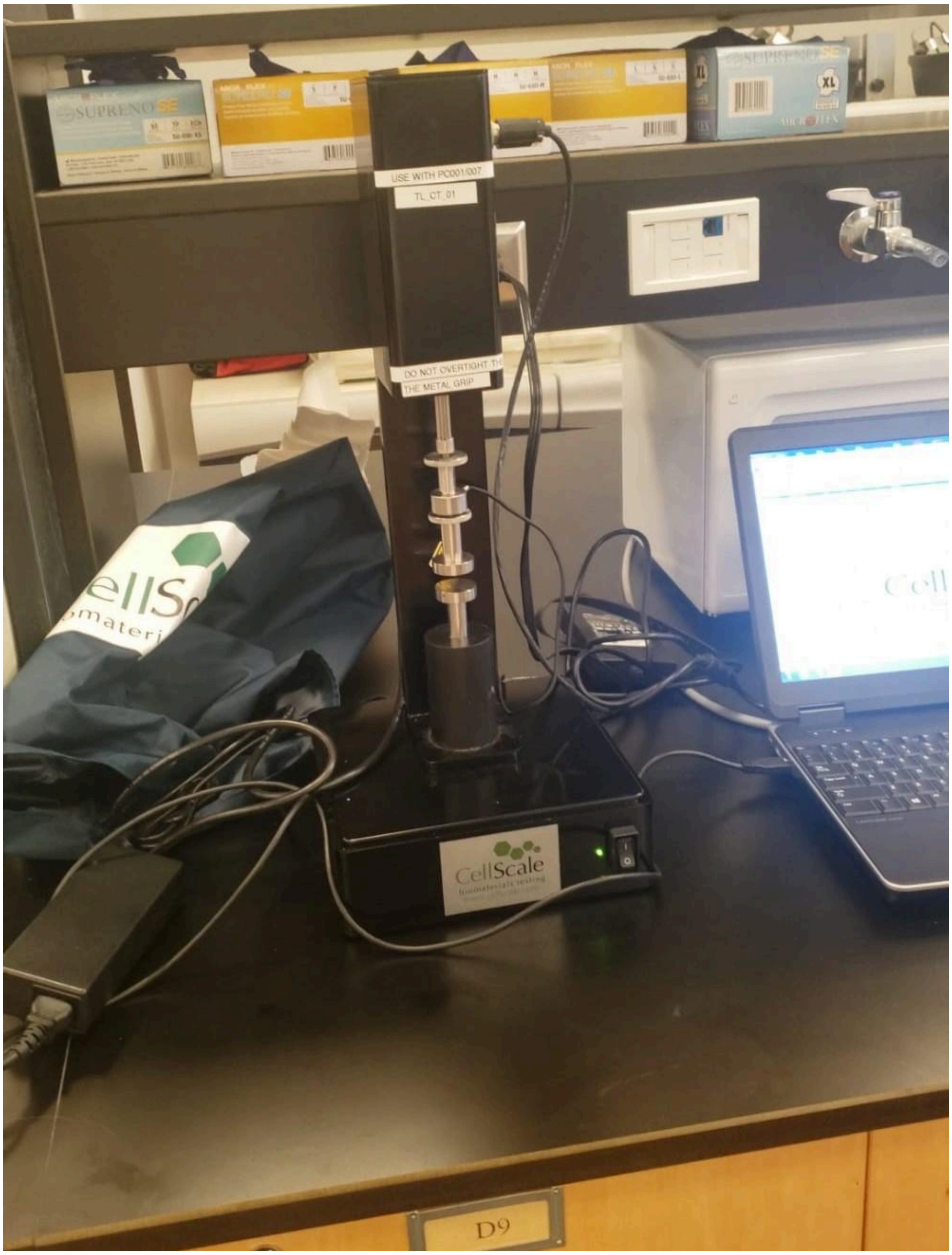


Figure 17. Testing Setup

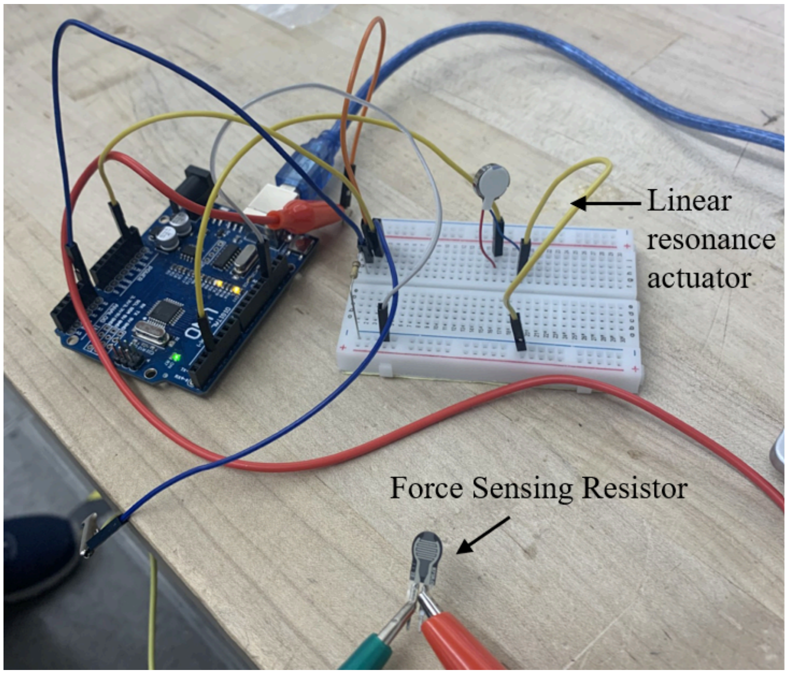


Figure 18. Experimental Set-up for script testing

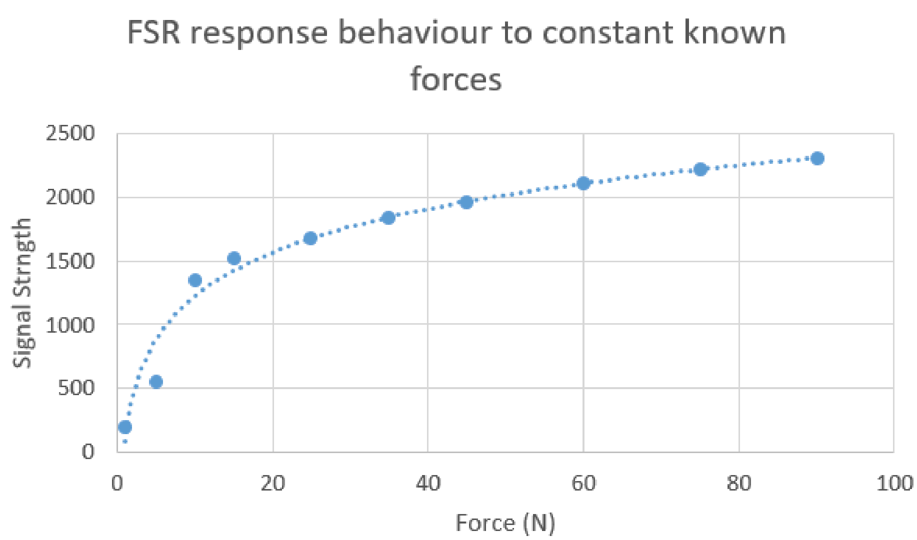


Figure 19. FSR response graph