Improving Range of Motion of Symbrachydactyly through Finger Exoskeletons with Vibrotactile Feedback

Alex Orr, Elianna Peng, and Yuqing Wang
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Abstract

Symbrachydactyly is a shortened or misshapen finger condition that causes both physical and social limitations. Many prosthetic and surgical solutions for this condition are invasive and expensive. Our design is cheap, easily customizable, non-invasive, and gives users an extra phalanx. In an interview with an individual with Symbrachydactyly, we learned about the difficulties of typing, grasping jars, and operating game controllers. Using these insights, we hypothesize that a finger exoskeleton structure with vibrotactile feedback can improve the range of motion and dexterity of the hand. A functional prototype of this "exoskeleton grasper" was created incorporating a force sensing resistor (FSR) and vibrating motor to provide dynamic haptic feedback dependent on the forces exerted on the extra phalanx. To determine the effectiveness of this device, we will study participants with Symbrachydactyly as they use this device to type on keyboards and grasp jars, measuring typing speed and accuracy as well as self-reported comfort levels. If the hypothesis proves true, this study can instigate the development of assistive technology incorporating haptic feedback and the adoption of these devices in both the medical and cosplay industries.

I. Introduction

Symbrachydactyly is a congenital condition affecting 1 in 32,000 newborns worldwide; children with the condition are born with fingers that are shortened, misshapen, webbed, or missing [1]. This condition usually only affects one hand, impacting it's entire bone structure. Symbrachydactyly can also cause significant social, physical, and emotional stress to those affected and may deter them from performing normative tasks. Currently, there is no known cause for the condition and most early treatment options are surgical, which are extremely invasive and range broadly in their success [2]. Fortunately, non-invasive and external options exist: prosthetic extensions that extend the fingers' reach and improve finger grasping. Having lengthened fingers will allow those with Symbrachydactyly to regain significant normative control in their daily activities. This report will explore the effects of a finger exoskeleton prototype on improving the range of motion, comfort, and dexterity for those with Symbrachydactyly.

A. Background

Due to the severity of the congenital symbrachydactyly condition, the development and use of prosthetics to extend the reach of fingers requires our attention. Plastic and 3D printing presents the most accessible and low-cost method for the fabrication of these devices, offering increased control in the human-object interactions through prosthetic sockets and joint enabled full hand prosthetics [3] [4]. These studies have explored specifics of the hand model itself, testing for differing hand cover thickness and viability. However, user testing was extremely limited, and it provides limited attempts toward increasing the patient's range of motion. In addition, there have also been research efforts to restore arm and chest muscle strength and force exertion in patients with Poland syndrome via arm exoskeletons [5] [6], yet dexterity remains our main focus.

Parallel to research, the most notable commercial products are the line of PIP and MCP Drivers created by Naked Prosthetics, addressing finger amputations from the middle and proximal phalanges. The body-powered devices utilize a series of linkages and materials that allow users to gain a normative range of motion. However, customizability comes at a high cost, is closed source and has a long lead time, all of which decreases accessibility.

One field where the above devices require improvement is tactile feedback. In the field of myoelectric prosthetic devices, vibrotactile feedback is a popular proposal, where contact between the prosthetic and objects is translated to the user through a vibration motor. Nabeel (2016) used a body-powered full hand prosthetic with a force-sensing resistor (FSR) to couple the vibration with pressure applied by the prosthetic finger. It demonstrated effectiveness in increasing ability to grasp objects of varying weights for normative and amputee subjects [7]. Pena (2019) further contributed to the building of our hypothesis by demonstrating that the vibrotactile feedback improved grasp force in a myoelectric prosthetic [8].

As such, both body powered finger extension devices and vibrotactile feedback used in prostheses exist and are well documented, however, there is much room for growth in developing a device that combines both methods for the short-fingered symbrachydactyly condition. In this project, we attempt to create a parallel version of the exoskeleton linkage system with additional haptic feedback to fill this gap in the field.

B. Overview

There are two main hypotheses we aim to explore in this report. First, is that a 4-bar linkage based on the natural movement of the human finger is just as effective if not more effective than invasive solutions such as distraction lengthening. Additionally, we believe that the addition of a vibrotactile feedback system within the device will minimize unnecessary forces, and therefore energy applied by the user when grasping objects. Section II assesses the needs of our subject through an interview conducted in the early stages of this project. Section III provides a framework for evaluating the device in regard to our hypotheses. Section IV summarizes our findings and hopes for future research in this area. Finally, section V gives an overview of the potential impacts made by our device and plans for mass implementation.

II. Preliminary results

Our interviewee is a 20-year-old adult male student with short-fingered symbrachydactyly and mild Poland syndrome, who had previously undergone a web deepening operation to increase finger dexterity. We were able to conduct an in-person interview with the interviewee and make observations as he demonstrated various dexterous and strength-based motions with various household objects. He also allowed us to examine and make measurements of his non-normative hand, as well as create a resin casting for fitting purposes. We obtained consent for a video recording and took manual notes on specific concerns and needs the interviewee stressed during the interview. Within the 2 hours of conversation, we summarized three pairs of key quotes and interpreted needs which can be seen in the table below.

Customer Statement	Customer Needs
"My right arm gets tired when I type because I have to hold it over the keyboard in order to type."	improved dexterity of dominant hand to reduce typing errors
"I can't grasp the entire jar with my right hand so I have to use my left [normative] hand."	Increased reach range for fingers
"My fingers can't reach all the buttons on my game controller."	Increase range of motion of fingers and allow for better fit in the hand

Our reasoning for the choices is as follows:

1. He is an avid gamer and keyboard user, which makes typing an essential skill to be able to perform consistently. Demonstrating the action, he pointed out that his wrist needed to hover in space instead of rest on the table to make up for the non-normative finger length— which introduces instability and typos.

2. He performs a large variety of chores around the house, including cooking, which involves opening and closing jars of different sizes. This presents a difficulty if the lid is too wide in diameter, and he

expressed annoyance at the workarounds he's developed (holding jar against the chest for friction, asking roommates for help, etc.)

3. As a typical phone user, often on the go, our need-knower described always having to type with two hands due to the non-normative finger range when stabilizing the phone. It is the third common issue upon which he expressed great annoyance at the situation and measures.

Given these primary needs, we set our main focus to be: increasing the dexterity as well as range of motion for the need-knower's right hand. Through ideation and brainstorming, we weighed potential solutions on those two criteria, as well as viability, novelty, and user-friendliness. As previously stated, we arrived at linkage-based exoskeleton grasper and hypothesized that incorporating vibrotactile haptic feedback will increase hand performance. It bears the closest connection with the course, and simultaneously, our market research covered in section I-A indicates that it presents the greatest field for improvement.

III. Methods

The aim of this device is to improve the subject's dexterity and grip by providing a distal interphalangeal (DIP) joint for each non-normative finger. To achieve this, a four-bar linkage based on the natural curling motion of the finger was designed where the subject's middle phalanx and proximal interphalangeal (PIP) joint acts as the driver for that respective finger. The coupler of the linkage is located past the subject's native fingertip and acts as the distal phalange and DIP joint. The device itself is secured to the subject's fingers via Velcro straps. Additionally, foam has been stuffed in the fingertip and plasti-dipped to add friction to the fingertip for gripping. Furthermore, we added a force sensor to the fingertip which measures the force via volts where the corresponding voltage triggers a vibrational motor located on the subject if the voltage is above the threshold. This was done to provide the user with haptic feedback when touching or grabbing objects. Finally, we want this device to be accessible to anyone and our chosen materials reflect this with each finger costing less than $20. We also aim to make the drawings and code open source so that anyone can download, modify, print, and assemble the device themselves. There are multiple ways that our goals with the device can be confirmed or disproved by our subject and our goal is to gather as much qualitative and quantitative feedback as possible to make a reasonable assessment.

First, we would like to be present for the subject's initial fitting and impressions of the device. Further, we would plan to follow up with the subject one or two weeks after the initial fitting to garner feedback on comfort and usability. Depending on this feedback we would make small changes to the device and present the new version to them as soon as possible. We would then plan to be in correspondence with the subject once a month unless there are any issues. In this case, we would encourage them to contact us immediately. The main qualitative feedback that we are hoping to gain in these interviews is the user's impressions on comfort, usability, appearance, and overall satisfaction of the device. Quantitatively, we aim to assess the range of motion, grip strength, and haptic feedback performance. For range of motion, we would assess the subject's range of motion with and without the device. Specifically, we would compare the positions of the natural and prosthetic fingertips when the middle phalanx is inline, diagonal, and perpendicular to the proximal phalanx in accordance with Fig.1 below.

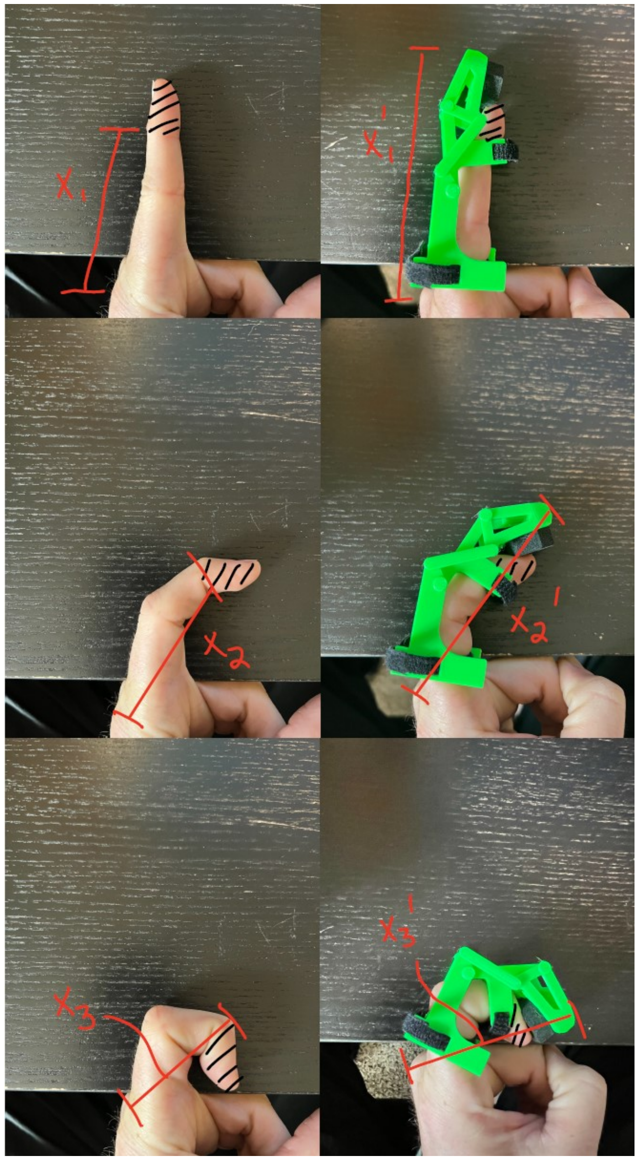

Fig. 1: Range of motion test. Note that subject is missing distal phalange.

We would also compare the range of motion of the user wearing the device to that of the respective normative finger on the user's opposite hand. We plan to evaluate the grip strength in two ways. First, we would measure the user's grip strength with a hand dynamometer with and without the device and compare the two. Next, we would have the user open a large container that they would normally have difficulty with due to their shortened digits. During this, we would observe and ask about their difficulty in opening the large container while wearing the device. Also, we plan to time them opening the large container with and without the device. It should be noted that this would be done after the user has gotten familiar with the device so that any potential time lost due to a learning curve is eliminated. In order to the assess haptic feedback system, we would attach force sensors to an object and have the user grab the object with the haptic feedback disabled and record the reading from the force sensors on the object. Then, we would enable the haptic feedback system and have the user grasp the same object. Finally, we would compare the force readings with and without haptic feedback and see if there is any difference. If the force reading on the object is less when haptic feedback is enabled, then it will be assumed that the haptic feedback assists in the overall performance of the device. It should be noted that there will be no actual testing on human subjects for this device.

IV. Intellectual Merit

Through our study and assistive technology device, we propose a strong myoelectric linkage prototype to improve dexterity of those with Symbrachydactyly. While there is room for improvement of this design, this study is able to validate the use of extensions and haptic feedback as an important tool and demonstrates the need for mechatronics in prostheses. To verify that the device addresses all needs of those with Symbrachydactyly, further research is needed. The usage, comfort, and feasibility of this design in various situations must be tested.

In the meantime, this work may motivate the use of vibrotactile feedback in combination with mechanical linkages in assistive devices made by companies, as well as research laboratories where force exerted by the robotic end effector is critical information to know.

V. Broader Impact

This study demonstrates the broad potential for an assistive medical device that can significantly impact those with Symbrachydactyly, and it's functionality is not limited to that condition alone. The design is adaptable to many who lack the distal phalanx, either through amputation or distal phalangeal nerve damage. Those with normative fingers can also adopt this product for costume design and novelty which can destigmatize the social implications of shortened fingers.

Our goal to publish the design on an open source platform enables the CAD model to be easily replicated and improved by the maker community. The code and electronic specifications would also be published to the community for further customization and cost reduction. To conclude, the assimilation of this product into the public can have significant impacts research and industrial efforts to re-enable control for those with non-normative hand structures.

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Appendix A
Discovery Decomposition

Topic of the interview: everyday manual activities with hemiparetic stoke.

1) Symbrachydactyly: [1].

- Background/Hypothesis: Symbrachydactyly is a congenital condition where there is a failure of formation of fingers.
- Methods: It occurs in 0.6/10,000 live births and usually isolated.
- Results: The cause is unknown but thought to occur during fetal development and arises through disruption of apical ectodermal ridge.
- Conclusion: It is characterized by short finger type, cleft hand type, monodactyly type, and peromelic type.
- Test Hypothesis: Some surgical treatment includes nonvascularized free toe phalanx transfers which is where toes are transplanted into the fingers. Another option is distraction lengthening involving bone grafting.

2) Nonvascularized toe phalangeal transfer and distraction lengthening for symbrachydactyly: [9].

- Background/Hypothesis: With Symbrachydactyly, surgeons have tried performing nonvascularized toe phalanx to hand transplants with distraction lengthening in order to restore function length. The goal is to improve length and enhance mechanical advantage and prehension.
- Methods: Incisions are made in the dorsal foot and dissection is carried to the extensor tension. The proximal phalanx is removed and the periosteum is preserved. The toe phalanx is placed into the tissue bed and secured and closed.
- Results: In one case a 6-month-old boy underwent this procedure and was able to begin the lengthening process.
- Conclusion: This procedure has proved successful especially when the patients are younger than 1.5 years. There are many complications including infection, the preservation of the periosteum, etc.
- Test Hypothesis: Will this be possible to complete for 0.8 of patients under 1.5 years?

3) Design and Analysis of 3D Printed Prosthetic Hand for Symbrachydactyly Patients: [4].

- Background/Hypothesis: Symbrachydactyly is not a common condition and due to its non-life-threatening position, few solutions are available to aid in patients' daily life. This group proposed to create a prosthetic hand that did not use any electrical components.
- Methods: The group started with designing the prosthetic with scans and then shifted to computational analysis with FEA to discover which parts to cover and the thickness. Then, came the fabrication which utilized a 3D printer.
- Results: A prosthetic was successfully created with varying thicknesses and palm covers.
- Conclusion: The objective was achieved and the best thickness for the palm cover was found to be 5mm with a safety factor of 7.2.
- Test Hypothesis: Create the same prosthesis but change the materials and look into the back of the hand and grips.

4) Three-dimensional printing of prosthetic hands for children: [10].

- Background/Hypothesis: Children with prostheses need a durable, inexpensive, versatile product that can adapt to their activities. This group looked into multiple 3D printers and 3D prostheses to create the optimal product.
- Methods: The majority of the product was 3D printed, but elastic cords, nylon line, screws, and Velcro were also required. Fingers were assembled first and then joints, palm and gauntlet.

- Results: The group was able to create a successful prosthesis but noticed that the first layer of a 3D print was most important and underextrusion was a common problem.
- Conclusion: While 3D printing is a cost efficient way to create prostheses there are many variables that can lead to the failure of the product.
- Test Hypothesis: The prostheses should be made using resin instead of traditional 3D printed. This method has smaller margins for failure and error.

5) A custom bicycle handlebar adaptation for children with below elbow amputations: [3].

- Background/Hypothesis: Children with upper limb physical disabilities face many challenges one of which is riding a bicycle. This is due to their decreased balance and arm differences.
- Methods: This group created a custom handlebar made from thermoplastic material, hose clamps, and padding. Each product is custom made for the child and fitted to their specific measurements.
- Results: One such patient was a 2 year old female child with symbrachydactyly and an absence of the right hand at the wrist level. With this prosthesis, she was able to steer the tricycle and maintain her balance riding as well as getting on and off.
- Conclusion: This simple, inexpensive solution will allow children with hand disabilities to develop their motor skills and interact with other children.
- Test Hypothesis: This device can work for many different people despite the differences in arm disability.

6) Symbrachydactyly — Diagnosis, Function, and Treatment: [11].

- Background/Hypothesis: Symbrachydactyly exists at birth, comes in many forms and can easily be misdiagnosed. It is classified by the number of affected digits, morphological characteristics, and overall function. Treatment is patient specific given the many different forms.
- Methods: Symbrachydactyly is divided into four categories: Short-finger, Oligodactylic, Monodactylic, and Peromelic. Our subject is short-finger type with Poland's. Function and appearance are two main priorities for treatment. Surgery is typically delayed unless functionality is severely affected.
- Results: For those with Short-finger, grip is stronger than other types, but may lack stability. Surgical options for short-finger included digit lengthening, web deepening, and arthrodesis.
- Conclusion: The levels of satisfaction among patients after surgical treatment varied quite a bit and was based on appearance, function, and psychological well-being.
- Test Hypothesis: Many SURGICAL treatments exist for patients with symbrachydatyly and are usually performed within 1 year of birth. Treatment should be based on patient's needs and desired function.

7) Clinical features and roentgenograms of symbrachydactyly: [12].

- Background/Hypothesis: In English literature, Short-webbed-finger (symbrachydactyly), atypical cleft hand, and transverse deficiency are different anomalies. German literature suggests that all three should be called symbrachydactyly as they are believed to be caused by the same underlying conditions.
- Methods: 76 cases of symbrachydactyly were examined and classified into four grades: short-finger (1), atypical cleft (2),monodactyly (3),and peromelia (4).1 was further classified into 3 types based on the number of missing phalanges. Common features, number of missing/hypoplastic phalanges/metacarpals, sex, affected side, and associated anomalies were recorded.
- Results: Each grade had varying levels of severity. The number of missing/hypolastic phalanges was greatest in central fingers. For 1, most cases were males' right hands. Pectoral muscle absence was significantly higher in 1.
- Conclusion: All cases of symbrachydactyly were unilateral. Grades 2,3 and 4 can be difficult to distinguish from other syndromes. Main distinguishing factor is existence of hypoplasia.

- Test Hypothesis: It's more suitable to describe the categorize the anomalies by transverse deficiency. 1-3 seem reasonably described but grade 4 needs further classification.

8) Functional assessment of children and adolescents with symbrachydactyly: a unilateral hand malformation: [13].

- Background/Hypothesis: Participants with symbrachydactyly were studied to see if their hand function depended on the number of opposable digits, and how their functionality and quality-of-life compared to the normal population.
- Methods: Participants were split into two groups. A had 0-1 opposable digits and B had $\geq$2 but $\leq$4. Pinch strength, bimanual performance, in-hand manipulation, daily activity difficulty, and psychological wellbeing were compared among the two groups and the norm.
- Results: B performed higher in pinch, bimanual, and in-hand manipulation than A. Both reported same level of difficulty for daily activities and tested normal for psychological wellbeing.
- Conclusion: Those with $\geq$2 opposable digits are able to use their affected hand better than those without. All participants showed a high level of function and mental wellbeing relative to the norm.
- Test Hypothesis: The number of opposable digits can affect hand function to a certain degree.However, it is not entirely clear given that both groups report same amount of difficulty in everyday activities.

9) Five-and 10-year follow-up of nonvascularized toe phalanx transfers: [2].

- Background/Hypothesis: Patients who underwent toe phalanx transfers were evaluated 5 and 10 years after their initial surgery
- Methods: 47 and 27 transfers were evaluated at the 5 and 10 year mark respectively. 10 children were lost before the 10-year mark. Growth rates of the transferred toes were calculated based on the non-transferred on the opposite foot. Motion and stability of the affected hand was also evaluated.
- Results: The average growth rate was 0.5mm/yr. Motion and Stability were rated good in 51% and 79% respectively.
- Conclusion: On average, the transferred toe phalanx on the hand grew 5.2mm. Having phalangeal remnants played a crucial role in stability and motion.
- Test Hypothesis: Nonvascularized toe phalanx transfer to lengthen digits can provide satisfactory function to one's hand depending on the individual's needs. However, this may not be the case if the user relies heavily on dexterous manipulation in their everyday life.

10) Digital lengthening in congenital hand deformities: [14].

- Background/Hypothesis: 3 methods of digital lengthening were used among 12 patients.The gained length,pinch,and aesthetics were then observed after a given length of time.
- Methods: on-top plasty,bone graft, and distraction lengthening were the three methods used for digital lengthening.
- Results: After surgery pinch improved in 7/8 of patients. Distraction method resulted in largest growth.
- Conclusion: The lengthening method depends on the amount of additional length needed to achieve a good pinch. Distraction lengthening was used for cosmetic appearance since it results in the largest growth.
- Test Hypothesis: Distraction lengthening is a viable option for patients struggling psychologically with their appearance. The other two are viable for patients struggling with function.

11) Vibrotactile stimulation for 3D printed prosthetic hand: [7].

- Background/Hypothesis: Active haptic feedback, or lack thereof in the prosthetic field, is critical to making device usage more effective. There is a need for the exteroceptive (exvironmental pressure) or proprioceptive (proper state of joing angles) to be experienced through direct sensory feedback.

- Methods: By generating vibrodactile feedback on the residual arm of the patient, via the prosthesis, to provide them with a cognitive response when interacting with objects. It was tested on 5 healthy participants and 1 patient amputee.
- Results: Coin shaped vibration motors, 0.5 inch circular diameter FSR provide haptic feedback from the prosthetic fingertips. 3D printing the majority of the parts in the prosthetic hand was chosen for it's cost efficiency.
- Conclusion: Subjects were capable of distinguishing the amount of force applied. Healthy subjects were also able to determine the objects themselves with some amount of practice, with great improvements in terms of device use over time.
- Test Hypothesis: Similar models of haptic sensing may be applied for force sensing, and feedback provided to the user through vibration on some sensitive skin surface.

12) Chapter 2.3.4 Poland syndrome: [15].

- Background/Hypothesis: A detailed overview of Poland syndrome, it's relation to symbrachdaktyly and the characteristic absence of the left pectoralis major (PM) muscle. Poland's syndrome as a whole is a unilateral congenital deformity that affects males and females at a quoted ratio of 3:1.
- Methods: The condition is diagnosed by the "partial absence, sternocostal head or complete absence, both the sternocostal and clavicular heads, of PM muscle and the associated breast deformities."
- Results/Conclusion: There is high levels of complexity involved in diagnosing and providing theraputic options for Poland syndrome deformities, and further study is required.
- Test Hypothesis: When appearing in conjunction with symbrachydactyly (short fingered), the PM muscle deficiency is the larger issue that bars daily function.

13) Intuitive Human Robot Interfaces for Upper Limb Prosthetics: [16].

- Background/Hypothesis: Modern robotic devices are overly complex and offer more degrees of freedom than can be reliably controlled by the user using EMG signals. By reframing the prosthetic control problem as a human robot interface problem will provide additional tools to eliminate or complement EMG signals.
- Methods: 20 human subjects performed 2 major experiments involving firstly 3 healthy-limb based options (teleoperating, gesture glove, fingernail worn devices) and secondly the combination of EMG with force myography.
- Conclusion: "1) Healthy limb based prosthetic device control can match the performance speed of EMG based control with very little training 2) Gesture based control of the healthy limb is faster than mirrored teleoperation except in the case of tasks which are mirrored by their nature 3) Bilateral hand movements combined with kinematic tracking of the healthy limb can be utilized to train a Force Myography (FMG) based classifier as well as an EMG based classifier, and that the combination of the two modalities hold promise to make a readily deployable multi-DOF EMG/FMG classifier system a reality."
- Test Hypothesis: Gesture based control operated by the healthy limb could be applicable for arm manipulation to supplement missing muscle mass.

14) When Less Is More – Discrete Tactile Feedback Dominates Continuous Audio Biofeedback in the Integrated Percept While Controlling a Myoelectric Prosthetic Hand: [17].

- Background/Hypothesis:
- Methods:
- Conclusion:
- Test Hypothesis:

15) Effects of vibrotactile feedback and grasp interface compliance on perception and control of a sensorized myoelectric hand: [8].

- Background/Hypothesis: Uses two vibrotactile sensory substitution (VSS) configurations to provide non-invasive sensory feedback in myolectric prosthetic hand
- Methods: Conducted a ”direct comparative assessment of these two VSS configurations...Six subjects completed a sensory perception experiment under a stimulation only paradigm; sixteen subjects completed experiments to compare VSS performance on perception and graded myoelectric control during grasp force and hand aperture tasks; and ten subjects completed experiments to investigate the effect of mechanical compliance of the myoelectric hand on the ability to control grasp force.”
- Conclusion: No significant difference between the two VSS configurations without active myolectric control, but with it, the coin tactor array was better than the single actuator, and grasp force inproved.
- Test Hypothesis: Supports the idea that the incorporation of vibrotactile feedback through various models would be helpful in controlling grasp force in a fully prosthetic myoelectric hand, we hypothesize that it could be a similar case for our finger extensions.

16) Preliminary Tests of the Active/Passive EXoskleton (APEX):* [5].

- Background/Hypothesis: Musculoskeletal conditions can be supplemented with devices available to perform active assistance methods (DC motors) or passive methods(springs), with a give and take between user capability and the use of powering system.
- Methods: A pneumadic system is constructed for a combination of the two states, with continuous passive assistance, and only requires power when ”changing the dynamic properties of the passive state.” The first prototype was tested on 6 healthy subjects as they performed hammer curls.
- Results: Changes in passive state of the system (pressure changes) affect the amount of curls performed by subjects, and one change resulted in a 65-92 percent improvement in performance
- Conclusion: There is potential for similarly designed devices to provide lightweight and energy efficient active/passive actuators.
- Test Hypothesis: A similar system designed around a specific task can reduce the amount of heavy duty electronics necessary to actuate movements that require a significant amount of force, e.g. lifting heavy items or doing a push-up.

17) Design of a Passive, Variable Stiffness Exoskeleton for Triceps Deficiency Mitigation: [6].

- Background/Hypothesis: Neurological impairments or spinal injuries sometimes require supplemental tricep strength to make up for arm functionality, especially performing activities that require large amounts of force to be handled by the limb, e.g. sit-skiing. Exoskeleton development is in the research stage, and no commercial options are yet available. Most designs rely on electrical motors that increase the bulk and weight, and passive options are incapable of handling the amount of force required.
- Methods: Using a passively actuated exoskeletal arm brace, this paper creates a mechanical elbow, functioning at two adjustable strength modes: low gravity compensation for an active range of motion and the second for more ’stringent weight bearing activities’
- Results: Through testing, the prototype demonstrates high strength band at a preloads of 0.86Nm and 4.6Nm, with five preloading conditions demonstrating distinct performance bands.
- Conclusion: The mechanism proves to be affordable, lightweight and modular that is customizable according to the users needs, and most importantly, sufficiently performs the tasks that conventional designs cannot.
- Test Hypothesis: This appears to be a viable,slim, mechanical option for those looking to increase their current arm/elbow strength and stamina.

Appendix B
Investigational Device Details

A. *Development of Exoskeleton Linkage*

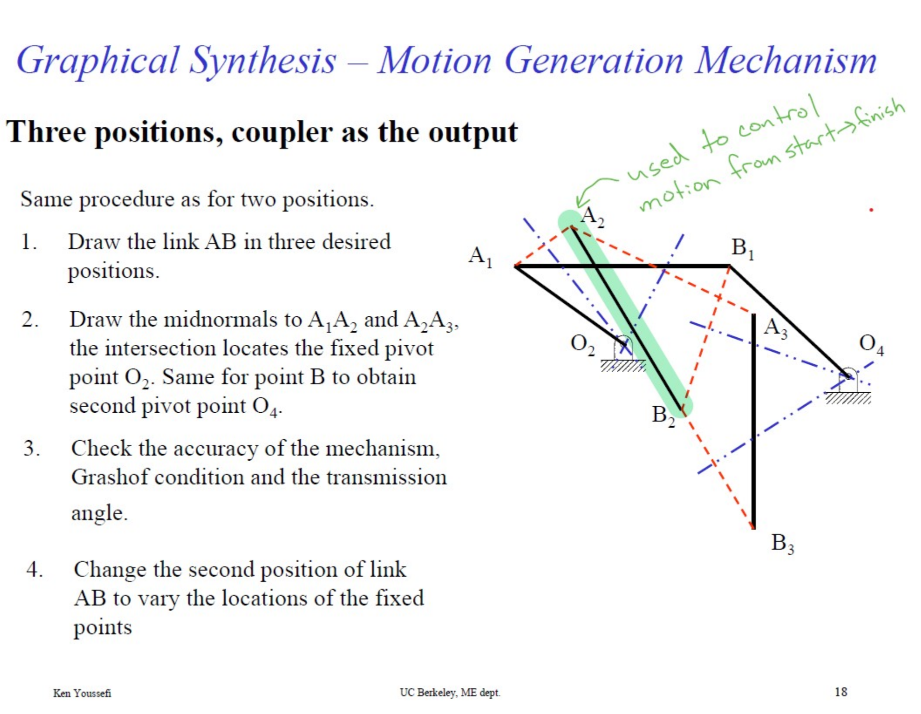


Fig. 2: Notes from ME130 ”Design of Planar Machinery” used to design linkage.

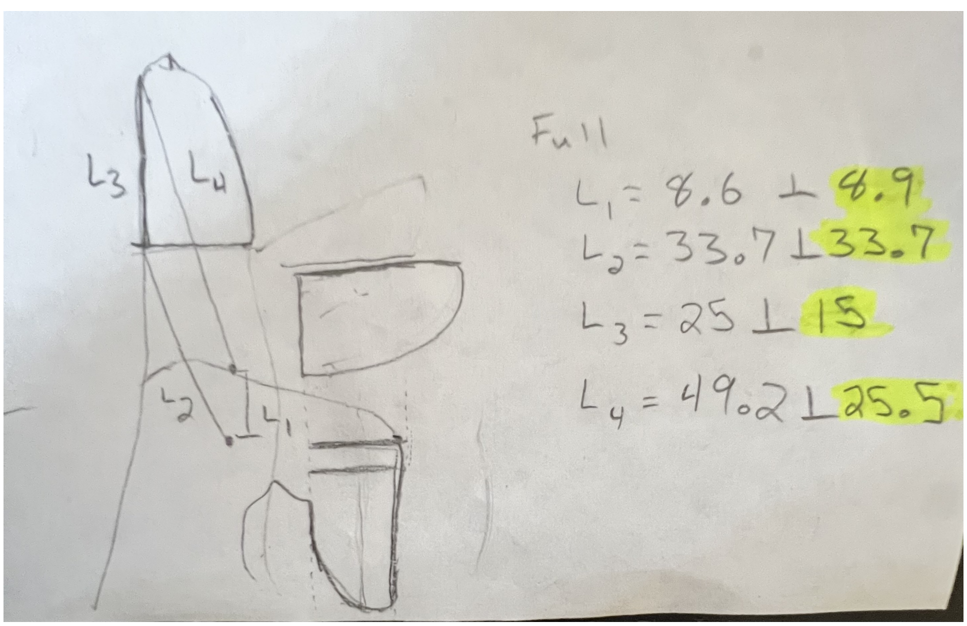


Fig. 3: Trace of finger used to determine the 3 positions of the coupler.

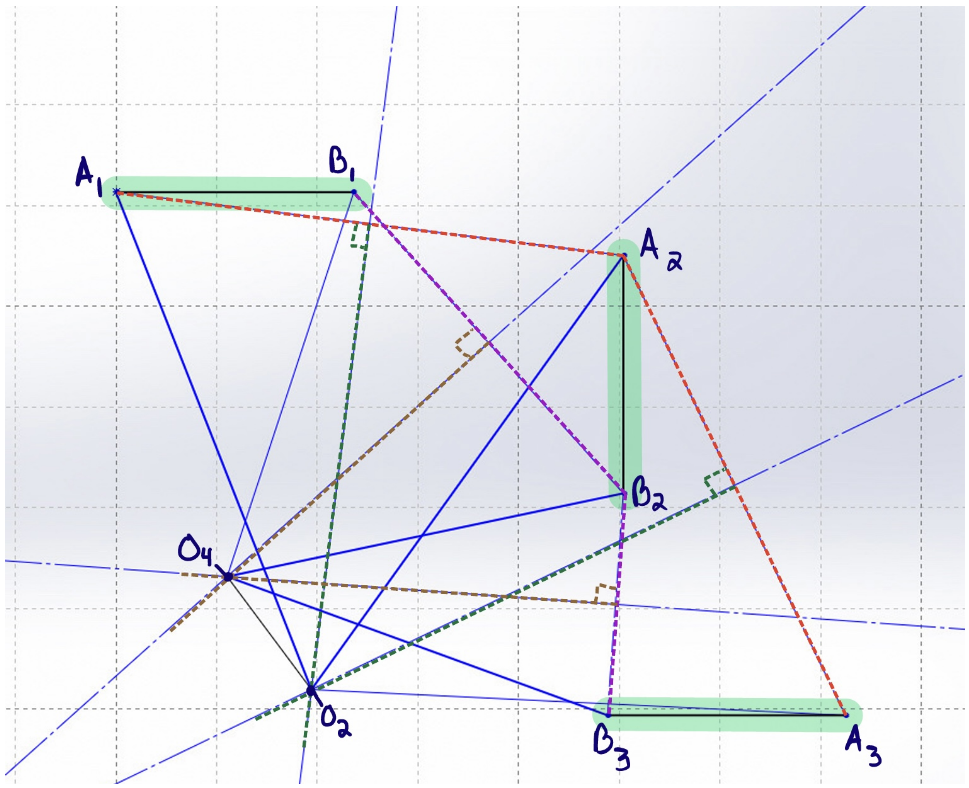


Fig. 4: Resulting design from ME130 Notes.

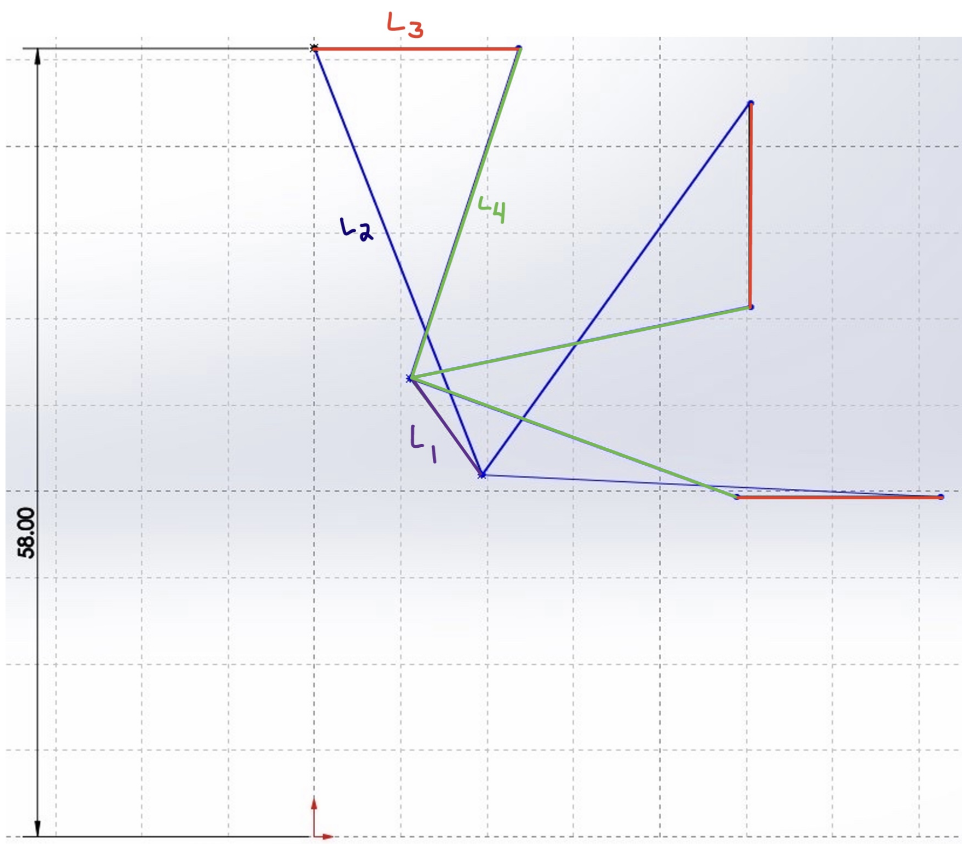


Fig. 5: Linkage design in the 3 designated positions

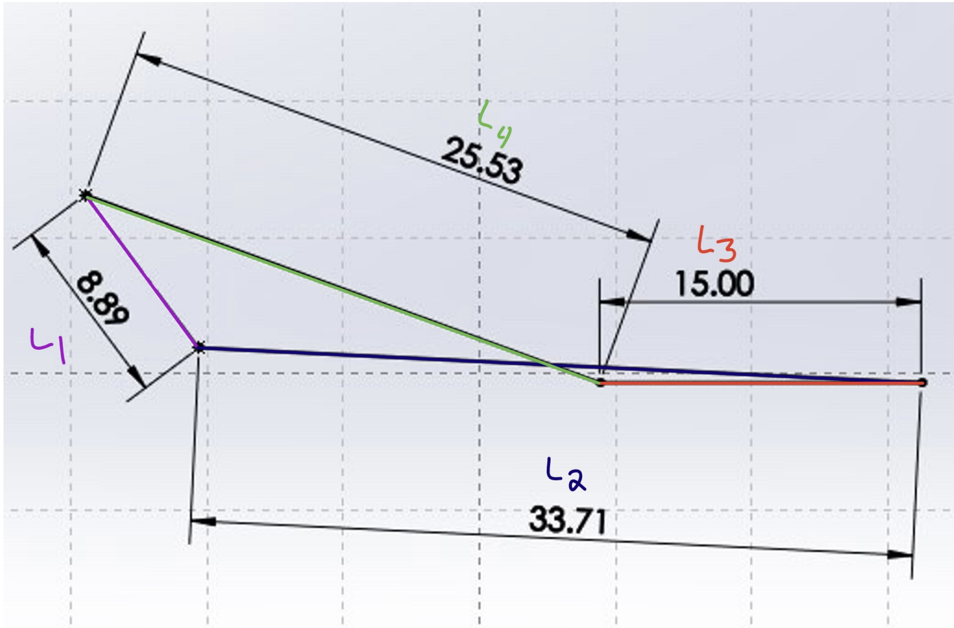


Fig. 6: Measurements of each link.

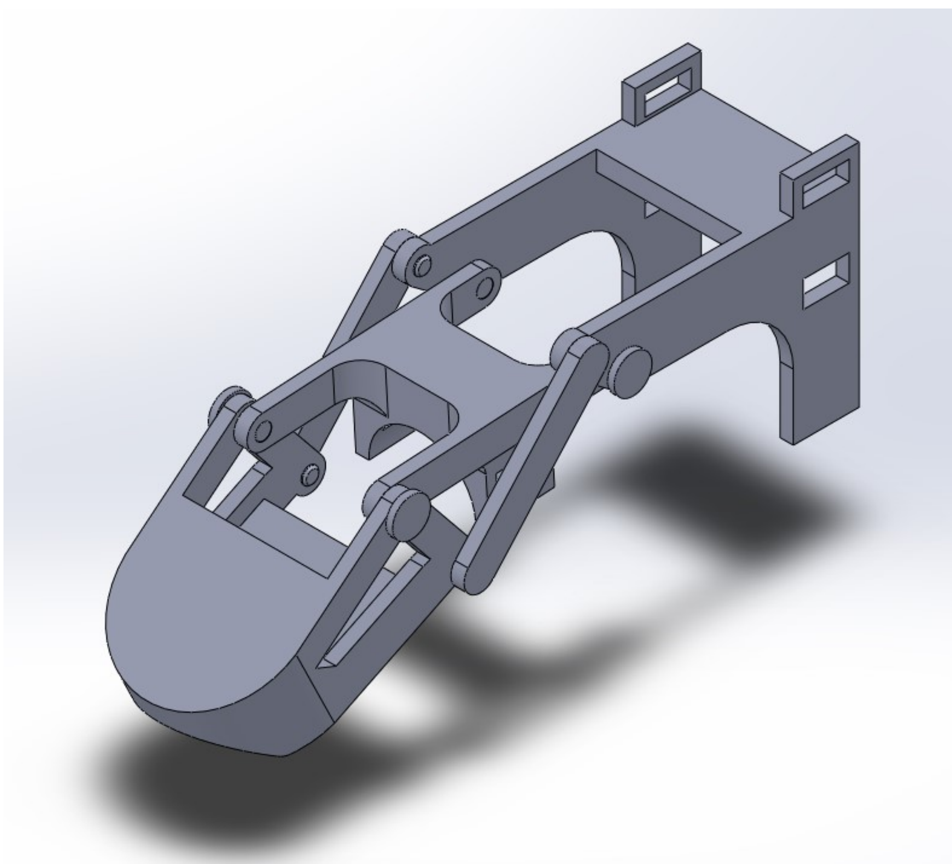
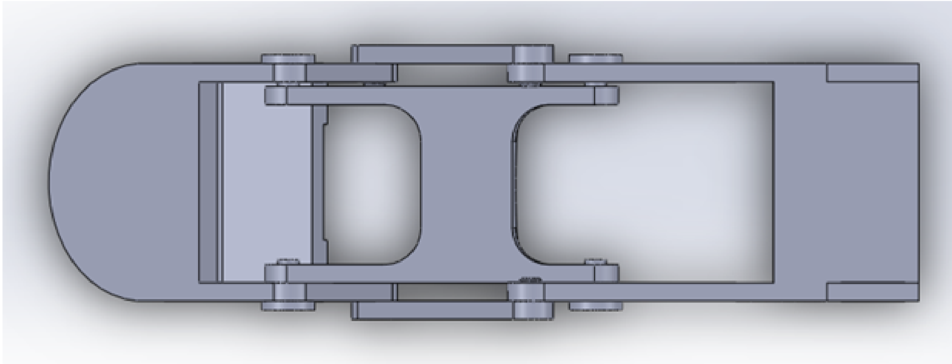
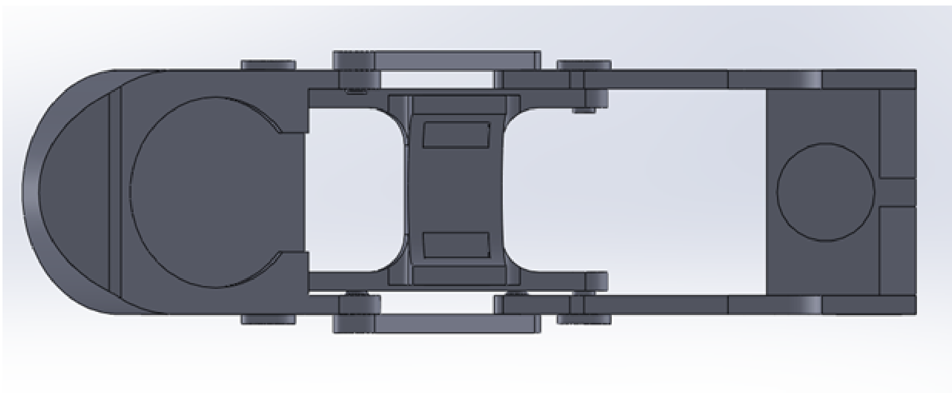


Fig. 7: Isometric view of final exoskeleton design



(a)



(b)

Fig. 8: Top and bottom views of final exoskeleton design

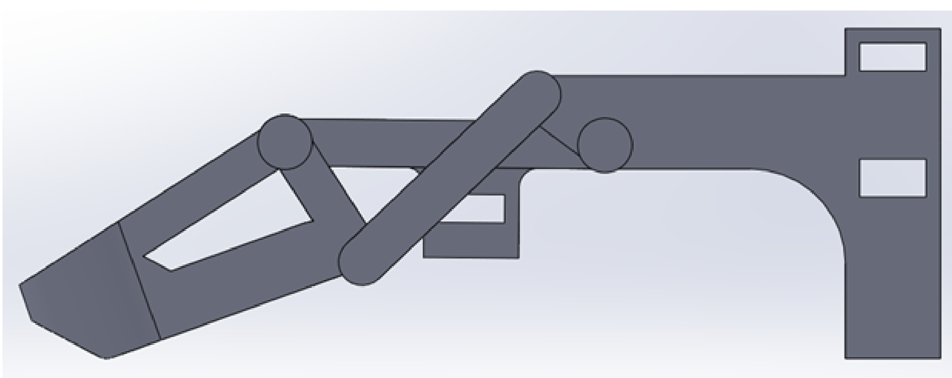


Fig. 9: Side view of final exoskeleton design

B. Code and Circuitry

```
// Measure the voltage at 5V and resistance of your 1k resistor, and enter
// their value's below:
const float VCC = 4.98; // Measured voltage of Ardunio 5V line
const float R_DIV = 1000.0; // Measured resistance of 3.3k resistor
const int LO1_THRESHOLD = 0.5; // set the low threshold
const int HI1_THRESHOLD = 1.2; // set the high threshold
const int LO2_THRESHOLD = 2.0; // set the low threshold
const int HI2_THRESHOLD = 3.8; // set the high threshold
int Threshold = HI1_THRESHOLD; // 512 +- 50
int TimeSense = 0;
int lastTimeSense = millis();
int dFSR = 0;
int lastFSR_in = 0;
int FSR=0;
int dt = 0;
#define M2PWM 7


//take derivative of force
//strain relief for demo day
// fix points so that plastic doesnt feel force

void setup() {
  Serial.begin(9600);
  pinMode(A3, INPUT);
}

void loop() {
  int sensorValue = analogRead(A3);
  // Convert the analog reading (which goes from 0 - 1023) to a voltage (0 - 5V):
  float voltage = sensorValue * (5.0 / 1023.0);
  // print out the value you read:
  Serial.println(voltage);
```

Fig. 10: Part 1 of Code

```
  if (voltage != 0) // If the analog reading is non-zero
  {
    static int State = 0;
    static int onoff = 0;

    TimeSense = millis();
    dt = TimeSense - lastTimeSense;
    if (dt >= 100) {
      dFSR = abs(voltage - lastFSR_in);
      if (dFSR > 0.5){
        analogWrite(M2PWM, 90*dFSR);
      }
      else analogWrite(M2PWM, 0);
      lastTimeSense = TimeSense;
      lastFSR_in = voltage;
      }

    Serial.println("onoff: " + String(onoff));
    Serial.println();
    Serial.println("input analog: " + String(voltage));

    delay(10);
    }
  }
```

Fig. 11: Part 2 of Code

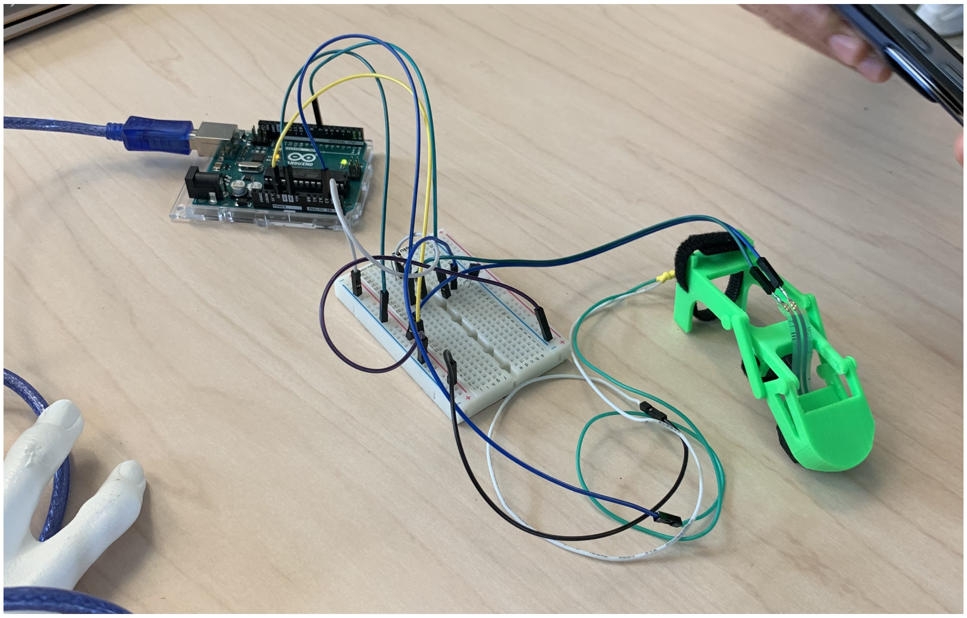


Fig. 12: Circuitry