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Developing a Testing Instrument to Evaluate the Performance Of 3D-Printed Body-Powered Prosthetic Hands

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Minnesota State University, Mankato

Developing a Testing Instrument to Evaluate the Performance Of 3D-Printed Body-Powered Prosthetic Hands

By

Araz Al-dawoodi

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Developing a Testing instrument to Evaluate the Performance Of 3D-Printed Body-powered

Prosthetic Hands

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This thesis has been examined and approved by the following members of the student's committee.

Dr. Kuldeep Agarwal
Advisor and Committee member

Dr. Shaheen Ahmed
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Dr. Harry Petersen
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Contents

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Abstract

A 3D printed prosthetic hand is an open source technology that became a good substitution for many products in the market. For many reasons, Low-cost, easy made / easy build. As an open source product, 3D printed prosthetic designs are available to anyone around the world, a good option for young children because they need to have a new prosthetic more frequent until they reach the adulthood age. Most families cannot pay a thousand dollars technology. From the research, it found that that there are not enough studies cover the open source wrist body-powered prosthetic. Other studies covered products used by adults which more physical ability than young children. Other studies covered a body-powered prosthetic that needs fewer efforts to run the wrist-powered prosthetic. To develop or design a product it is essential to have the correct, valid information and data to develop the product. A quantitative data provides a realistic assessment for the prosthetic efficiency. The study aims to design the electrical circuit for a group of sensors that will be used to collect the pressure force to compare it with the applied force. The author success to detect signal form four sensors circuit. The author also provides a design for sliding motor plate to maintain the torque from the stepper motor to mechanical part of the robotic wrist.

Introduction

Children limb defects and Types

Pediatric patients with limb defects classified in two main categories. Congenital deficiencies and amputations (John R. Fisk,). Congenital deficiencies or limb reduction when the child born with a condition when full or part of fetus limb does not grow fully during pregnancy. (Division of Birth Defects and Developmental Disabilities, NCBDDD, Centers for Disease Control and Prevention, 2018) . Amputations when the part lost after the birth.

Amputation Statistics

Amputation distal has a high ranking among another limb amputation. Fingers amputation has the most significant ratio of 74%. While thumb defects fall in second place with 16%. (Dillingham, Pezzin, & MacKenzie, 2002)

According to the CDC (Center of Disease Control and Prevention) estimation, there are 1,500 upper limb Congenital amputation conditions among the newborns in the United States yearly. (Division of Birth Defects and Developmental Disabilities, NCBDDD, Centers for Disease Control and Prevention, 2018)

Prosthetic

According to Britannica encyclopedia, The prosthesis is an artificial replacement works as a substance for a lost part (parts) of the body. The artificial limbs are the limbs that used to replace the lost upper and or lower limbs. (Encyclopædia Britannica,) According to Prosthetic limb categorized to the following types according to the amputee

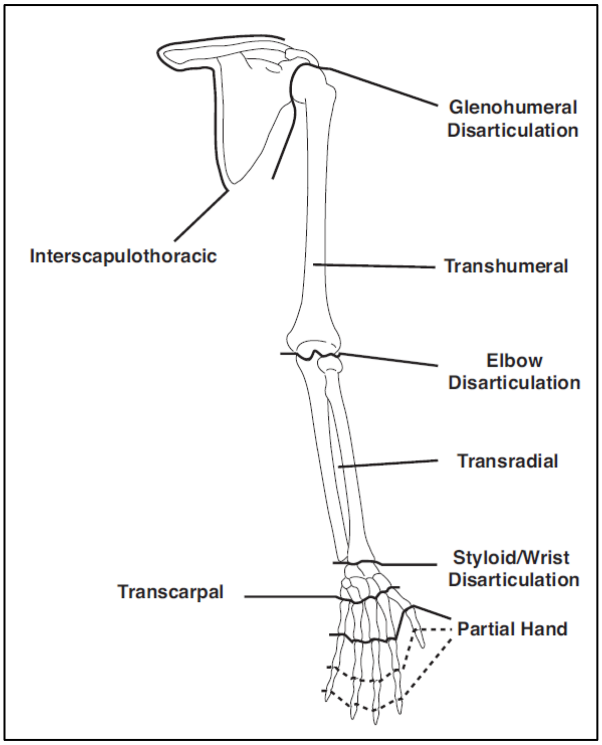

Figure 1 Upper limb amputation levels.

Illustration: Adapted with permission from Otto Bock HealthCare, Minneapolis, Minnesota.

The types of prostheses recommended/selected are based on many factors, including the level of amputation, the condition of the residual limb, individual goals, and work requirements. Often, more than one option is required for an individual to accomplish all of his or her goals.

Electrically powered prosthesis

This model used a small electrical motor to generate the movement for the limb. The limbs part can be hand or hook, wrist, and elbow. The limb used a rechargeable battery as a source of energy. There are different techniques used to control the prosthesis, but the myoelectric control is the most popular. Myoelectric obtain the signal from voluntary control muscles using electrodes which attached with the prosthetic socket to contact with the muscles on specific locations to transfer the signal to the prosthetic. (Coyner, 2019; Wilk & Arrigo, 2018)

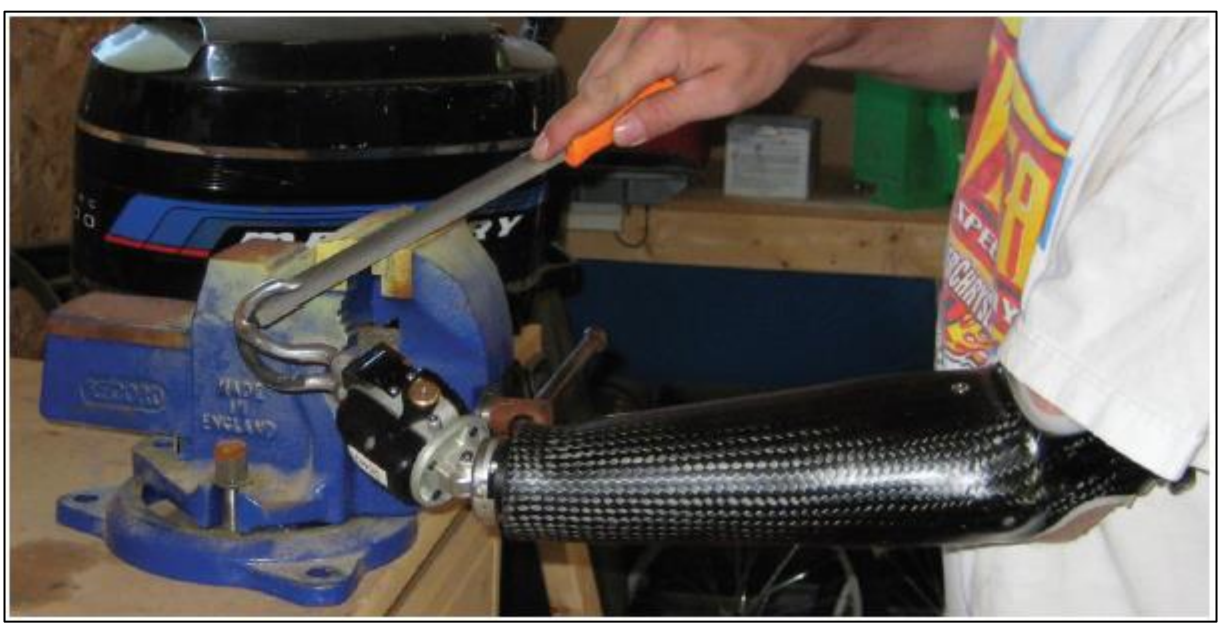

Figure 2 Photograph: Artificial limb provided by Advanced Arm Dynamics, Inc, Redondo Beach, California

Body-Powered Prosthesis

A body-powered prosthesis is a full mechanical function limb also named conventional or cable-driven prosthesis. The body-powered prosthesis used the body movement to move and control the limb. The movements derived from the body parts like shoulder, upper arm or chest or wrist like 3D printed prosthetic.

When the body part moves, the harness transfer the movement to the terminal devices (TD) hand or hook, that connected to the cable.

A body-powered prosthesis sometimes referred to as a conventional or cable-driven prosthesis, is powered and controlled by gross body movements. These movements—usually of the shoulder, upper arm, or chest—are captured by a harness system and used to pull a cable that is connected to a TD (hook or hand). In some amputation or deficiency condition, an elbow part added to the prosthetic to obtain the required motion. The patient should have the ability to make one or more of the following movements

glenohumeral flexion,

• Scapular abduction or adduction,

• Shoulder depression and elevation,

• Chest expansion, and

• Elbow flexion.

Also, the patient should have enough or suitable remaining limb length, enough musculature and satisfactory range of movement to provide the ability to attach the limb and the required motion to run the limb. Therefore body-powered prosthetic is not suitable for conditions with no or short limb remaining like the humeral neck, glenohumeral disarticulation, and inter scapulothoracic amputation levels. (Coyner, 2019b)

Figure 3 Boddy-powered prosthetic

https://www.ottobock-export.com/en/prosthetics/upper-limb/solution-overview/arm-prostheses-body-powered/

Hybrid Prosthesis

Hybrid prosthesis types have both electrical and mechanical control. Which is usually for a patient who have the elbow or higher amputation. The person can switch between the two-control mode. For instance, a person with distal humeral deficiency used a hyperiid prosthesis with the body-powered elbow because there is enough range of movement to move the elbow without needing to electrical one while a myoelectrically controlled hand like attached to the prosthesis. (Kuyper, Breedijk, Mulders, Post, & Prevo, 2001)

Passive/Cosmetic Restoration

It is one of the most common prosthesis. It is a cosmetic prosthesis designed to be very similar to the lost body part. It can be used for cosmetic non-function limb, or it can help in body balancing and lifting purposes. It is named as a passive prosthesis due to it does not provide any grasping ability. Different types of materials are used to make a passive prosthesis like flexible latex, rigid PVC (polyvinyl chloride), or silicon.

The highly finished silicone model with details is used as a cosmetic glove for the electric hands and body-powered hands. The passive prosthesis is lighter, easy to maintain due to less complicity with non-movement parts and long life period than the other prosthetic limbs. (Coyner, 2019; Gow & Hooper, 1992)

Figure 4 Passive/Cosmetic Restoration

https://www.amputee-coalition.org/how-prosthetic-hands-work/

Task-Specific Prosthesis

Task-Specific Prosthesis is designed for a specific task like fishing, swimming, golfing, hunting, bicycle riding, weight lifting, playing musical instruments and other tasks. When the other types of prostheses have a limitation in using. This type of prosthesis helps the person to enhance the performance level of the task. (Coyner, 2019b)

Figure 5 Task-Specific Prosthesis

http://pinnlab.com/what-we-offer/

3D printed Prosthetic

3D printed prosthetic is a new technology in prosthetic hand field with the high capability of development because it is a free open source that available for everyone to develop, edit and built a DIY prosthetic hand. In contrast with other types, it is a low-cost product with a huge price gap from thousands of dollars in other models to less than 50 dollars in 3D printed prosthetic hand.

The 3D printed prosthetic hand may not have the same level of durability and functionality like other models Nevertheless the technology provides the community with a low-cost product with high development potential because it is available for all creative individuals around the world to improve and develop new models. (3D printed prosthetics | where we are today 2019)

e-NABLE is one of the most significant online Maker community of 3D printed prosthetic hand consists of people from different skills and backgrounds like engineers, teachers, designers, and parents. e-NABLE provides a store of multiple design open source products which are available for everyone around the world with the ability to download the STL (stereolithography) file with ability to build or edit the designs. (e-NABLE,)

Additive Manufacturing Technology

Additive technology is the process to build layer over layer of material by joining them together and make a 3D final object from the 3D model with all details and complicity without needing to extra work. Additive manufacturing is different from the common subtractive manufacturing like machining when the material is removed from raw material to make the part. (EPMA additive manufacturing; Hausman & Horne, 2014)

According to Britannica 3D printing is a group of the process of making one 3D object by laying a 2D layers of material one over the top of the previous. It is similar to the process between the ink and the paper of normal printing, but in 3D printing, the joining material like liquid or powder solidified at each spot in the horizontal cross-section. The 3D object finishes after repeating the layering process for hundreds or thousands of times. (Encyclopædia Britannica,)

Additive manufacturing process stages

The first stage of AM additive manufacturing is 3D modeling.3D modeling is a sectional request stage of AM manufacturing. In this stage a 3D model of the object designed in 3D design software. It is necessary to have a 3D modeling geometry to allow sharing the design with other project team member to do other studies and analysis like FEM finite element details, drafting and planning for the manufacturing process.

ABS

ABS also noun as acrylic butadiene styrene. ABS is a low-cost filament with excellent mechanical properties. Easy to print to the required extrusion temperature. ABS is rigid and rigid structure and it. The properties affected by the components and the colors ratio of the ABS. For example, a high ratio of styrene components increases rigidity and brittleness. Some colors components effect on ABS transition. The changing of components affects the printing process setting like the temperature. ABS can be glued with epoxy and solvent welding cement which increase the design ability and reduce the associated post-print processing cost.

The large variety of ABS components increase the ABS filaments options with deferent mechanical and physical properties too. (Smyth & Smyth, 2015)

PLA

PLA or Polylactic acid is a low-cost bioplastic, biodegradable and transparent that extract from corn and dextrose sources. PLA has good mechanical properties, low shrinkage, and relatively low extrusion temperature. PLA is a suitable filament for 3D printing because of the relatively low glass transition and extrusion temperature. PLA has a post-printing reshaped ability. It could back to the original shape if it dipped in hot water. It also has lower warping and thermal distortion comparing with ABS.PLA comes with a broad range of variety of hardnesses, from very hard to rubbery depends on the ration of compositions and additional materials. Due to its natural transparency clear colors, PLA is available in different shapes color and dimensions. (Smyth & Smyth, 2015)

FDM Technology

Fused deposition modeling the process also known fused filament fabrication (FFF) due to FDM is a trademark is one type of additive manufacturing. The process invented by Stratasys in the United States in the late 1980s. The process lay down layers of the filament material, a layer over the top of the previous one, by the three-axis movement of the machine using the STL files generated by the 3D printing systems. The filament material solidified immediately just after the filament wire placed over the previous layer. There are different materials used in FDA like wax, polyamide, polypropylene, ABS, and so on. The printing in FDA is high-speed which make it a good option for low-cost, fast fabrication option.

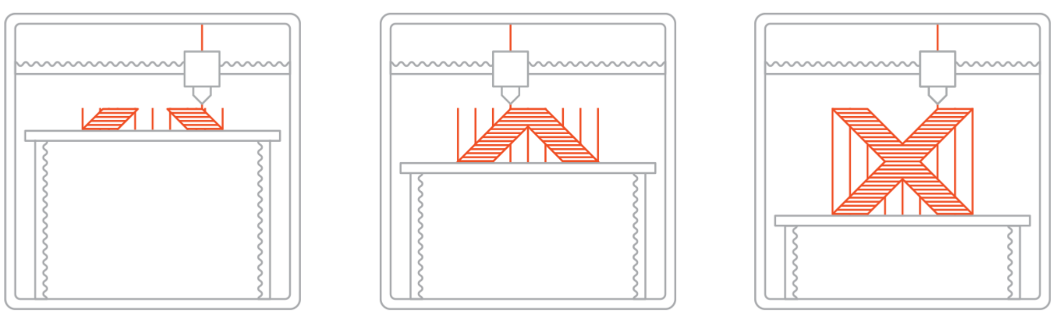

Figure 6 FDM technology

https://www.3dhubs.com/knowledge-base/introduction-fdm-3d-printing

Literature Review

In this literature, the review the author presents the current and current work related to the research topic. The research aims to find the current works of designing the testing device and procedure and importance of testing to the design process of the prosthetic hand.

(Resnik, 2011) In this article, Resink illustrates the definition and requirements of usability testing process for upper-limb prosthetic limbs. In the article the author emphasis on the importance of the testing process for upper-limb prosthetics to the evaluation, development, and designing of the prosthetics. The author mentions that the usefulness should be the primary aim of the testing process to find out the usefulness of the prosthetics. The article also mentions that the testing process aims to reach the optimization of the existing prosthetic hand technology which helps the researcher to point out the importance of the evaluation of the 3D printing prosthetics hand as an existing technology with few research-works on evaluation factors during the design or final product stage. The author shows that the testing process can be conducted by a real user or by researchers by building a testing technology. Finally, the article mentions that the evaluation is essential to help the researchers to meet the users' needs by identifying the recommendations to optimize the final product.

(Lyle, 2017).In this research, the author studies the mechanical properties of the different filament materials that used in children 3D printed prosthetic hand by apply Lateral Failure Mode Test (tensile test) for different 3D printed prosthetic hands that printed with different types of ABS plastic. The author mention that the PLA is excluded from the study due to brittleness and tendency to fail under stress test rather than bend. The 3D prosthetic that included in the study are Flexy Hand, Cyborg Beast, Raptor and Reloaded Raptor. The study found that ABS is the most robust filament material. The study also found that there is no significant effect on the tensile test results. The author also mentions that gripping testing test was inapplicable due to the prosthetics digits does not fit with the hand dynamometer and could not have a repeatable test.

(Gao, Rodriguez, & Kapp, 2014), in their works, the group design an apparatus to do a quantitative evaluation for a body-powered prosthesis. The prosthesis uses a harness to transmit the movement from the person body to the prosthetic to run the prothesis grip. The system has a group of sensors to collect the data and share it with LabVIEW software. The Sensors are used to collect cable tension, cable excursion, and grip force. The model built from a body of a wooden mannequin and integrated major mechanical joints.

(Ayub, Villarreal, Gregg, & Gao, 2017). In this experiment, the researchers study the relationship between the body and upper-limb prosthetic position. The researcher used a robotic limb that simulates the amputee limb. The study methodology is to build a robotic limb that simulates the human limb to reach the optimize the prosthetic usage condition by minimizing the input force and maximize the output gripping force. The study found that the force transmission efficiency depends on the body configuration and the prosthetic limb setting.

(Chamberlain-Simon, Desai, Dimoff, Sterling, & Wang,) A group of engineers in Rice University worked on building a test device to evaluate the gripping force of wrist-powered 3D printed prosthetic hand named CARPAL DIEM device. The device is a robotic wrist that simulates a human wrist movement used Arduino 2560 to control the wrist movement. The group design objects similar to objects that we grip in our daily activity. The objects are a cylinder, sphere, and rectangular. Each object has a group of sensors that used to collect the gripping force that applied to the object. The team uses Processing software to design a Graphical user interface GUI to control the wrist movement and collect sensors' information and export it to excel file.

Study Aims

The study aims to build a robotic limb that simulates the human amputated limb. The wrist provides the movement to the 3D printed prosthetic that installed on the robotic wrist to collect the gripping force of the prosthetic hand. A group of pressure sensors used in the ergonomic application is used to collect the data from the prosthetic hand. The sensors attached to different shaped to simulate the daily life objects that we need to grip or hold.

Methodology

In the following section the author will discusses the project main idea, the methodology of each stage, also author will describe the technology that used in the project.

As it shown in the figure 7 . The main idea of the project is to build a robotic wrist that simulate the human hand wrist movement. A prosthetic hand will be attached on the arm and the wrist of the skeleton. A stepper motor will provide a motion that transfer to the wrist by a roller chain. An object like cylinder or sphere will simulate the common object that we need to grip in our daily life. Sensors will be attached on these objects to collect the data.

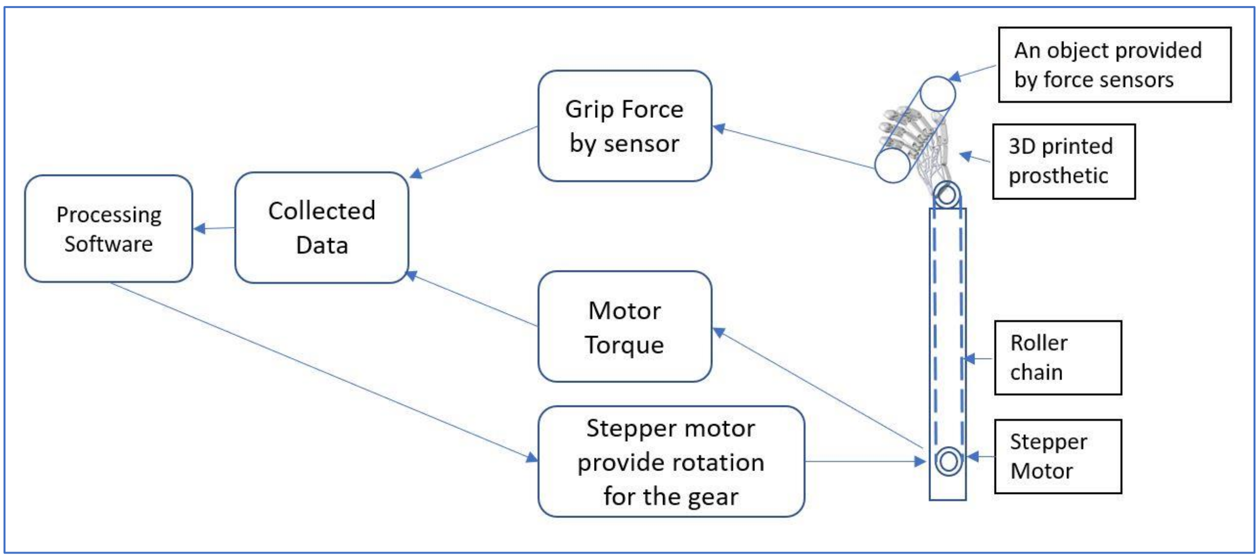

Figure 7 shows the illustration of the whole project.

The following figure 8 shows the technology that used in the project. The following section will discuss each parts in details.

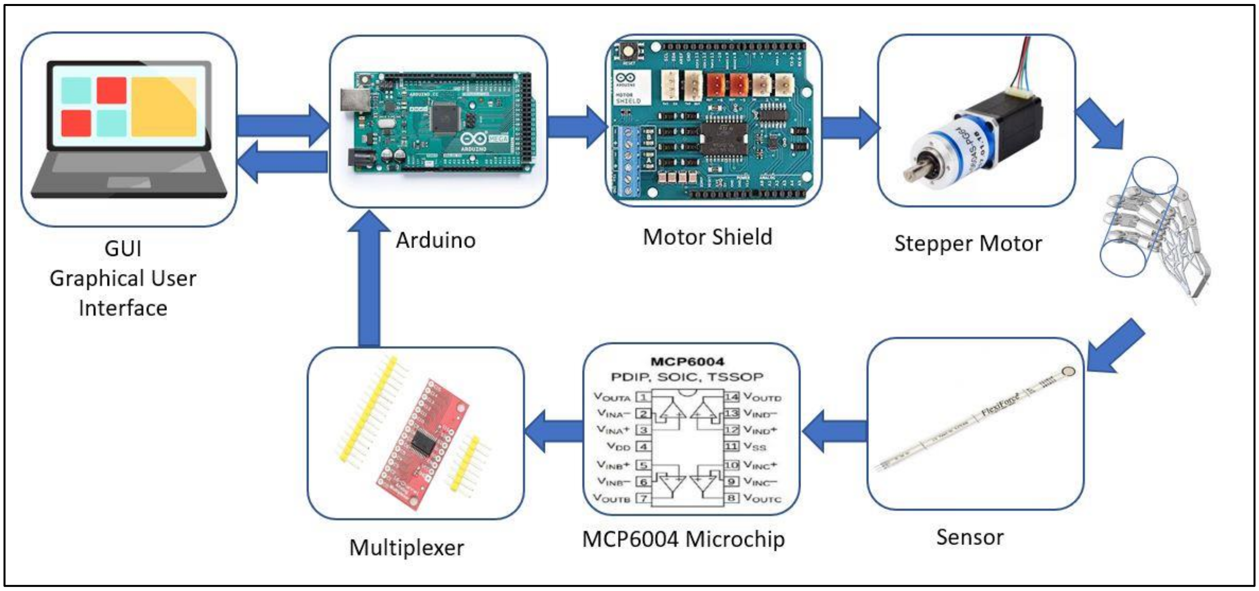

Figure 8 Technology that used in the project

Preparing the 3D printed prosthetic

The author study different 3D printed prosthetic hand that available in the open source community that concern about the upper 3D printed prosthesis. E-NABLE is one of the most popular websites that represents the 3D printed prosthetic community. The community consists of designers, teachers, engineers, parents, and others. A collection of the 3D printing prosthetics are ready to download and print by anyone around the world. Each model comes to full instructions and videos on how to to print and assemble the prosthesis step-by-step. Two models have been chosen to study due to the differences in the design and setting. The hands are Raptor and Talon3.

The author starts with building the prototype of the 3D printed prosthetic hand to improve a better understanding of the whole procedure to have the final product.

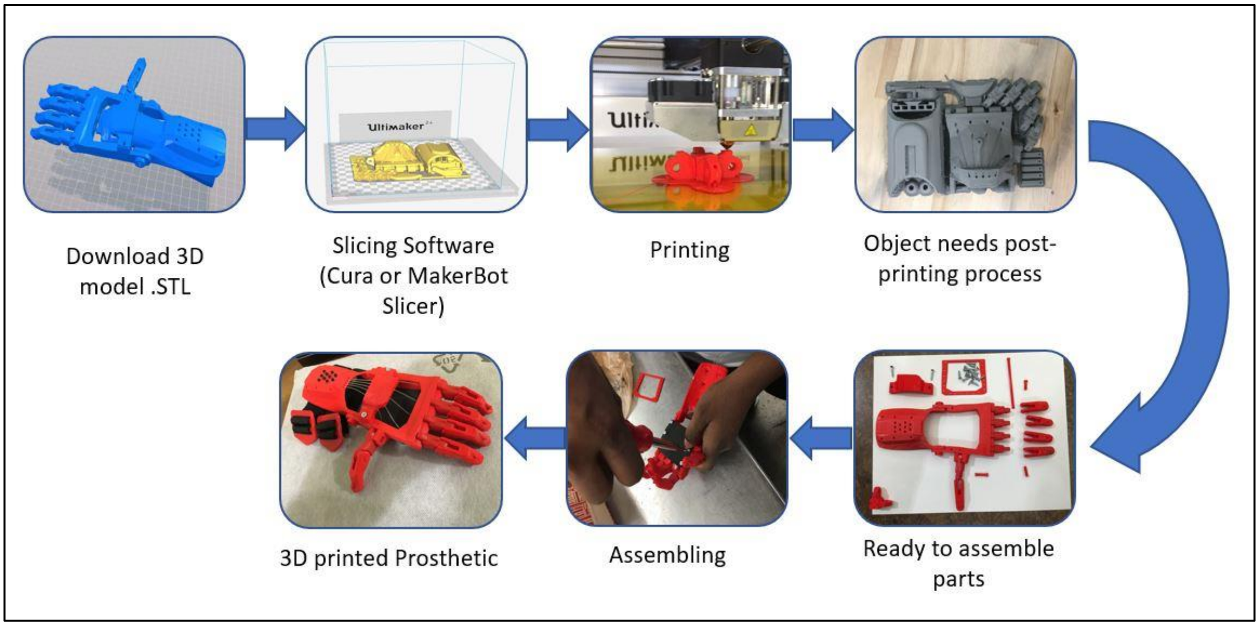

Figure 9 Production procedure of 3D printed prosthetic

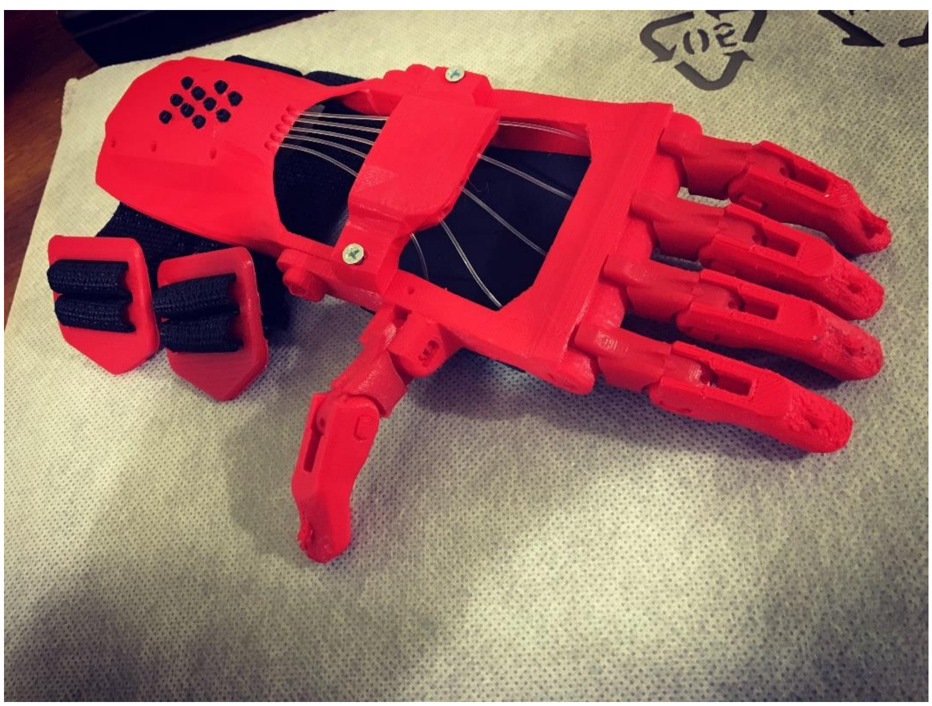

Figure 10 Full assembled 3D printed prosthetic Talon 3

Each model has been printed in two materials PLA and ABS, The PLA hands printed by Ultimaker 2+ and unltimaker3 while the ABS hands printed by MakerBot.

The author starts to learn how to use the 3D printers by co-operating with the facilitator in Additive Manufacturing lab at Minnesota State University, Mankato.

All parts downloaded from links provided by e-NABLE which is lead to Thingiverse website which included all parts file with instructions.

For Ultimaker 2+ and Ultimaker 3, the printing faces a couple of troubleshooting like bed leveling, nozzle cleaning issues and others that effect on the parts finish and quality. The facilitator helps to fix these problems. The researcher reprints a couple of pieces because of the troubleshoots.

The ABS parts printed in MakerBot printer. MakerBot also has a couple of troubleshoots. In the beginning, we faced issues with the bed because objects did not fix on the bed during printing which leads to defects in the printed parts. The author also noticed that the parts need more post-printing working, like removing the extras and smoothing the surfaces.

After finishing the printing of all parts, the researchers start to assemble the 3D printed hand. The team orders the required extra parts that not printable like, screws, plastic fishing wire, and strips. The researchers follow the instructions and assemble the hands.

The researcher builds four hands two Talon 3 model printed with PLA and ABS and Raptor hands printed with PLA and ABS too.

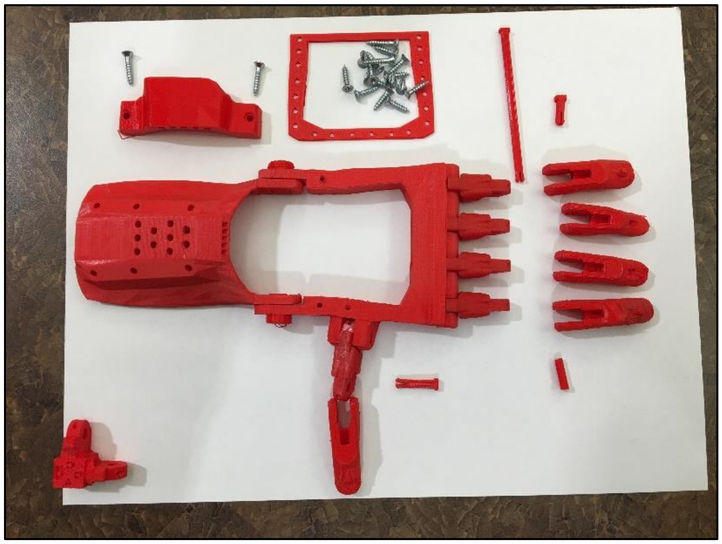

Figure 11 Talon 3 prosthetic hand parts

Figure 12 a graduate student (Sumanth Gokapai) assembling the Talon 3 prosthetic hand

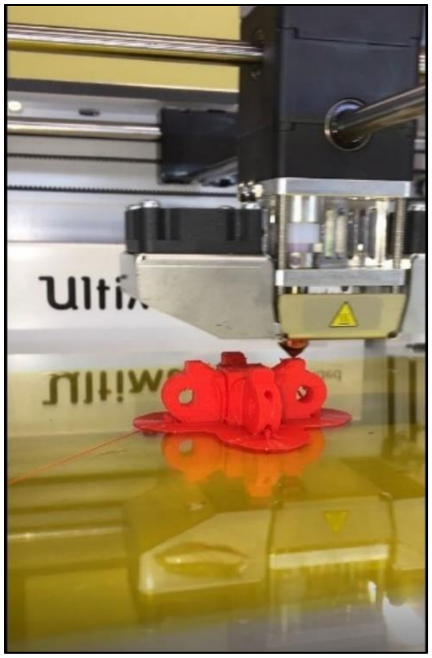

Figure 13 Ultimaker 2 during printing

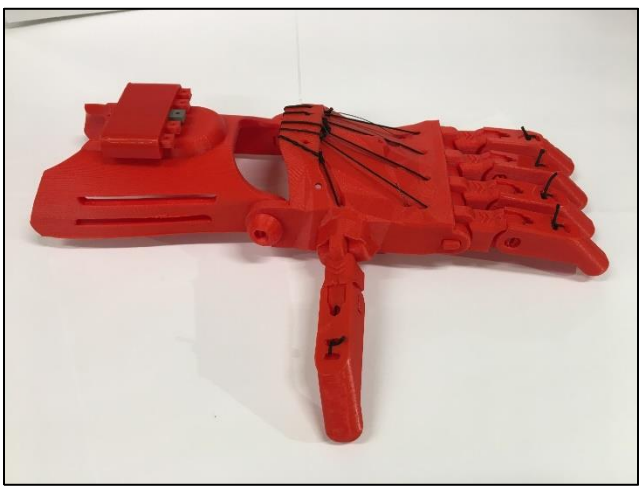

Figure 14 Raptor hand

Build the Electrical Circuit

After research about the pressure sensors, specifically that used in measuring the gripping force. The author chooses Tekscan sensors because the company has many products that used in ergonomic and sports applications.

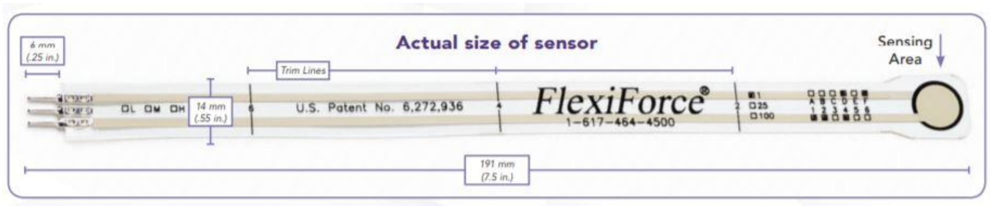

Figure 15 Tekscan FlexiForce sensor

The recommended circuit for the sensors is shown in Figure 16

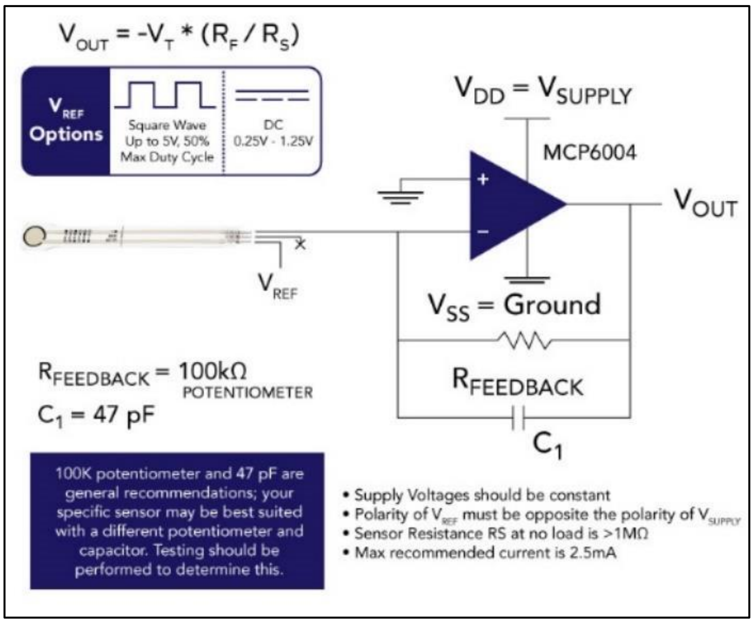

Figure 16 A recommended circuit for Tekscan sensor

https://www.tekscan.com

As is shown in the Figure 17, the microchip MCP6004 is recommended by the manufacturer. Besides, the author studies the instruction of the Carpal Diem device, the circuit consists a voltage divider as it has shown in the following figure 13

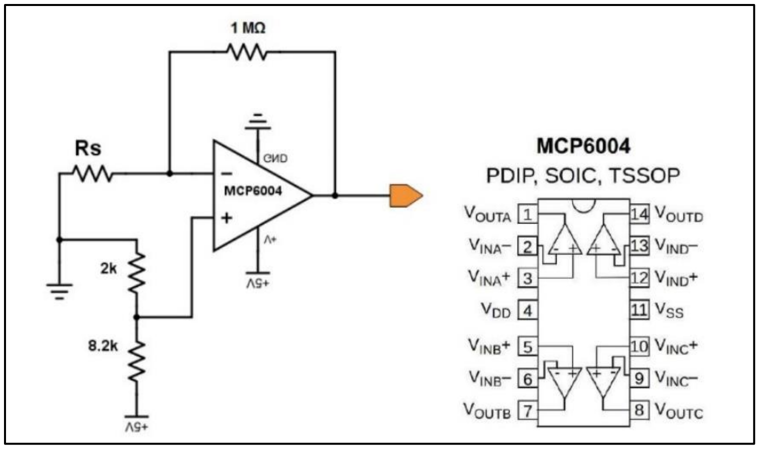

Figure 17 MCP6004 chipset and the recommended circuit

Which is the same recommended circuit for the MCP6004 manufacturer instruction for using the MCP6004 as an amplifier for the sensor signal

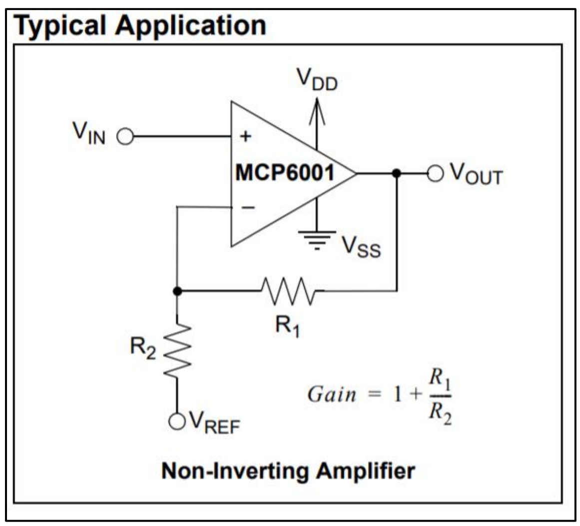

Figure 18 MCP6004 chipset and the recommended circuit

https://ww1.microchip.com

The author starts work with Mr. Kevin Schull in Prototyping lab to build the sensor/MCP6004 circuit.

The first circuit is tested one sensor only without the Arduino, The Input power supplied by the BK precision power supply 9123a and output signal measured by the Fluke voltmeter, the output signal was the changing in the resistance of the sensor because of the pressure sensor work as a variable resistance.

The power supply set on 5V. During the test, the researcher applies thumb pressure on the sensor; then the voltmeter shows the difference in the resistance. The resistance reduced when the force increased on the sensors.

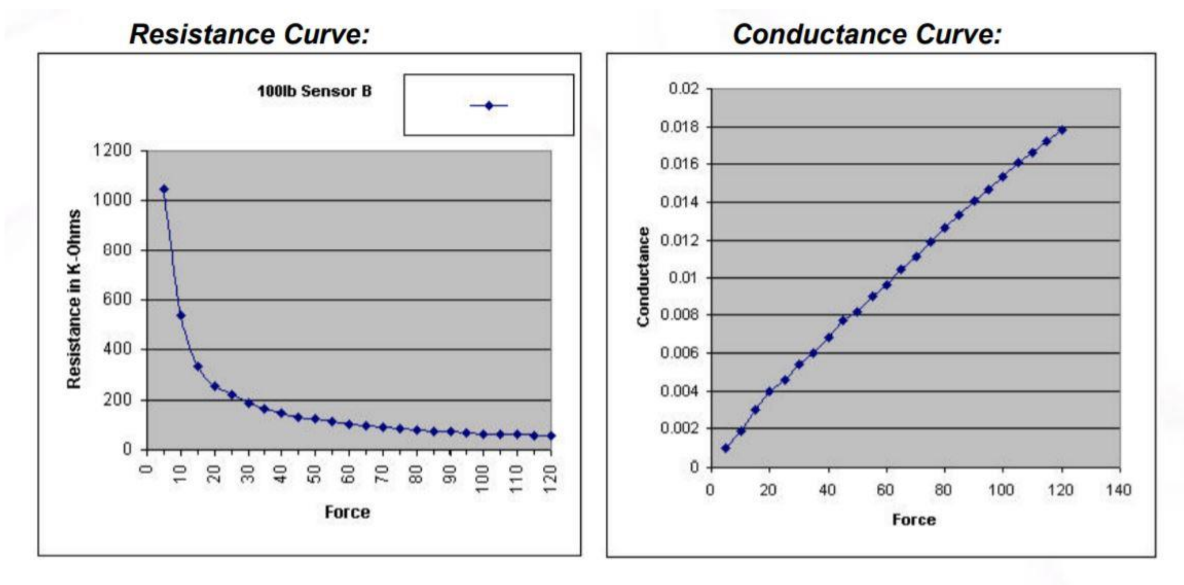

Figure 19 on the left is a Resistance – Force curve, on the right is Conductance – Force curve

https://www.tekscan.com/

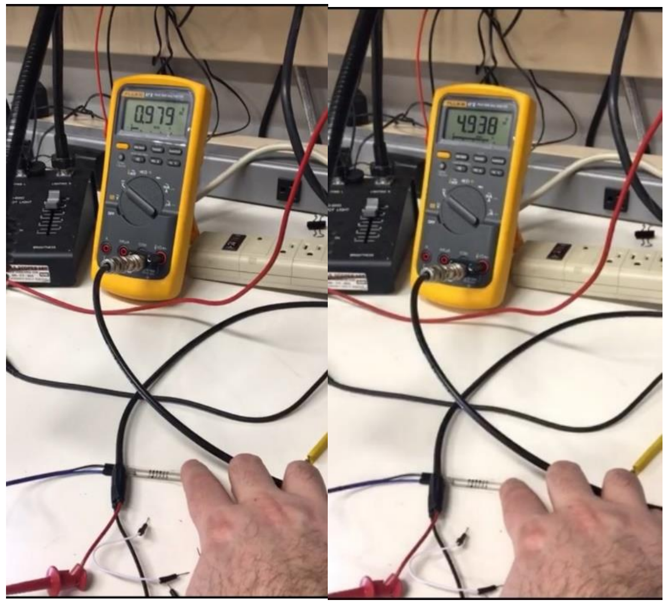

Figure 20 Left the no force apply low voltage read, the right applied pressure increasing the voltage close to the maximum 5V.

The testing process needs number of sensors to be connected to the Arduino2560.

Arduino Mega 2560

(Arduino 2560.) According to the manufacturer, Arduino Mega 2560 is a microcontroller board using the ATmega2560 which is 8-bit Atmel Microcontroller with 16/32/64KB In-System Programmable Flash.

The Arduino 2560 using for complex projects therefore it has 54 digital input/output pins as following

A. 15 can be used as PWM outputs

B. 16 analog inputs.

C. 4 UARTs (hardware serial ports).

D.16 MHz crystal oscillator

E.USB connection.

F. Power jack

G. ICSP header.

H. Reset button.

It can be powered by a USB cable or power with AC-to-DC adapter or battery.

Arduino started as a project in 2005 by students in Interaction Design Institute Ivrea in Ivrea, Italy.

The students used BASIC Stamp, a small microcontroller device programmable in PBASIC (a variation of the BASIC programming language), the BASIC stamp was considered expensive for students' budget. Arduino is an excellent low-cost substitution for the BASIC stamp with more function with more flexibility which makes Arduino as an excellent tool for any new projects.

Multipixel

Multipixel is a microchip card that used to connect a large of sensors to the Arduino with few pins required. The Multipixel that used in the circuit has 16 channels. Which is mean each multipixel can connect 16 sensors to the Arduino.

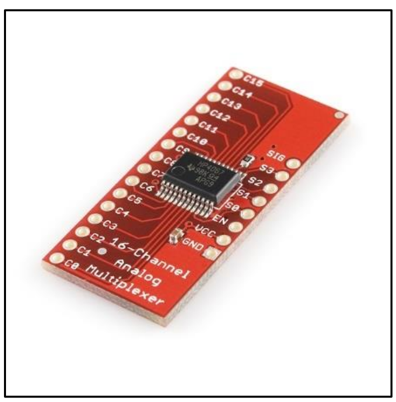

Figure 21 The SparkFun Analog/Digital work to connect sixteen sensors to the Arduino.

Stepper motor

To run the wrist with accurate angles, the stepper motor is an excellent choice due to the high accuracy stopping position. The Stepper motor used to provide the rotating motion to the wrist. The motor is Nema 8 Stepper Motor. The motor is bipolar which is mean it has two coils and produces high torque.

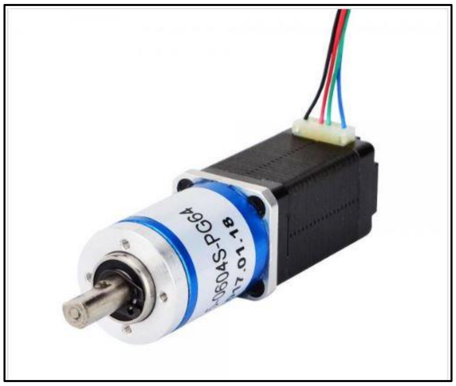

Figure 22 Nema 8 Stepper Motor

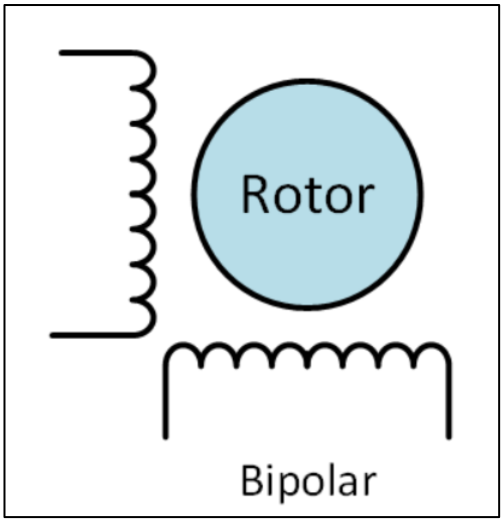

Figure 23 Bipolar motor coils

https://learn.adafruit.com

Motor Shield

Arduino is an open source project; Therefore, many people design printed circuit boards that can add more function to the Arduino by placing the boards on the top of the Arduino and connected with Arduino board by pins. Arduino Motor shield is used when there is a need to a motor by Arduino. The motor shield helps to control the stepper motor by the Arduino. In addition, the Arduino card itself can not provide enough power to run the motor. But the most important task for the motor shield is to protect the Arduino card because sometime the motor when it turned off can make a voltage spike. The shield is connected (Langbridge, 2015)

As it shown in the following figure 24 the Motor Shield is placed on the Arduino top.

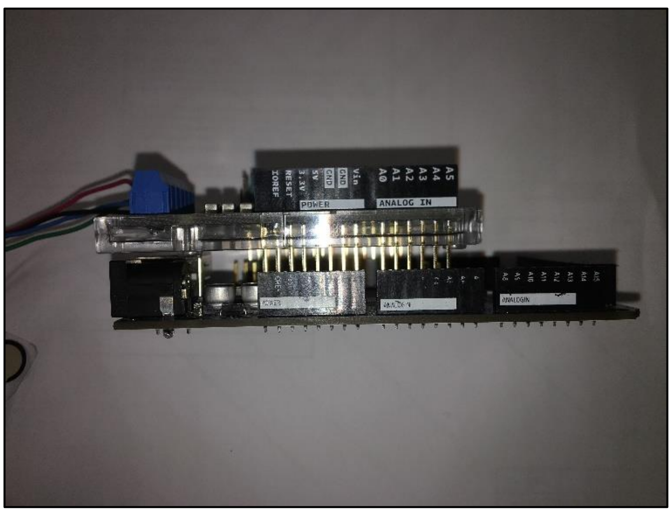

Figure 24 The motor shield attached on the top of Arduino 2560

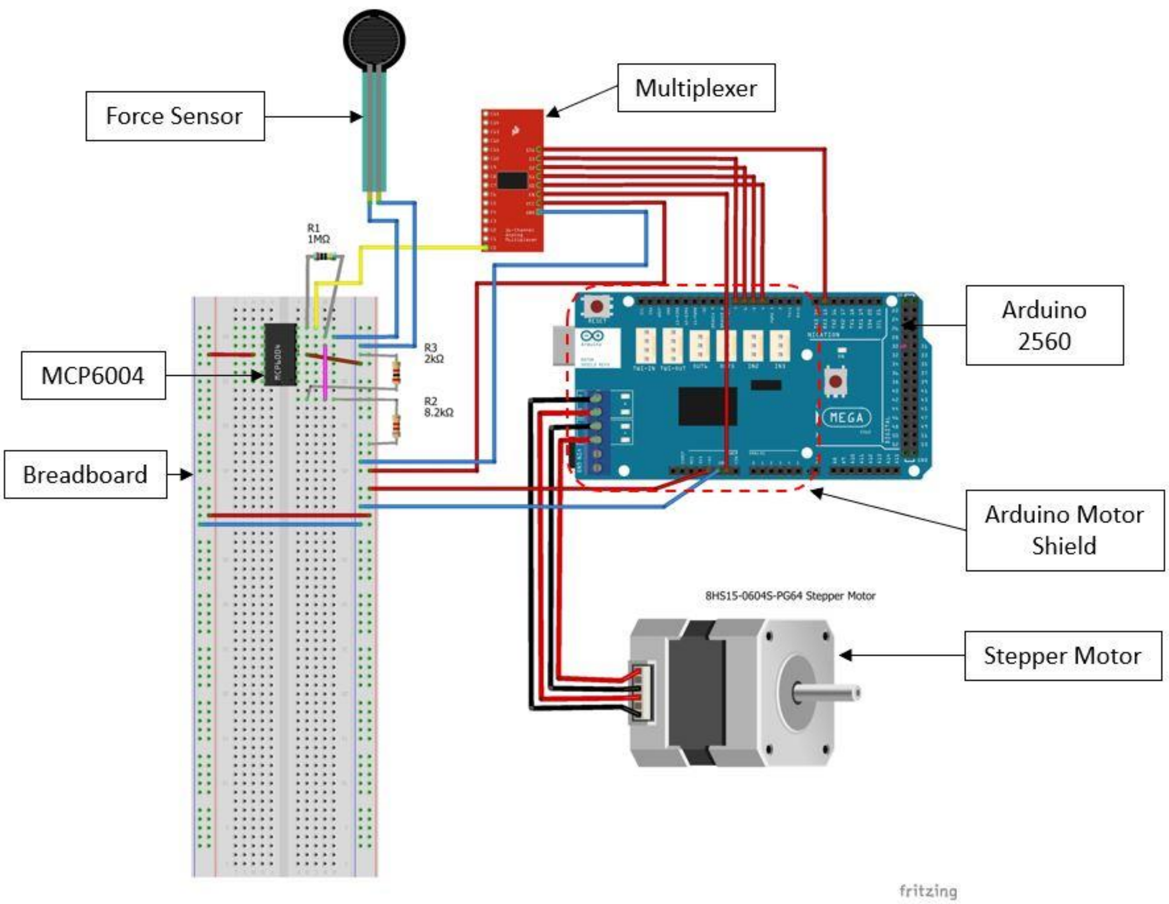

Figure 25 the full circuit for one sensor and the stepper motor

The Coding

The author starts to learn coding basics of Arduino 2560 from using the learning kit. Usually, the learning kit comes with a library of projects codes library. Also, there are many online libraries and hubs for projects and codes blocks.

Two software has been used for the experiment. Arduino IDE and Processing IDE. The Arduino IDE used to interact with Arduino 2560 board. The Processing IDE used to control the motor shield motion, chose the testing objects and export sensors data to excel sheet.

The Arduino can be programmed by C/C+ language. Learning to code is time-consuming; therefore, the author uses the CARPAL DIEM projects codes for both Arduino and Processing GUI codes. The author studies the codes and extracts the equations used in the CARPAL DIEM project.

The researcher success to collect data from the sensors after adjusting the codes.

The codes for the Arduino and the Processing. The author after contact the Rice University team success to have part of the project document. The document consists of links for the codes for both the processing and the Arduino.

The author cooperates with his colleague to run the sensors and multiplexer by the Arduino. In this stage, the experiment consists of running four sensors. Through the test the team success to record a signal from the sensors.

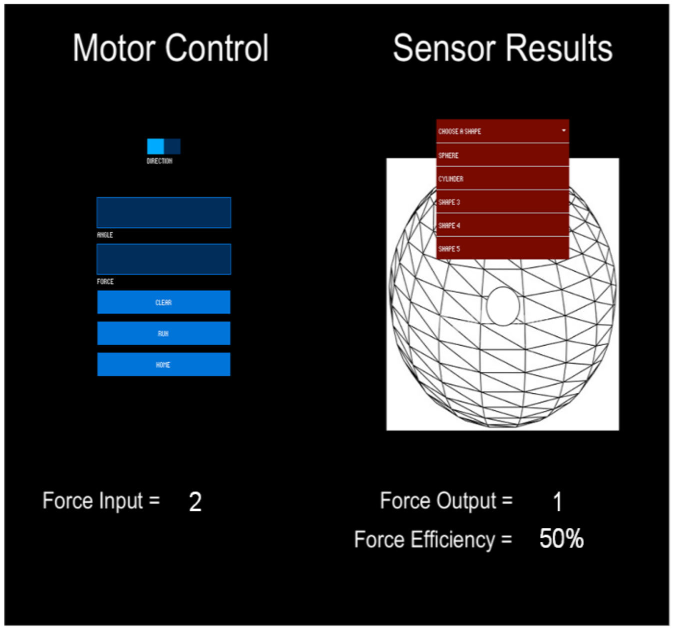

Figure 26 the GUI of Carpal Diem device.

Results

The researcher built the sensor circuit and detect a signal for four sensors that connected to on MCP6004 microchip. The stepper motor circuit faced couple of troubleshoots that related to the motor shield but in the end the stepper works using the Arduino and processing codes that used in another similar project which is shared in online hub (Carpal Diem project). The new design of sliding motor plate will help to maintain the tension in the roller chain and that's will help to transit the torque from the stepper to the robotic wrist effectively, the motor plate design illustration is under the future work because it does not enter the production stage yet.

Future Work

- Increase the number of the sensors in the system, the current work of the project reached four sensors with one MCP6004 microchip, the steps will be replaying the same one sensor procedure that will replied according to the required number of sensors.
- Calibrate the sensors using the manufacturer recommended procedures.
- Update or re-code the current code that used during testing steps due to the researcher still working to develop the theoretical part of collecting the data.
- Develop the testing object the used to collect the data to make it more flexible and provide flat surface under the sensors due to the sensors does not work in bending condition.
- Develop a motor plate. The researcher develops a slide motor plate to maintain a tension on the chain that transfer the torque from the motor to the wrist.

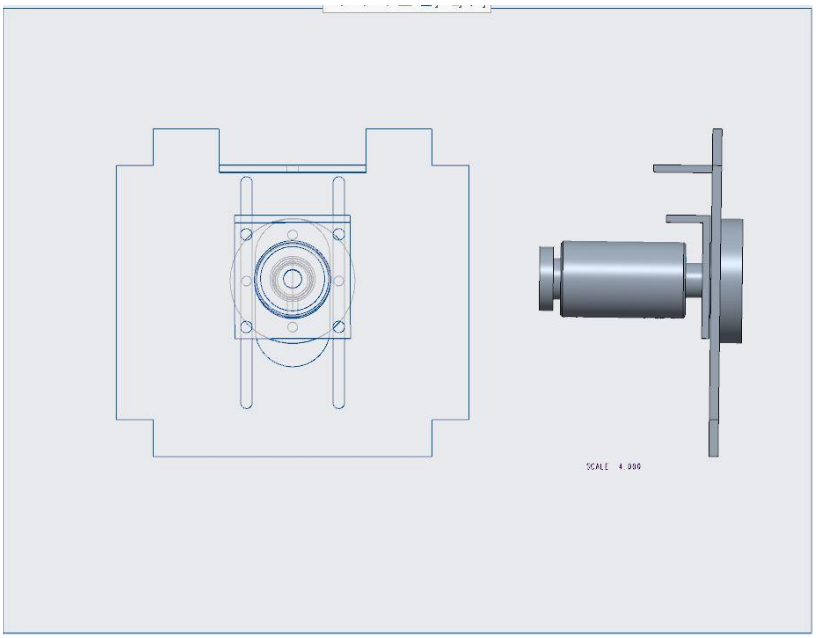

Figure 27 The sliding motor plate, motor gears and coupling

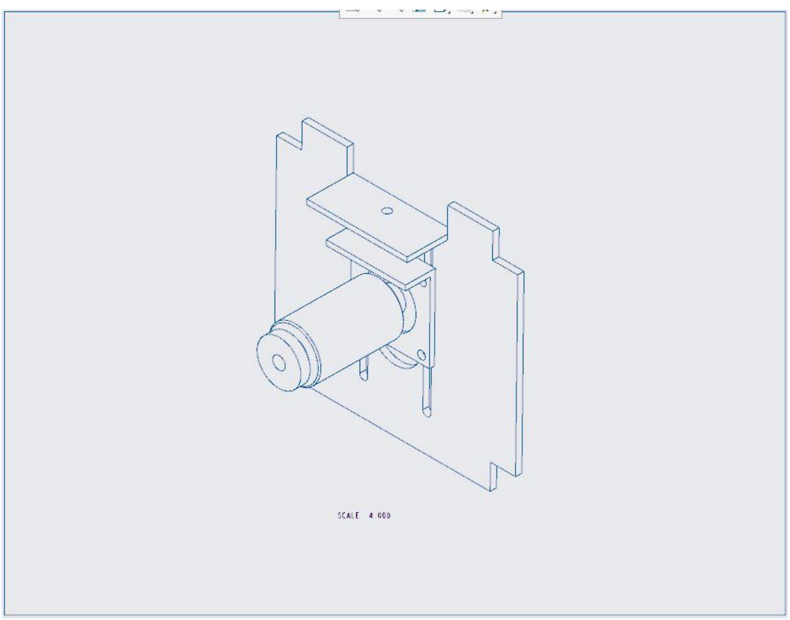

Figure 28 Isometric view for sliding motor plate, motor gears and coupling

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