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GRADUATE COLLEGE

# PIEZORESISTIVE SENSING IN ADDITIVELY MANUFACTURED PROSTHETICS

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PIEZORESISTIVE SENSING IN ADDITIVELY MANUFACTURED PROSTHETICS

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BY THE COMMITTEE CONSISTING OF

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# Abstract

This paper attempts to determine whether hobbyist 3D printers can be used to advance prosthetic capabilities. We attempt to answer this by designing, printing, and testing a prosthetic hand using a hobbyist 3D printer and hobbyist materials. The prosthetic hand with an opposable thumb was drafted from scratch and 3D printed collectively across four different fused deposition modeling printers; A Craftbot Plus Pro, CR-10, Jgaurora, and Qidi X-Plus. Once assembled, a material study was conducted against three different materials to identify the plausibility of sensing force using the materials piezoresistivity. Piezoresistivity is a measurement of resistance when a mechanical strain is applied. It was concluded that touch sensing capabilities could be utilized with 3D printed materials while on a hobbyist grade 3D printer. None of the materials required a heated chamber however, the argument of a heated bed improving the printability is undeniable. The likelihood of successfully incorporating this function into a 3D printed prosthetic had immense potential and promise.

# Chapter 1: Introduction

## Prosthetic History

The first recorded use and creation of prosthetics dates back to somewhere between 950 and 710 B.C.E by the Egyptians with the oldest prosthetic being a big toe [1]. The nearly 3000 year old prosthetic was made crafted from wood and leather [2]. Prosthetics have been created for years by different cultures and for many different reasons. The first documented wearer of a prosthetic limb was general Marcus Sergius, who lost his hand in the second Punic War [3], his new prosthetic hand was crafted from iron and allowed him to bear a shield and remain in battle [3]. It wasn't until after World War I where the Surgeon General of the U.S. army took action to assist in the creation of the American Prosthetics and Orthotics Association [4]. Even then, it wasn't until post World War II, where the U.S. government would provide funding to military companies for the advancement of form and function in prosthetics; allowing an opportunity for modern materials to be used such as plastics, aluminum, and other composites [4]. Prosthetics have come a long way since the ancient times and now can help wearers live a close to normal life.

*Figure 1 The oldest documented prosthetic found on a 3000-year-old mummy [1]*

## Prosthetic Development

Today, prosthetics assist many citizens with completing daily functions such as walking, reaching, and even eating. Today's prosthetics are also made of much more suitable and practical materials such as stainless steel, aluminum, titanium, carbon fiber, and even 3D printed material [5]. There have also been advances in prosthetic development that make the prosthetic more personal and customizable for the user. Today's practices include first obtaining a patient, performing the computed tomography (CT) scan and 3D reconstruction, breaking down the design, isolating a suitable additive or subtractive manufacturing process, fabricating the prosthetic, customizing the implant for the patient, and repeating the process if necessary [6].

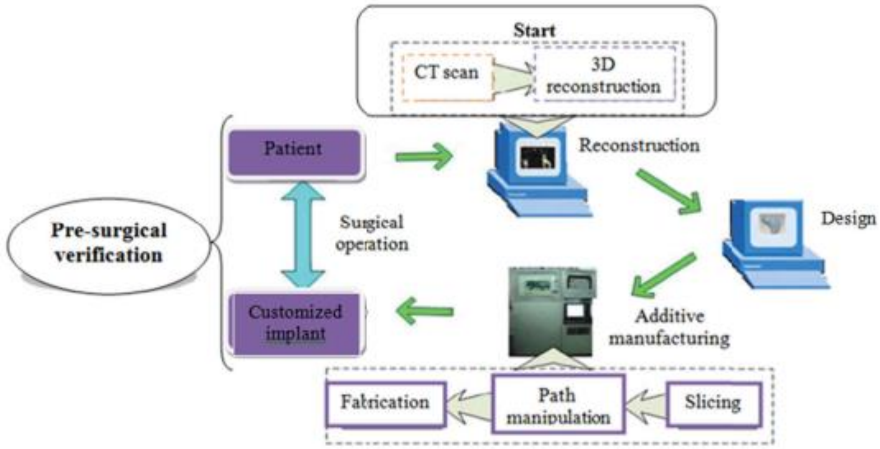


*Figure 2 Biomedical AM process [6]*

Additive Manufacturing

The process of additive manufacturing is defined by the American Society for Testing and Materials (ASTM) as “a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies” [7, 8]. This process of material addition also known as “3D Printing” comes in many forms. Some of the categories include material extrusion, powder bed fusion, electrostatic force-driven, binder jetting, and sheet lamination to name a few [9-13]. Subcategories of those include fused deposition modeling (FDM), direct in writing (DIW), electron beam melting (EBM), Stereolithography (SLA), and many more [14-16].

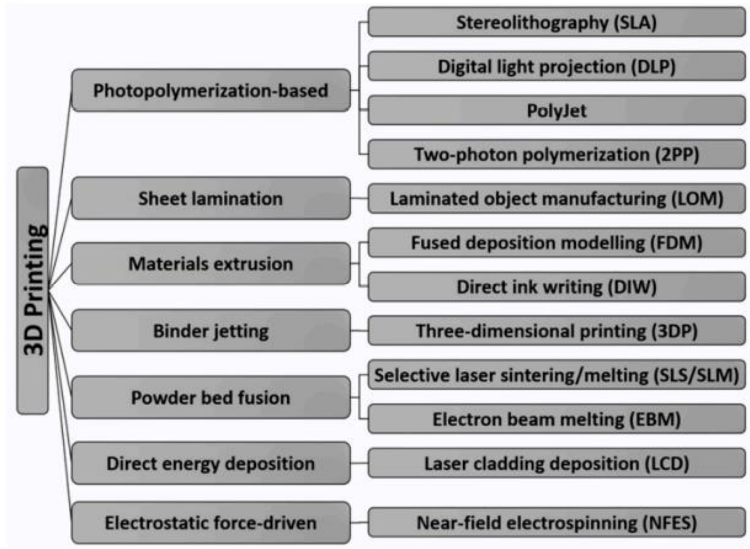


*Figure 3 Additive manufacturing methods [17]*

Of the many available options for additive manufacturing, we will focus on the material extrusion methods as those are the most commercially available with photopolymerizations-based, specifically SLA, coming in a close second [18-20]. FDM printers utilize a heated nozzle to melt polymer filament and form 3D objects, usually with standard triangular language (STL) data. Some of the available materials include polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), polyethylene terephthalate glycol (PETG), thermoplastic polyurethane (TPU), nylon, and even polyetherimide (PEI) better known as ULTEM. Within the material extrusion family, we also have DIW additive manufacturing. DIW utilizes a pneumatic nozzle or syringe nozzle to extrude printable inks with appropriate rheological properties to form 3D objects. This method provides the opportunity to acquire slurries of materials and material properties in order to fine tune the final characteristics of the printed product. However, this method is not simple, cheap, nor readily available to the average consumer.

## The impact of additive manufacturing on prosthetic development

When examining the impact of additive manufacturing in the prosthetic realm, it is extremely important to understand the many different applicable applications. These applications include but are not limited to knee implants, hip implants, jaw replacements, and limb replacements [21-23]. The idea of combining additive manufacturing and biomedicine to produce prosthetics can be labeled as biomedical applications of/in additive manufacturing. This conjunction encompasses the ASTM definition of 3D printing and its processes while utilizing the methodology to produce usable production scale prosthetics. This allows for medical devices to be rapidly prototyped and developed for not only research, but also for applications and services as well. The first ever 3D printed biocompatible part was created by Charles W. Hull in 1983. The device was a 3D printed eye wash cup [24, 25].

*Figure 4 The first 3D printed object, an eye wash cup invented by Chuck Hull [24]*

In today's biomedical additive manufacturing market, processes such as EBM, selective laser sintering (SLS), selective laser melting (SLM), bio-printing FDM, SLA, and inkjet printing can all be found abundantly used among medical professionals, each having its own advantage over another [6]. Current issues with some of these processes involve low strength, corrosion, poor dimensional accuracy, poor surface characteristics, microstructure issues, questionable bio-compatibility, and limited functionality. The ASTM provides committees and codes to help govern the development of these additively manufactured prosthetics. For example, ASTM – F42 is a committee that pertains to additive manufacturing technologies in terms of testing methods, designs, materials and processes [6]. Relating to the chemical characterization, ISO 10993 - 1 and ASTM – F2129 handle the biological evaluation of medical devices and standard testing methods for corrosive susceptibility of small implant devices respectively [6]. As for the biocompatibility of the implant ASTM – 756 provide standard practices for assessment of hemolytic properties and ISO 10993 – 6 denotes the test for local effects after implementation [6]. These standards and test procedures are applied across prosthetics in vivo and in vitro. When looking directly at appendage prosthetics, outside of issues such as surface roughness, poor surface characteristics, low strength, and low functionality; price would have to be the biggest limiting factor/issue.

## Piezoresistive Sensing and Applications in Prosthetics

Piezoresistive effects have been employed for sensing applications due to the unique variation of electrical resistance of materials under applied loading conditions. The application of piezoresistive sensors has progressed enormously in the well–known fields, such as robotics, control, measurement, polymers, composites, and prosthetics [26, 27]. Although polymers are not electrically conductive in general, the dispersion of nanoparticles within polymers can significantly improve their electrical conductivity, leading to potential piezoresistive based capability for sensing applications. A significant amount of work has been focused on the development of polymer-based nanocomposites [28, 29]. Certain research has resulted in novel piezoresistive sensors that can be used to monitor human motions and biomedical information [30]. Additionally, advanced manufacturing technologies, such as additive manufacturing and microwave-induced curing, have been employed for the piezoresistive sensor fabrication [31-33]. The developed piezoresistive sensors can be used for broad prosthetics for position and load monitoring.

## Purpose

The purpose of this research is to examine the possibility of producing a functional low-cost prosthetic appendage (hand) on a relatively low-cost home 3D printer. The criteria for production are. The fingers needed to allow for three points of relatively independent bending motion. The hand could not require extremely small or complex components for operation. Lastly, the design had to remain simple enough to be 3D printed on a hobbyist machine.

# Chapter 2: Design

## Design criteria

In order to mimic a prosthetic hand, potential designs had to be modeled and created. There were many designs that were considered, and hand drafted. However, the practicality, ease of use, and ease of manufacturability phased many of these design options out during the modeling phase. In order to narrow down the proposed designs, the hand, as stated before, needed to fit a set of criteria.

1. The hand needed to allow for three points of relatively independent bending
2. The hand cannot require extremely small or complex components for operation
3. The design must remain simple enough to be 3D printed on a hobbyist machine.

## Piston Pusher Design

The first design that was considered was a cylindrical piston pusher.

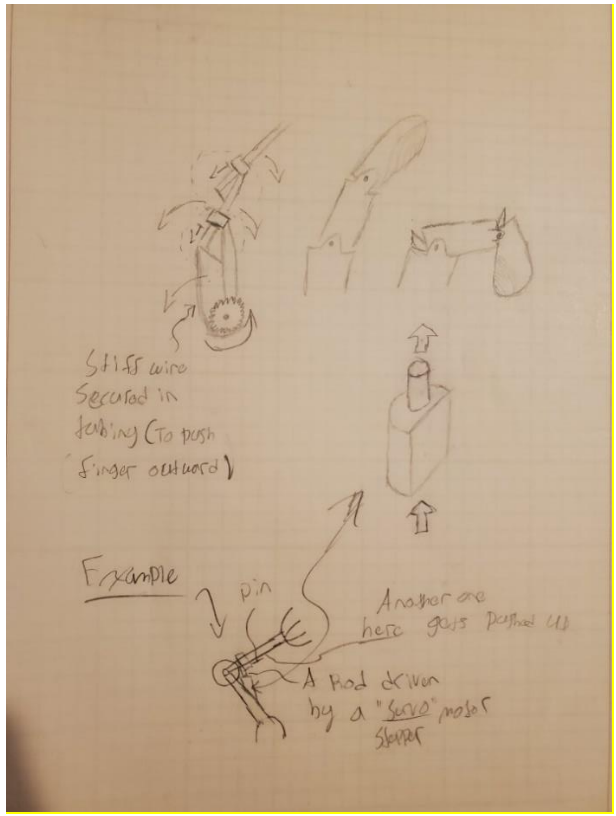


*Figure 5 Hand drawn, piston pusher design*

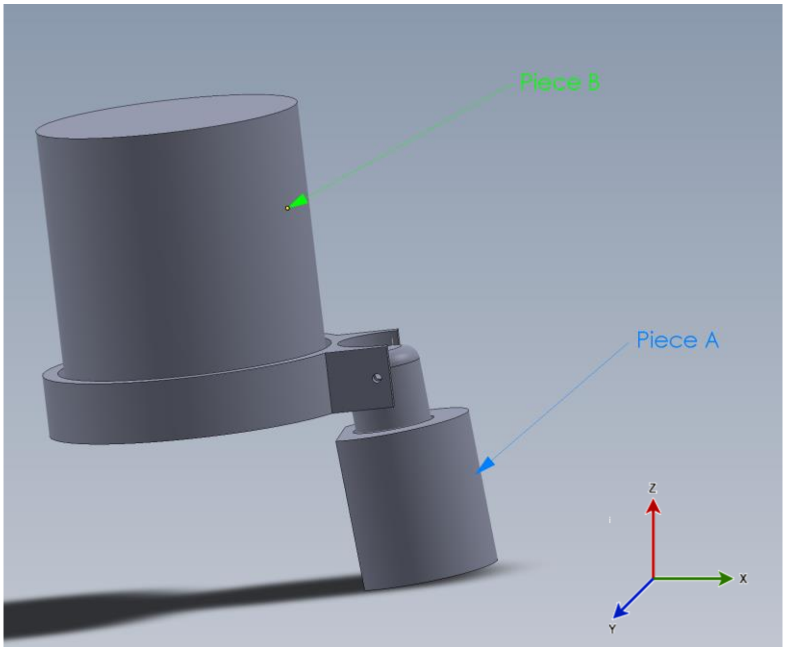

*Figure 6 Modeled Piston Pusher design*

The premise of the above design was that piece B would act as a joint section in the finger, while piece A would mount on the back of the hand or a lower finger joint (counting from the back of the hand to the tip of the finger). A cylindrical rod would apply a force in the positive Z direction along the bottom of piece A causing piece B rotation about the Y axis. This would provide the opening and closing motion of the hand.

Unfortunately, this design fell short based on criteria number 2. This design would not work for this experiment considering how many intricate assembly components would be required in relation to the available resources and when considering how many pivot points would be required for everything to mount securely and still apply enough force.

## Tendon Swing Design

The second design attempted to mimic the functionality of a knee brace.

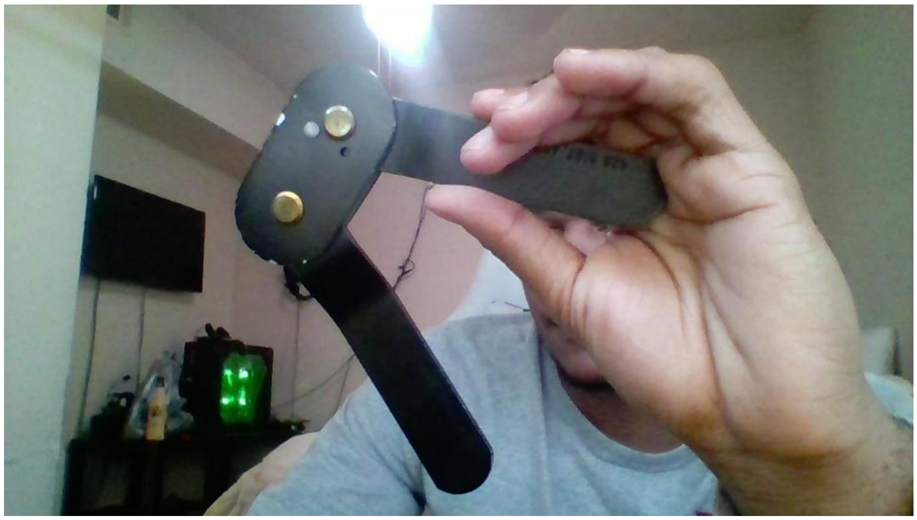

*Figure 7 Tendon Swing concept*

The finger would require three mounting locations. One at the base of the finger where it would be connected to the hand and two in the middle section that would function with the assistance of gears. This would allow for three points of bending and satisfy criteria number one. However, the stability of the design to hold a position was questionable. Once the drawing was modeled, the locomotion and actuation mechanism proved unreliable and unable to function properly. After even further assessment, it was noted that this design failed the first criteria due to the utilization of gears preventing independent bending. This led us to design three.

## Tendon Spring

The third design relied on a string and spring design.

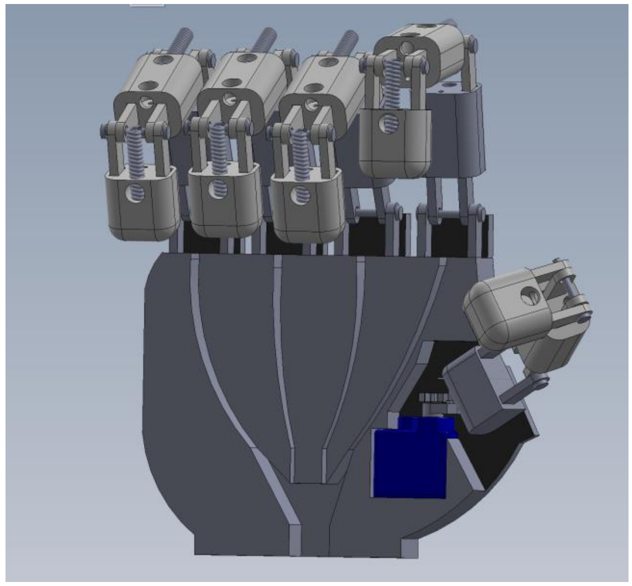

*Figure 8 Tendon Spring with Thumb Gear*

A string would run through the front palm-side of the finger while springs would mount on the rear knuckle side of the finger. The strings would navigate from the fingertips, through each joint, down through the palm, and connect to an actuating motor that would be located lower in the forearm section. The finger joints would be held together via 3D printed inserts.

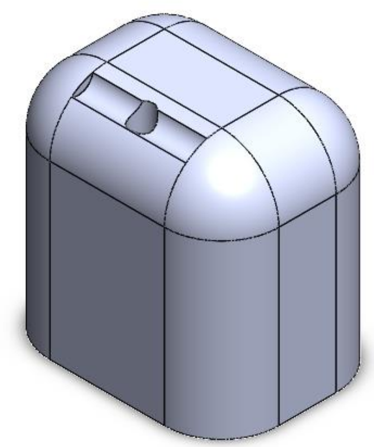

*Figure 9 Iso Tip Front*

The string would be secured at the tip with a knot.

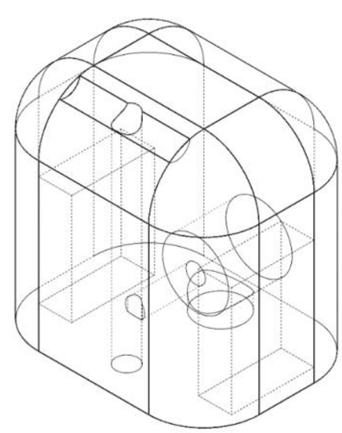

*Figure 10 Iso wire tip front*

The back of the finger joints would house a system that would allow for a spring to be inserted from the bottom and secured in the back with a screw eye

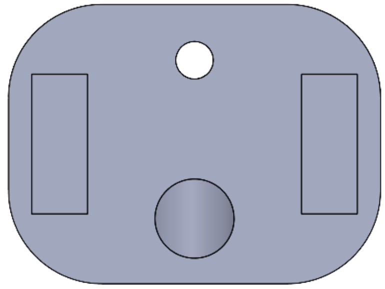

*Figure 11 Tip, bottom view*

The .08 inch through hole traveled through the joint entirely while the .17-inch spring hole only went up high enough to meet with the screw eye hole, roughly .3 inches

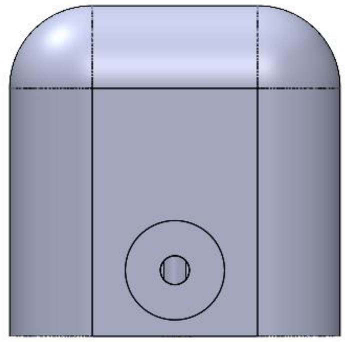

*Figure 12 Tip, back view*

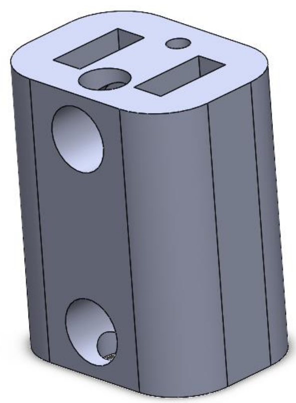

*Figure 13 middle and lower section, back Iso view*

The middle sections of the fingers had a similar design to the fingertips except, there were spring holes, screw eye holes, and section connectors on both sides to mount to the tip, bottom joint, and palm.

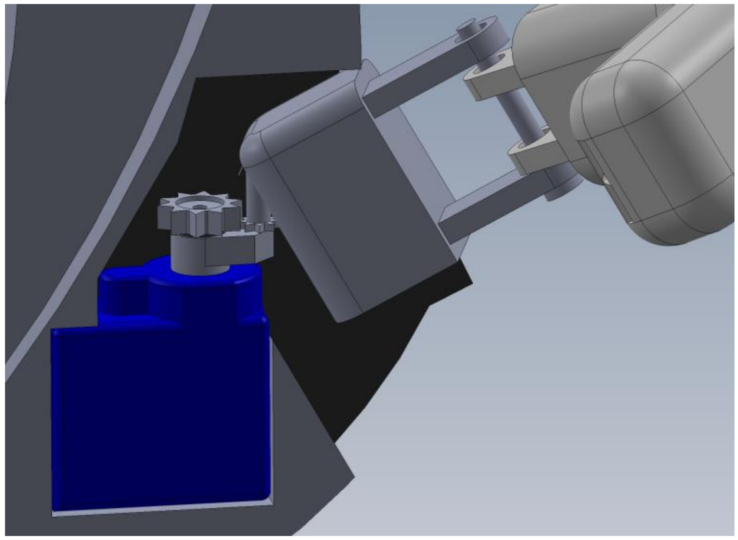

*Figure 14 Tendon Spring with Thumb Gear, Stability Issue*

Once the modeling of the fingers and palm were complete, the actuation of the thumb section began development. The initial design of the thumb section appeared to be mechanically unstable for even light loads and also ended up failing criteria number 2. Improvements needed to be made to accommodate the servo's geared teeth surface area for the momental force required to actuate the thumb inward and outward.

## Tendon Spring Improved

The final design was a replica of the tendon spring design, except with an improvement to the thumb section. The new design was able to solve the issue that design three presented while meeting all three of the identified criteria. The improved thumb design provided a greater surface area for the actuating and resting points of contact between the servo motor and palm frame, respectively. An additional 3D printed piece would rest on top of the servo motor and slide into the thumb's pivot point in a puzzle piece like manor. This would supply the torque needed to rotate the thumb inward and outward.

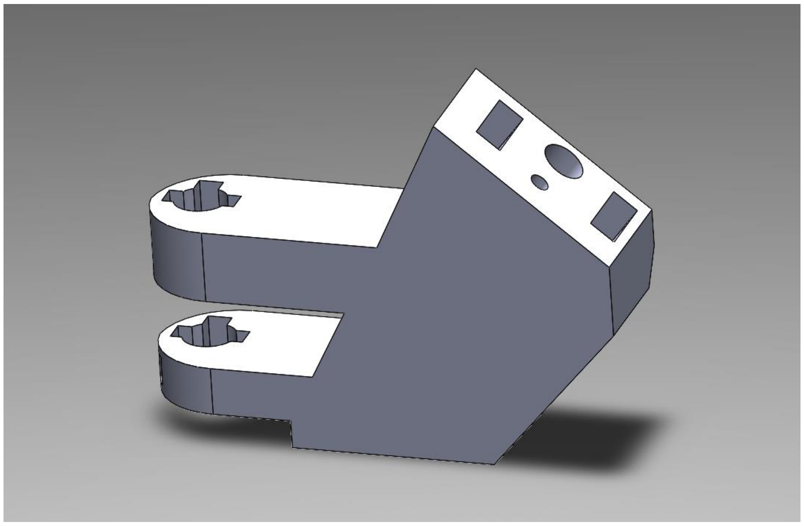

*Figure 15 Improved Thumb Design*

Channels were run through the palm of the hand to provide an area for the strings to reside, travel, and actuate the finger individually

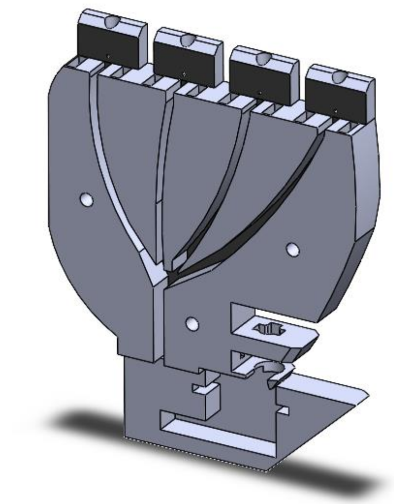

*Figure 16 Palm, Iso view*

The servo motor would reside inside of the base of the palm right below the thumb. A palm cover would be installed on the front face of the palm to conceal the string channels and strings.

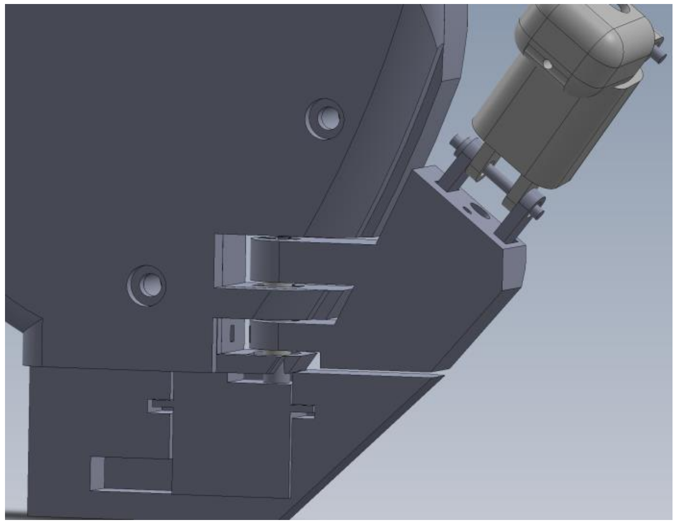

*Figure 17 Modeled design 4, Tendon Spring, thumb remedy*

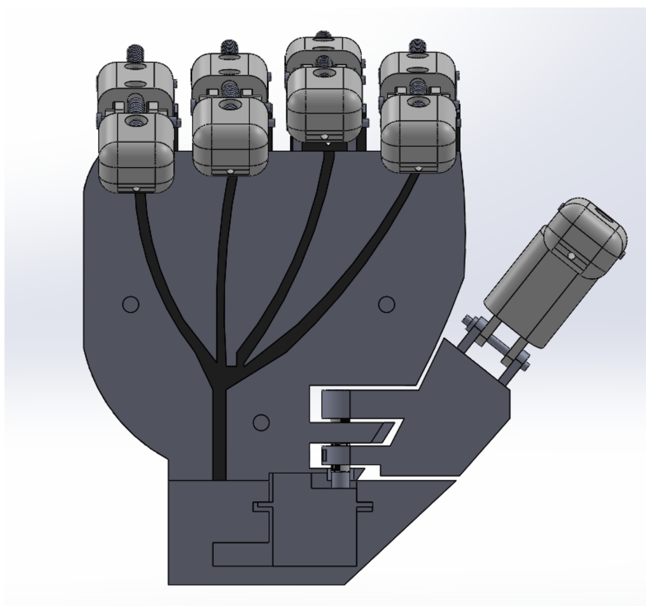

*Figure 18 Modeled Design 4, Tendon Spring, front view*

Chamfers and fillets were incorporated in order to not only provide safety from sharp edges, but also to increase the aesthetics of the prosthetic

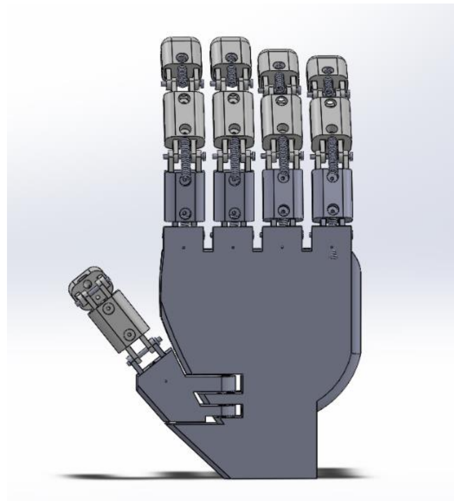

*Figure 19 Modeled design 4, Tendon Spring, rear view*

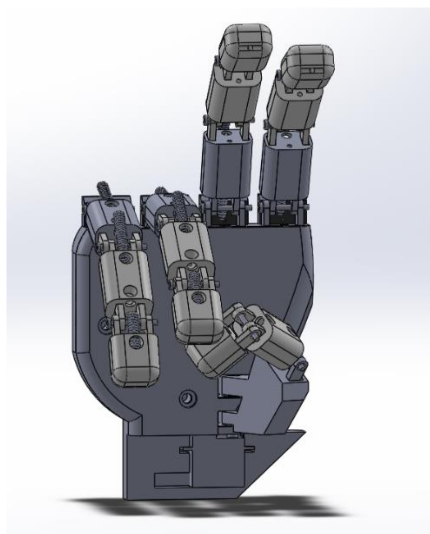

*Figure 20 Modeled design 4, Tendon Spring, finger functionality*

# Chapter 3: Prototype

Once the final design was selected, the manufacturing began. The first step was identifying the required materials for assembly, then to print the design, followed by assembly and testing.

## Materials

As previously mentioned, the first step in developing this prototype was to identify the required materials. See Table 1 below for a materials list.

In preparation for heavy loads, a 65lb braided microfilament fishing line was chosen as the string choice. The screw eyes and springs were picked out from Ace hardware due to their small size and low price. The hot glue and glue gun were picked up from Walmart. Lastly, the servo motor was purchased online from a reputable servo manufacture, MKS servo. The servo was chosen due to its small size, metal gearing, light weight, and low price.

| Table 1 | |
|---|---|
| Item | Brand |
| 3D Printer | Qidi X-Plus, Craftbot Plus Pro, CR-10, Jgaurora |
| PLA material | Hatchbox (multi-colored) |
| String | Power Pro, 65 LB |
| Allen Screws | Prime-Line, #10-24 x 5/8 |
| Screw Eyes | National hardware, .05in x 15/32 in |
| Springs | Prime-Line 1 in x .156 in |
| Hot Glue | AdTech Crystal Clear mini sized |
| Servo Motor | MKS servo, DS6100 |

*Table 1 Materials*

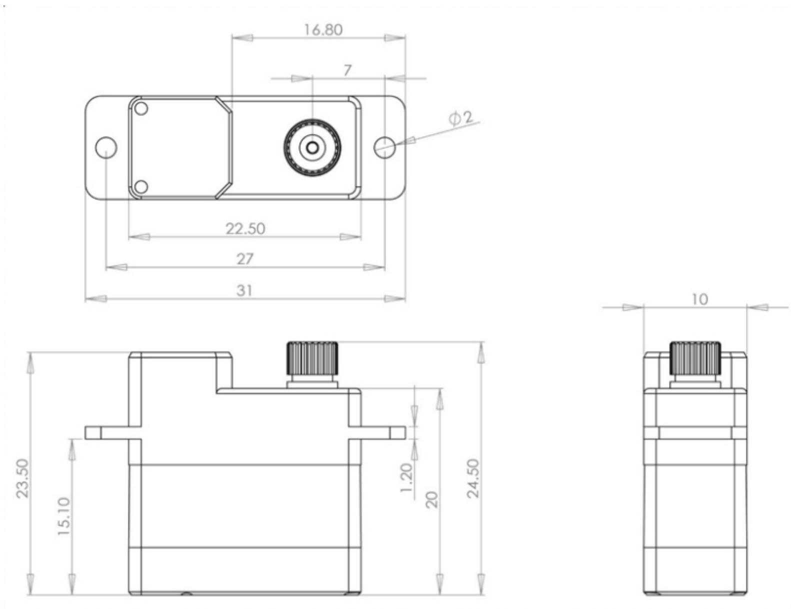


*Figure 21 Servo Size [34]*

The servo weighed in at 9.5 grams, operated with 5 volts DC, and provided a stall torque of 3.32 kg.cm.

## Printing

The printing of the hand was completed on a multitude of hobbyist printers. A Craftbot Plus Pro, CR-10, Jgaurora, and Qidi X-Plus. I was prepared to troubleshoot the printers and print processes for issues such as poor layer adhesion, poor surface finish, bad bed adhesion and many other issues; however, outside of a few required design and dimensional changes, the printers provided no further issues. The biggest issue faced actually occurred during the print removal process. At times, some of the components that were printed flat with a large surface area on the bed would simply refuse to adhere from the build surface. The range of build surfaces included glass sheets, painters tape, and Polyetherimide (PEI) sheets. Many of the modeled pieces were drafted and orientated in a manner that would require a minimal amount of support material and overhangs. No brims were utilized, and only one raft was required. The raft was for the pivot pins that held the finger segments together. The main additional print parameter that was added were skirts. The skirts ensure that no unwanted ooze material would be applied to the first layer of the print.

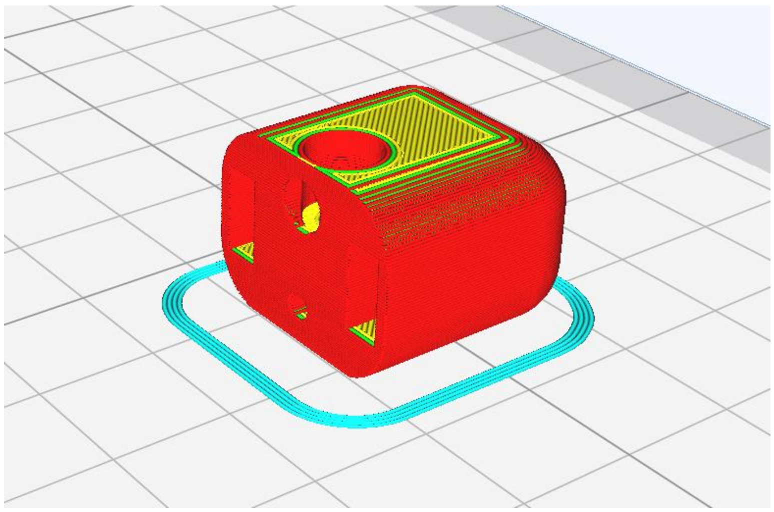

*Figure 22 Sliced Fingertip G-code*

As stated previously, many components of the hand were orientated in a manor to require the least amount of support material. The only parameter that would trump the surface area, no support requirement was if a component had critical dimensions that had to be accounted for. As displayed in the image above, the critical screw eye hold on the back of the finger segment was faced upward to hold a tighter tolerance. The segment inserts were taken care of by the printers “bridging” capability.

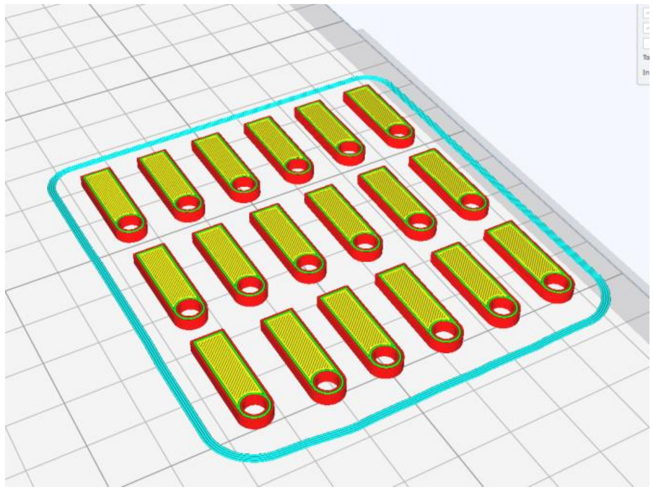

*Figure 23 Sliced segment links G-code*

Nearly every component of the hand was 3D printed. From the joint segments, to the segment connectors and pivot rods. The only components not 3D printed were listed in the material section which included the springs, screw eyes, screws, glue, string, and servo motor.

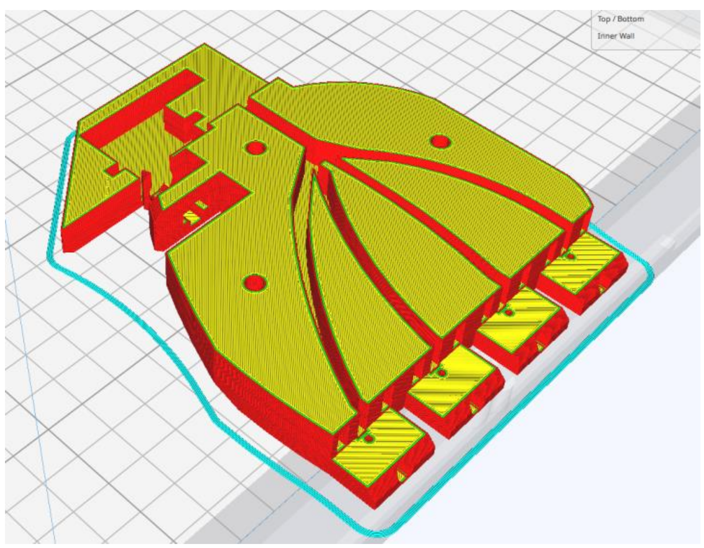


*Figure 24 Sliced palm G-code*

The palm provided no print issue at all even with the overhang servo connection section. The only trouble was removing the part from the print bed without damaging the part, the printer, or the print bed. During the removal process some of the painters tape was removed along with the print.

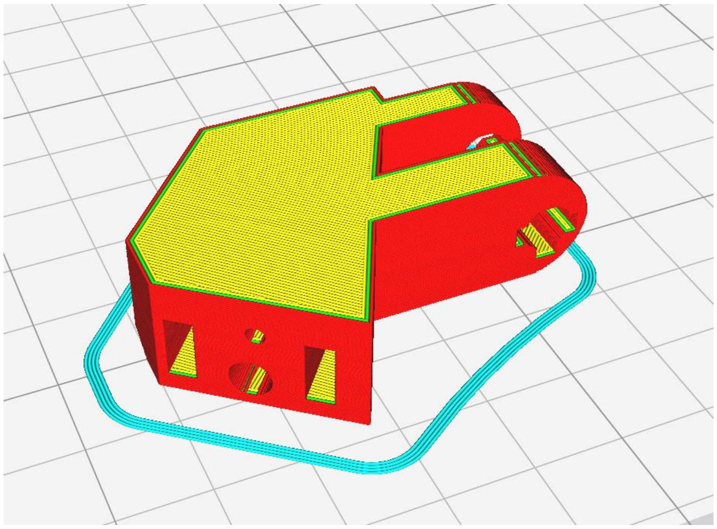

*Figure 25 Sliced thumb section G-code*

The thumb section was the only part that had to go through a couple of iterations. The sizing of the servo connection arm section had to be made slightly larger due to some material shrinkage/expansion and rough overhangs.

## Assembly

The assembly process was straight forward. There were little to no issues presented that inhibited the assembly outside of a few components needing to be reprinted due to dimensional tolerances not being met. The thumb mount was the main culprit in this. The palm also needed reprinted however, that was due to a user error in the modeling process.

The hand was assembled finger by finger. Once the hot gluing of the segments, segment connectors, and pivot rods was completed, the string was installed. Lastly, the springs and screw eyes were installed before installing the fingers onto the palm. The servo and thumb mount were installed prior to any finger installations. The purpose of the string was to function as a tendon for each individual finger.

*Figure 26 3D printed finger assembled*

Once each finger had been assembled and installed, the cover was ready for installation. The cover was held on by 3 #10-24 allen head screws. each hole that was designed to hold a screw was sized to be self-tapped; this includes both the screw eyes and allen screws.

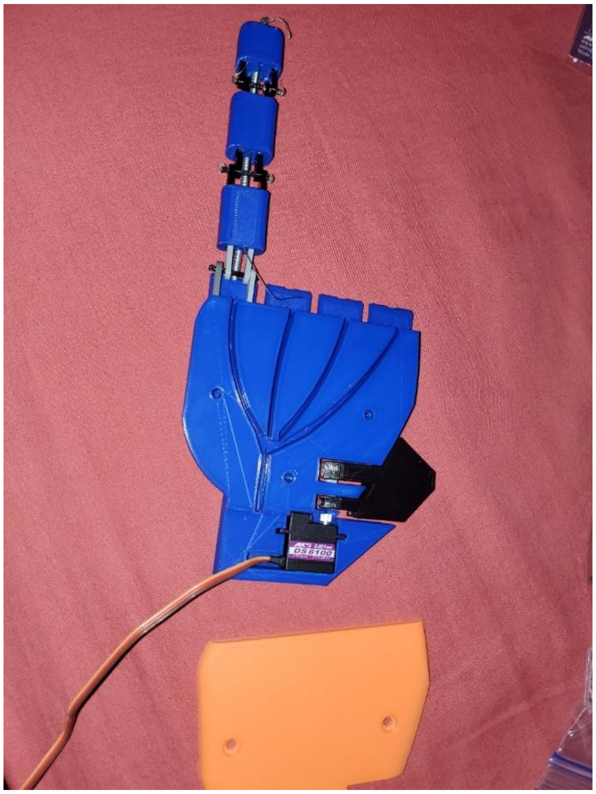

*Figure 27 3D printed, palm and finger assembled with motor installed*

## Application

Once assembled, the coding and testing phase began. The hand was successful in retracting and extending each finger.

*Figure 28 3D printed finger bent*

Arduino code was written in C++ language to support the thumb actuation. The code was just a simple program that could be triggered by the press of a button. An Arduino had not been officially identified for use with this project therefore an Arduino nano was utilized in the meantime.

Thumb_button_test | Arduino 1.8.19

File Edit Sketch Tools Help

Thumb_button_test

```
#include <Servo.h>

Servo myservo;  // create servo object to control a servo
// twelve servo objects can be created on most boards

int pos = 70;  // variable to store the servo position
int Sw = 2;
int State;
void setup()
{
  myservo.attach(3);  // attaches the servo on pin 3 to the servo object
  pinMode(Sw, INPUT);
  myservo.write(pos); // tell servo to go to position in variable 'pos'
  Serial.begin(9600);
}

void loop()
{
  State = digitalRead(Sw);
  delay(100);
  ///*
  if ((pos == 70) && (State == HIGH))
  {
    State = digitalRead(Sw);
    pos = pos + 30;
    myservo.write(pos);
    Serial.println(pos);
  }
  delay(100);
  if ((pos == 100) && (State == HIGH))
  {
    State = digitalRead(Sw);
    pos = pos + 40;
    myservo.write(pos);
    Serial.println(pos);
  }
  delay(100);
  if ((pos == 140) && (State == HIGH))
  {
    State = digitalRead(Sw);
    pos = pos - 70;
    myservo.write(pos);
    Serial.println(pos);
  }
  //  */
}
```

*Figure 29 Hand operating Arduino Code*

The hand was rather large and slightly flimsy. Since the springs utilized were extension springs, the reactive compressive forces applied to them prevented the fingers from bending backwards.

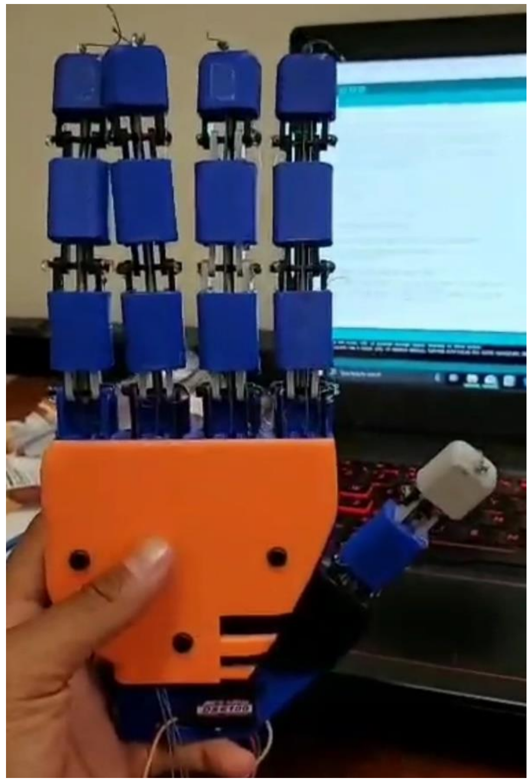

*Figure 30 3D printed hand fully assembled*

The hand was able to grasp and release a foam ball with the biggest obstacle being object retention due to the low surface friction of the PLA material.

# Chapter 4: Testing of additional materials

Once the regular PLA hand had been designed, modeled, printed, and assembled; the next phase began. The next phase of the research was to alter the material to a more suitable one for translating force. Three different 3D printed materials were examined and compared.

## Material Identification

The next phase of the research was to alter the material to a more suitable one for translating force. Three different materials were examined and compared, PLA, TPU, and Conductive Polylactic Acid (CPLA). The PLA material was a common brand known as Hatchbox, it was a typical basic hobbyist filament boasting no conductivity or elasticity, mainly highlighting its reliability and a fine dimensional tolerance of +/- .03 mm [35]. The TPU sample was manufactured by Overture. It listed a shore hardness of 95A and the capability to stretch 3 times more than its original length [36]. The manufacturer stated the filament having a dimensional tolerance of +/- .05 mm [36]. The CPLA was Proto-Pasta's conductive PLA material consisting of a PLA base with carbon black and polymer additives. The material density was approximately 1.24 grams per cubic inches with a melting point of 155 degrees Celsius [37]. Unprinted, it featured a volume resistivity of 15 ohm-cm; The volume resistivity of a printed sample in the X and Y direction was stated to be 30 ohm-cm and in the Z direction was 115 ohm-cm [37]. The resistance of a 10 cm section of 1.75 mm diameter filament was listed to be 2 – 3 Kilohms (Kohm) [37], when measured, the resistance read 3.04 Kohm for a 10 cm segment of filament however, this was fresh from the spool resulting in a slightly curved piece.

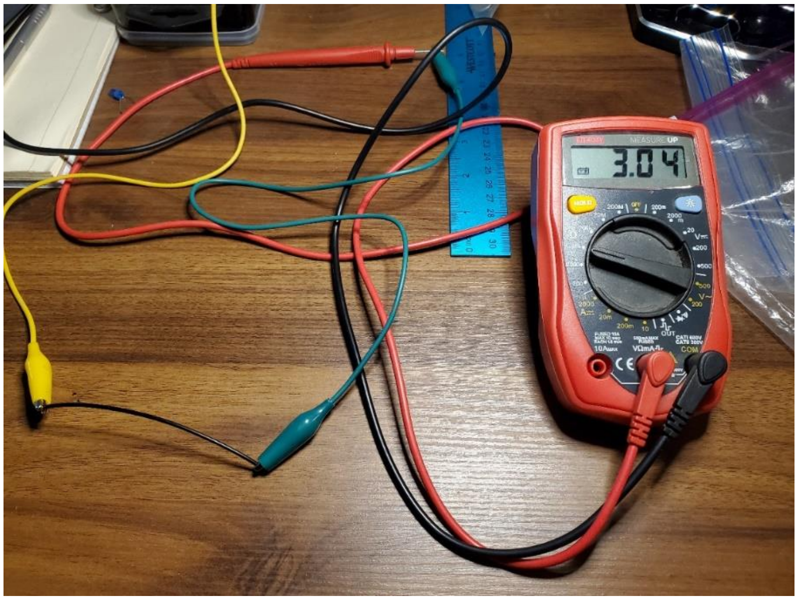


*Figure 31 Multimeter reading for a 10 cm CPLA segment*

A small test sample was printed in order to witness the conductivity of the material. The base of the sample was printed in white PLA with two paths of CPLA on top.

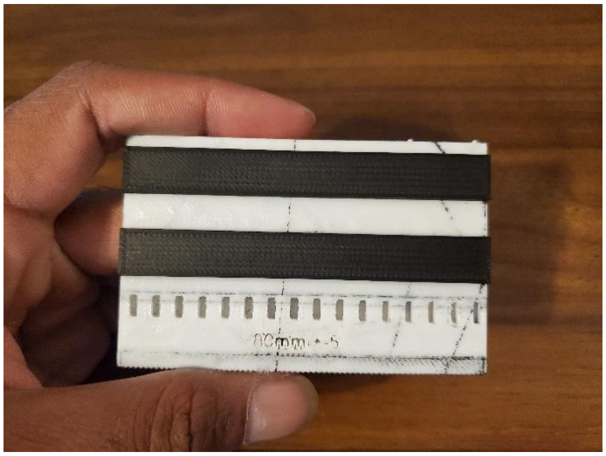

*Figure 32 CPLA conduction test*

A 9V battery was placed on one end and an LED was placed on the opposite end.

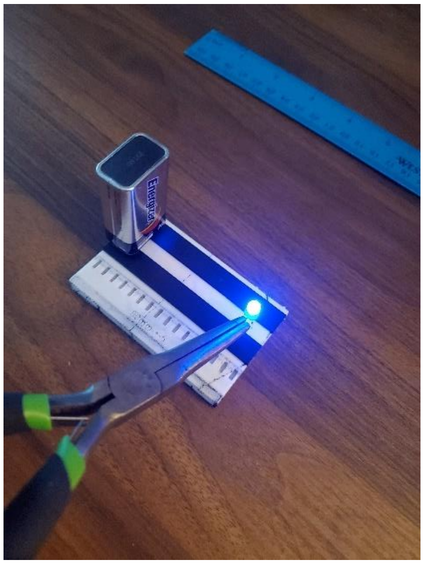

*Figure 33 9V LED conductive test ~70 mm*

As the LED was moved to different locations along the test piece in an effort to see if the brightness would fluctuate or change.

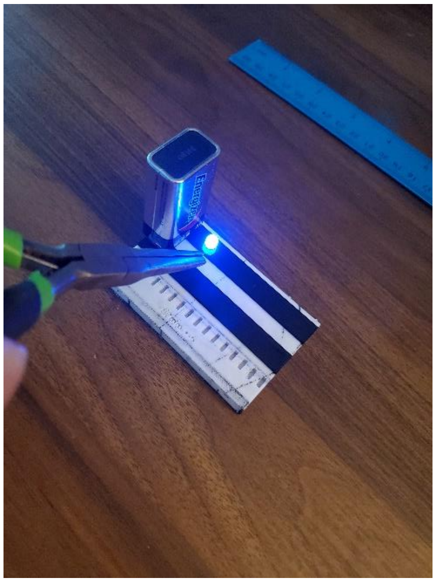

*Figure 34 9V LED conductive test ~1 5 mm*

While conductivity was evident, no change in brightness was witnessed.

In order to continue the idea of low cost and hobbyist printer/person friendly, a Wheatstone bridge was created using 1K Ohm resistors, an Arduino nano, and a 40x3x2 mm test sample.


*Figure 35 40x3x2 mm test sample*

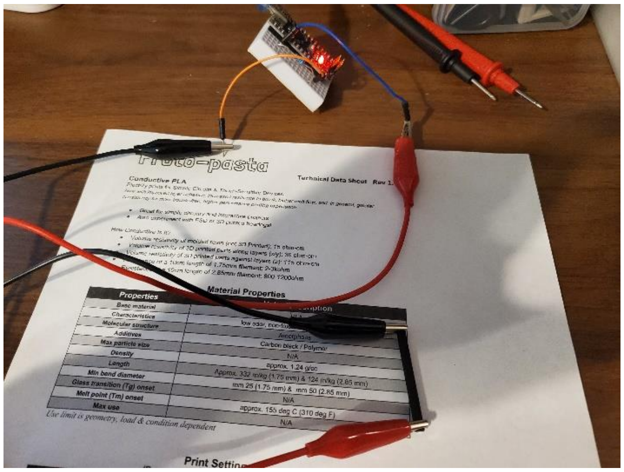


*Figure 36 1k ohm Wheatstone bridge circuit with CPLA*

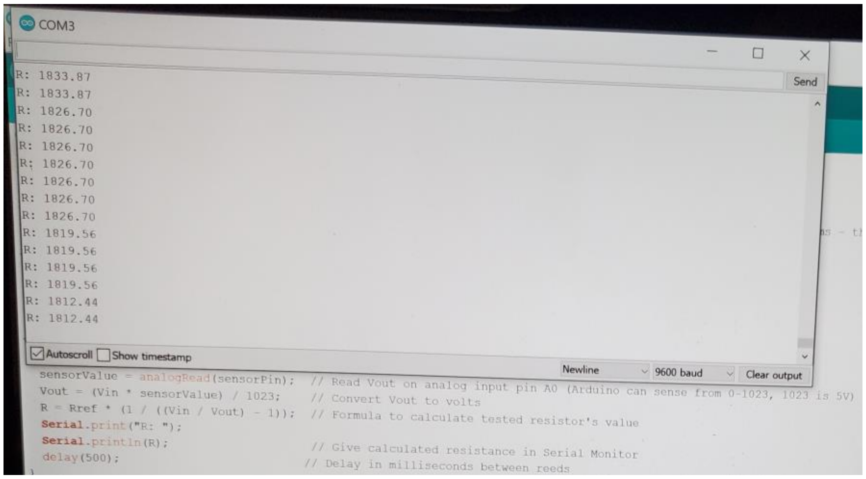


*Figure 37 CPLA Wheatstone bridge ohm reading*

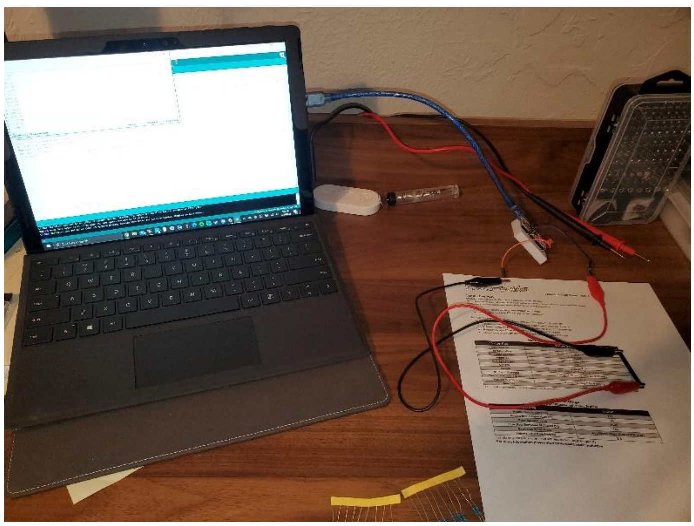

*Figure 38 Functional Wheatstone bridge utilizing CPLA sample*

The Wheatstone bridge functioned as intended

## Test and Testing Procedures

When comparing the materials against each other for piezoresistivity, industrial testing equipment was utilized, two of the three test materials were evaluated twice on dog-bone shaped 3D printed samples each made of a different material.

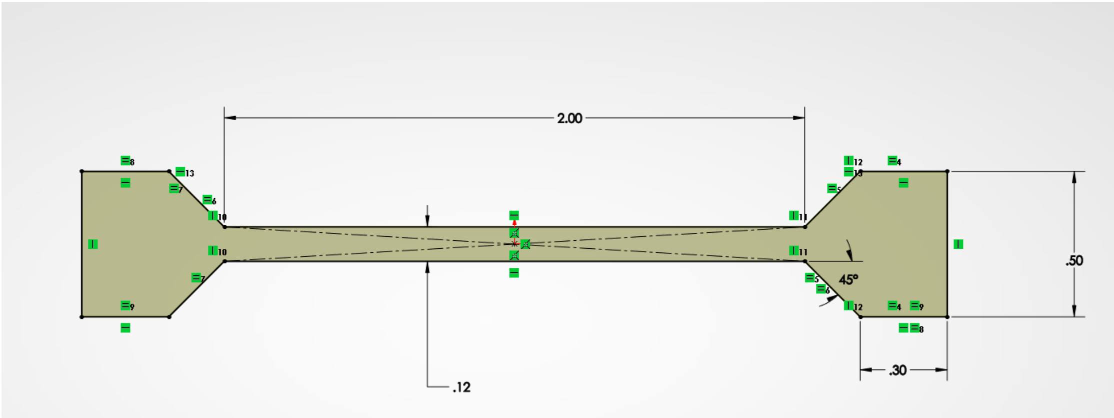


*Figure 39 Dogbone CAD drawing*

The TPU was evaluated one time due to its test results. The machines utilized for the material test were the Instron 5969 for tensile testing and the Hioki RM3545 multimeter for resistance measuring.

*Figure 40 Instron 5969 test machine [38]*


*Figure 41 Hioki RM3545 multimeter [39]*

The parameters tested were resistance verses deformation, or piezoresistivity. The piezoresistivity is a measurement of the change in electrical resistance as a force is applied to the surface of the piezoresistive device or material.

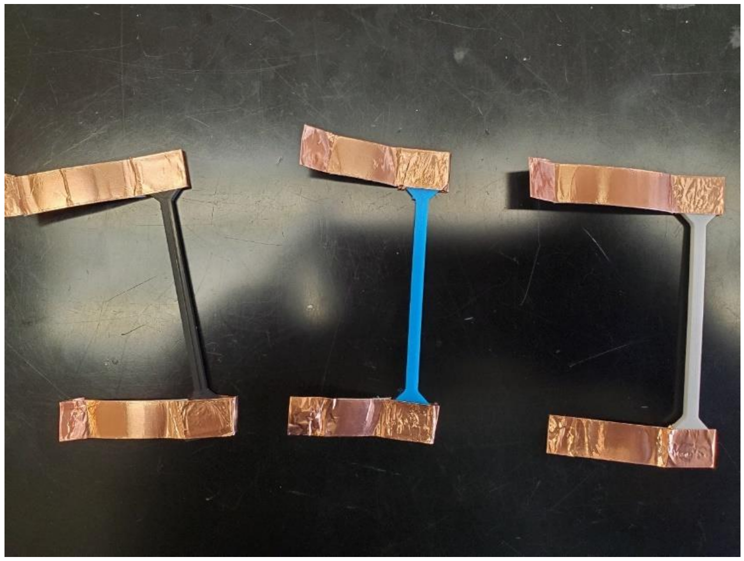

*Figure 42 Dogbone test samples*

Copper tape was attached to each end of the test samples so that a clear, noise reduced, ohm reading could be captured. The PLA material was tested first.

## Results

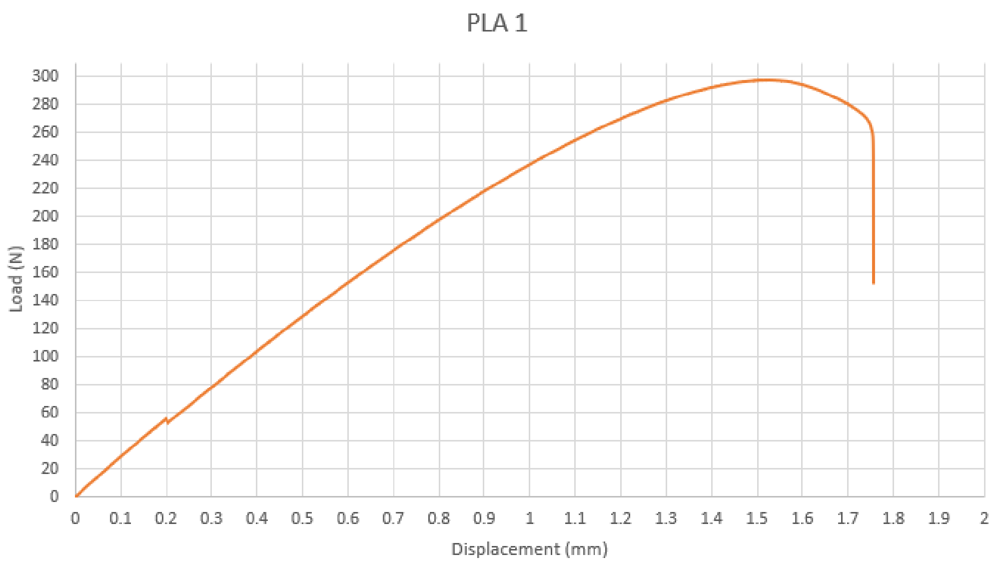


*Figure 43 Results for PLA 1*

The original PLA material used did not provide a piezoresistive reading therefore, a comparison against the materials resistance was not provided. The first PLA sample began to yield around 290 newtons of force before becoming plastically deformed, yielding, and failing at 258 newtons.

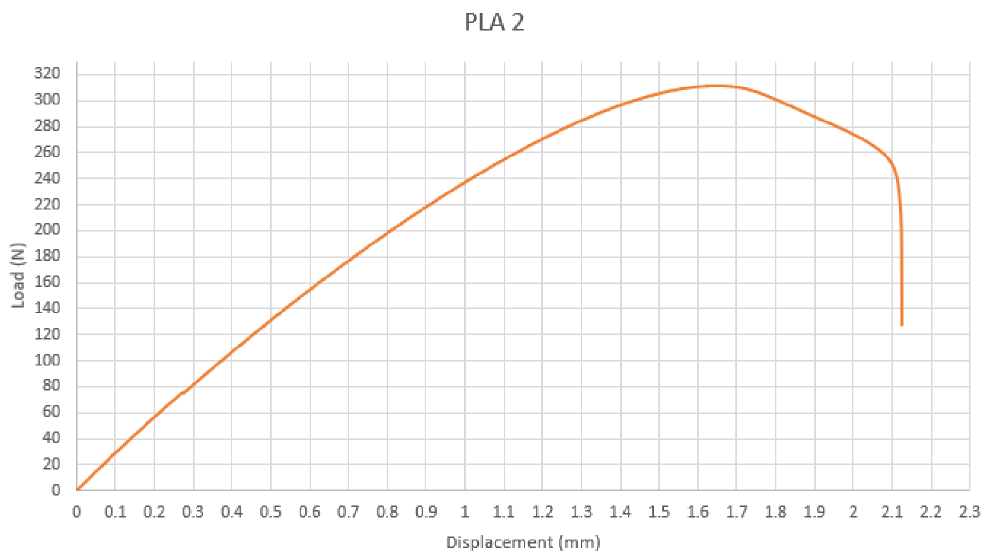


*Figure 44 Results for PLA 2*

The second PLA test sample experienced nearly 310 newtons of force before yielding and failing at 211 newtons.

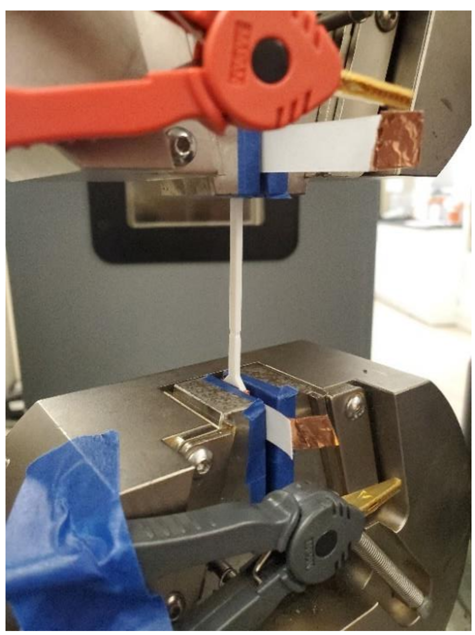

*Figure 45 PLA test sample and setup*

As displayed below, the multimeter read a null resistance reading.

*Figure 46 PLA resistance reading*

Next, TPU-95A was prepared and tested for piezoresistivity.

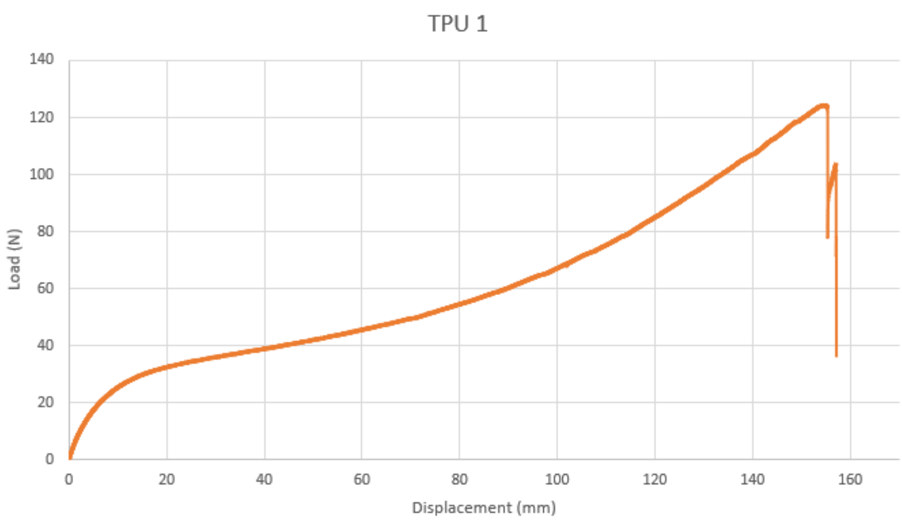


*Figure 47 Results for TPU-95A 1*

The TPU-95A test sample also provided a null resistance reading when monitored with the Hioki RM3545 therefor, its resistance graph reading was omitted from display. The TPU test sample took over an hour to fail and elongated over three times its original length however, its peak load experienced was only half that of the PLA samples. Due to this, only one TPU sample was tested.

*Figure 48 TPU 95A test sample and setup*

As stated before, the TPU's resistance fell in the same category as the PLA's resistance, too high to read. Its data chart was omitted from this section of the research paper.

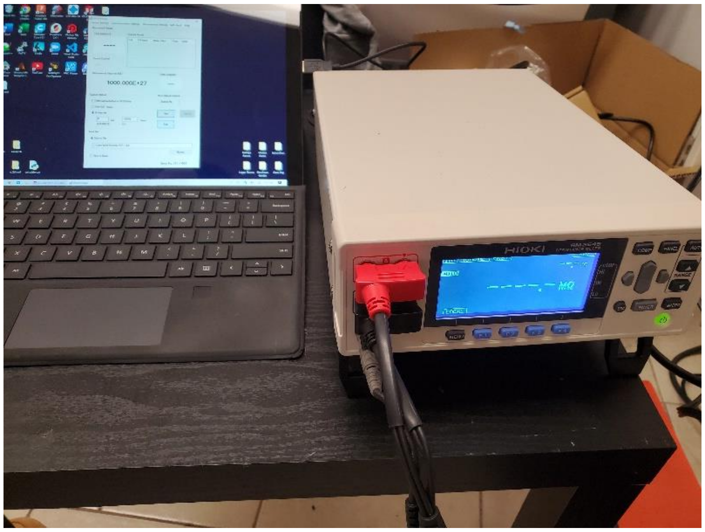


*Figure 49 TPU resistance reading*

The next set of samples tested were the CPLA samples.


*Figure 50 CPLA test sample and setup*

These test samples were the only ones that provided a resistance reading. Displayed on the left side of the graph is the force applied in newtons, the right side of the graph displays the ohm or electrical resistance reading.

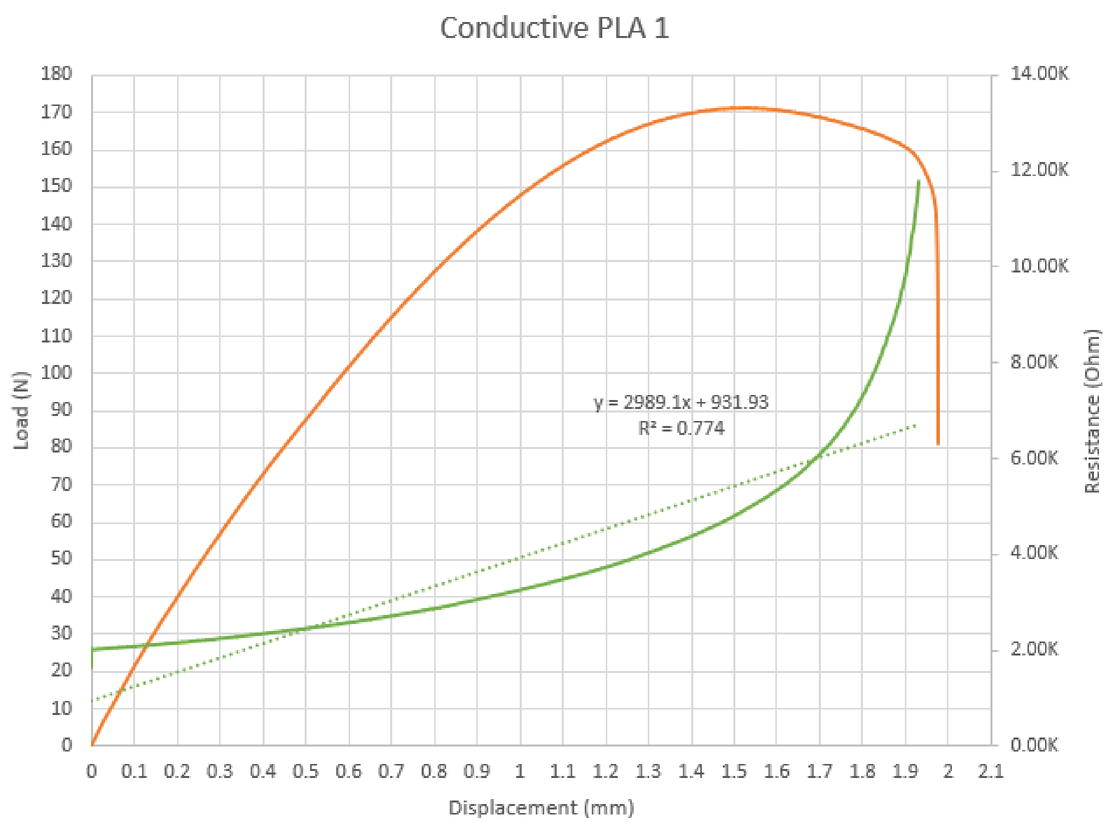


*Figure 51 Piezoresistivity results for CPLA 1*

This data was interpolated due to the two different testing devices operating at different sample rates. The tensile machine provided data every .1 second while the multimeter provided data every .02 seconds. The conductive material proved the concept of piezoresistive force translation. Its operation and principle followed suit with that of a strain gauge. As more load was applied, the resistance value increased.

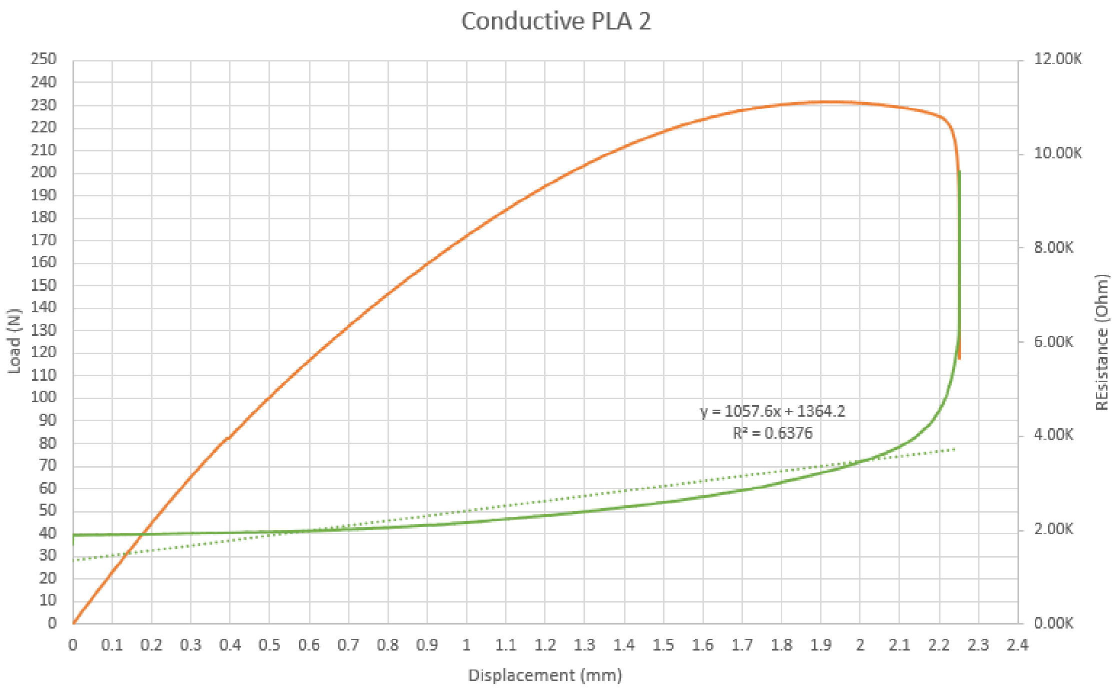


*Figure 52 Piezoresistivity Results for CPLA 2*

The CPLA test sample two followed suit of the first one. Changing its resistance upon an applied load until failure, where the resistance became unreadable.

*Figure 53 CPLA multimeter reading*

Due to the CPLA's addition of carbon black it allowed for the change in resistance across an applied force to be represented much better than the other test samples.

# Chapter 5: Way Forward

## Functionality Redesign

The way forward for this research includes methods of improved testing, sizing stipulations for the hand and material application/incorporation. The methods of improved testing would include cyclic loading test of the finger segments/joints until failure. This would provide data supporting assumptions for the longevity of the prosthetic device for both mechanical and chemical properties. The current hand weighed a total of 312 grams (.688 lbs.) with the palm assembly, motor included, weighing 213 grams and each finger weighing roughly 21 grams each. This could be improved by altering the print and design parameters such as the infill pattern and density which was 40%, reducing the overall length and width of the hand, and even going as far as conducting a topology optimization study to identify the critical areas and reducing the hand down to those key areas. Lastly, for a functional redesign, new material incorporation would be required. The proposed materials would be a combination of TPU for comfort and flexibility and conductive PLA on the tips for sensing piezoresistivity. Regular PLA would be applied to some areas where higher flexural strength was needed. It is important to note that other materials could be utilized within the hand design. The deciding factor comes down to budget and functionality.

# Chapter 6 Conclusion

The goal of this research was to prove the idea that a 3D printed prosthetic could be printed on a hobbyist level printer with materials accessible to the common public. Another goal was to verify that pressure could be translated from a force into readable data and applied to the prosthetic with 3D printed materials. The most difficult portion of this research was obtaining low-cost conductive filament. Many of the listed websites claiming to sell filament spools with graphene or carbon black content were either extremely expensive, sold out, or no longer in service. With many iterations of improvement and fine tuning, this discovery could tilt the odds in favor of an amputee without substantial income to afford the average 15k prosthetic [40]. As previously stated, the improvements would fall in the realm of not only incorporating a material possessing force sensing capabilities, but also improving the weight, size, and versatility of the hand. In conclusion, it was found that FDM methods on a hobbyist level printer with low-cost materials allowed for the production of a working prosthetic.

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