Introduction to Soft Robotics

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TABLE OF CONTENTS

NOMENCLATURE

Alloy	A mixture of metallic materials
Critical temperature	Temperature at which phase transformation occurs in a smart material
Cross section	The shape/area of a beam exposed if cut perpendicular to its length
(Electrical) current	The flow of electrical charge through a material via electrons
Directly proportional	When one variable increases the other increases by the same factor
Distal joint	The joint in the finger closest to the finger tip
Elastic Region	Range of deformation where stress and strain are directly proportional; deformation is impermanent
Good (electrical) conductor	A material that greatly resists the flow of electrical current or traveling electrons
Inversely proportional	When one variable increases the other decreases and vice versa
Joule heating	Dissipating heat by passing a current through a resistor
(Bending) moment	The extent to which a force causes bending of a body (usually a rod or beam)
Moment of inertia	The resistance of a particular cross section to bending about a specific axis
Phalanx (phalanges)	A bone (or bones) of the fingers or toes
Poor (electrical) conductor	A material in which the flow of electrical current or traveling electrons
(Electrical) resistance	Opposition to movement of electrons or passage of electrical current
Shape memory effect	The ability of a material to return to its original shape when heated to a critical temperature
Smart material	A material whose properties (strength, stiffness, conductivity, etc.) change significantly when its environment (temperature, electric field, etc.) changes
Strain	Object's response to applied stress
Stress	Force per unit area within material body
Yield point	Point at which chemical bonds begin breaking and permanent deformation occurs

1. INTRODUCTION

Most traditional robots are used in isolated environments because their size, heaviness, and rapid movement can be dangerous or unhelpful for interaction with humans. There is a growing interest and need for technology that allows capable robots to be used alongside humans for application domains including home health care, medical procedures and interventions, factory automation, and military personnel support. The main challenge in developing robots of this nature is achieving flexibility and dexterity without sacrificing the strength necessary to perform useful tasks such as lifting a person out of bed.

Studying the brilliantly complex design of the human body proves that such capabilities are possible. Unfortunately, current technology does not allow for exact replication of the complicated tissue in the human body which can be both strong and flexible. However, the basic ideas of rigid bones with joint motion controlled by tendons serves as inspiration for robot technology.
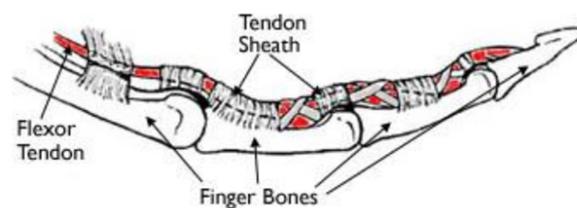

Figure 1: Diagram of Human Finger.

Consider the human hand, for example, where fingers, are capable of straightening and curling inward with great force. Strong tendons, as seen in Figure 1, pull on the bones of the finger when muscles in the forearm contract. These long tendons provide high strength, and they control most of the motion of the fingers. Smaller muscles in the hand control small movements such as side-to-side motion at the base of the fingers. Similar design concepts from the human hand may be incorporated into a robotic hand with similar capabilities.

2. BACKGROUND THEORY

Many of the biological concepts may be integrated in a robotic hand with similar capabilities using simple engineering principles. Understanding the engineering principles behind the design of the hand is the first step in creating a functional replica.

2.1 STRESS

Stress is defined as the force per unit area within a material with an applied load. It represents the force experienced relative to the size of the object being stressed. For example, consider two pieces of wire that are identical except in their diameter. If both wires are pulled with the same force, which one will experience greater stress? Intuitively, we can expect that the narrow wire experiences higher stress than the thick wire because the thin wire has less material (or cross-sectional area) to share the load with.

Alternatively, we can consider the question from a mathematical perspective. When the force is applied in tension (pulling the material along its axis), the stress is calculated from F/A, where F is the applied force and A is the cross-sectional area of the object. Since the area appears on the bottom of the fraction, we can say that the stress and the cross-sectional area are inversely proportional. This means that when the area increases, the stress decreases; and when the area decreases, the stress increases. Since the thin wire has a smaller cross-sectional area, it experiences higher stress when pulled with the same force as the thick wire.

2.2 STRAIN

Strain is the object's response to an applied force; it can be thought of as a measure of elongation relative to the length of the object. Consider the same two wires being pulled with the same force again. Regardless of what the wire is made of, we can expect that they will stretch at least a little. The thin wire will stretch more under the same load as the thick wire, so the thin wire is said to experience higher strain. The wire's strain represents how much the wire stretches; it depends on the stiffness of the material and the stress experienced by the object.

2.3 STRESS-STRAIN RELATIONSHIP

Often in engineering, a stress-strain curve is used to characterize the properties of a material. To make a stress-strain curve, data is usually collected from a simple tension test experiment. Similar to the wire example, a rod of the material is gripped at both ends by a machine that pulls the rod in tension. As the rod is slowly stretched, the tension in the rod and the amount of stretching are measured simultaneously.
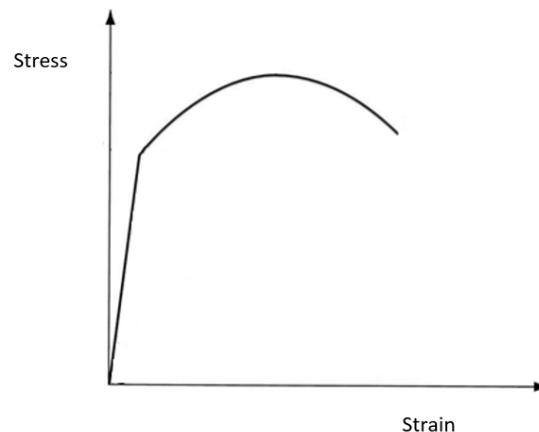

Figure 2: Typical stress-strain curve for metal material.

These tension (force) and stretching measurements can then be converted into stress and strain values using the dimensions of the rod. Plotting the stress on the Y-axis with the strain on the X-axis gives us a graph that characterizes the material's behavior under different loadings. Figure 2 shows a typical stress-strain curve for a metal material.

The first portion of the curve is linear; this is called the elastic region. When materials are stressed within the elastic range, the stress and strain are directly proportional, meaning that if the force applied (or stress) is doubled, the resulting strain (or elongation) is also doubled. Elastic deformation is reversible, so the material will return to its original length when the tension is released.

The point at the end of the linear region is called the yield point. Stressing the material beyond the yield point causes some permanent deformation as chemical bonds begin to break. As the material is stretched beyond the elastic region, the relationship between the stress and strain changes such that a large increase in elongation (strain) is caused by increasing the stress (or applied force) only slightly.
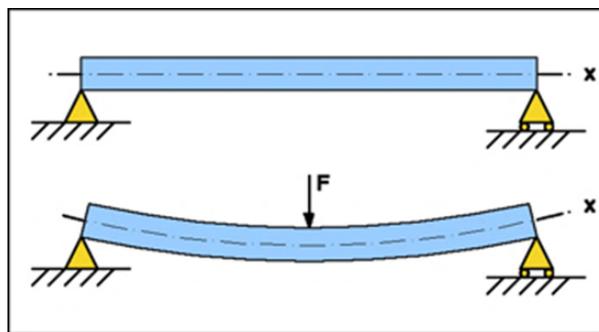
2.4   BENDING MOMENT

Figure 3: Example of a bending moment caused by a downward force applied at the center of a beam.

A moment measures the extent to which a force causes bending of a body (usually a rod or beam). A typical example of a bending moment is shown in Figure 3, where a simple beam experiences a bending moment caused by a downward force applied at the center.

In the case of the human finger, the tendon running along the finger bone causes a bending moment in the joints which makes the finger bend. The moment is calculated from F×d, where F is the applied force and d is the perpendicular distance from the force to the joint. The bending moment is thus dependent on the distance from the force to the joint, meaning that the offset of the tendon from the bones is crucial.

Figure 4: Two joint designs demonstrating the importance of the offset between the tendon and the joint/bones.

For example, consider the two joint scenarios shown in Figure 4. Notice how changing the offset of the tendon from the bones/joint affects the bending moment on the joint.

Since the moment is directly proportional to d, applying the same force to each setup will cause a larger bending moment about the joint in the setup on the left. This means that a larger force is required to bend the finger if the tendon runs very close to the bones/joint.
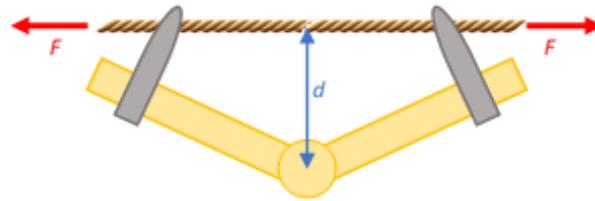

Figure 5: Bent joint with increased bending moment due to increased distance between tendon and joint.

The distance between the tendon and joint is also affected by the angle of the joint. As seen in Figure 5, d (and thus M) increases when the joint is bent. This means that the same force can cause a larger bending moment in the joint when it is bent. For this reason, the human fingers are stronger when they are curled than when they are straight.

2.5 MOMENT OF INERTIA

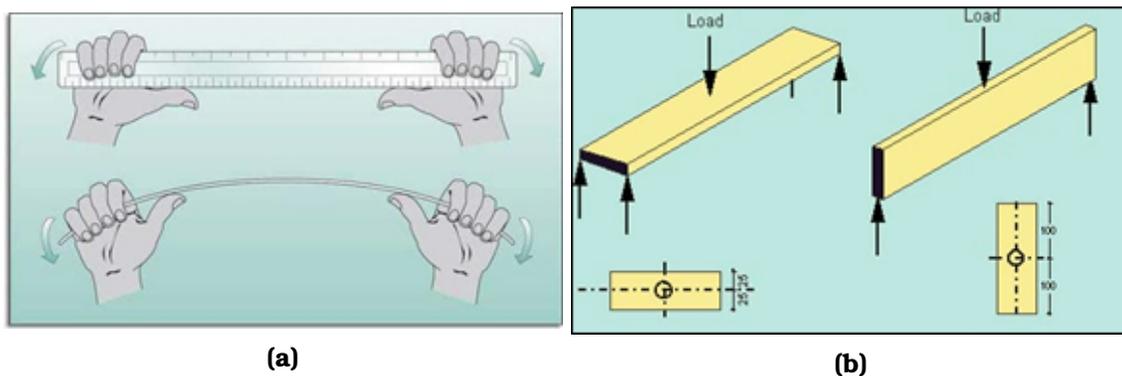(a)   (b)

Figure 6: (a) Bending inertia of ruler affected by orientation. (b) Increased height significantly increases the bending inertia.

The moment of inertia represents the resistance of a particular cross section to bending about a specific axis. Consider the bending of a ruler as shown in Figure 6a. Bending is much easier in one direction than the other. This is because the ruler has a different moment of inertia about the different axes.

When studying the bending of the human finger, the moment of inertia plays a significant role in the force required to bend the finger. In general, increasing the cross-sectional area (especially the height) of the member increases its resistance to bending. Thus, a greater force is required to bend thick fingers due to their higher bending inertia.

2.6   SMART MATERIALS

Smart materials are materials whose properties (strength, stiffness, conductivity, etc.) change significantly when their environment (temperature, electric field, etc.) changes. These types of materials are especially useful for soft robotics because they can mimic biological members such as human muscle tissue which is flexible but can become strong and rigid when contraction occurs.

Nitinol is a smart material with unique properties that lend themselves well to the soft robotics domain. It is an alloy (mixture) of nickel and titanium with properties that change at a specific critical temperature. Above the critical temperature, the Nitinol becomes very stiff and thus resistant to bending. Below the critical temperature, it undergoes a phase transformation making it bendable and significantly softer. When the material is reheated above its critical temperature, it returns to its initial shape. This unique behavior is called the shape memory effect.

Another smart material of interest is Field's metal. Field's metal is composed of a mixture of Tin, Indium, and Bismuth combined in a specific ratio such that the Field's metal melts at a very low temperature (62°C). This low melting-temp metal is useful for robotics applications because it is stiff in its solid state (above 62°C) and liquid (0 stiffness) below its melting point.

Similarly, PCL (polyacrylonitrile) is a plastic that can be considered a smart material because is softens and melts at very low temperatures. The plastic is rigid at room temperature but softens and melts around 50°C.

2.7   ELECTRICAL RESISTANCE

Remembering from chemistry class, electrons have a negative charge while protons hold a positive charge. The flow of negative charge as electrons travel through a material is called electrical current. Some materials, including most metals, allow electrons to pass through easily; we call these materials good conductors. Good conductors have low electrical resistance because they do not resist the flow of electrons. Other materials such as plastics and some ceramics hold electrons tightly and thus resist the flow of electrons. These materials have a high electrical resistance and are classified as poor conductors. Good conductors (low electrical resistance) are usually desirable for efficiency because resistance slows the charge transfer and causes energy loss. However, in some cases energy loss is a desirable outcome as it produces heat. Similar to frictional resistance on a moving object, energy lost through electrical resistance also causes energy to be dissipated as heat. This principle is called Joule heating. The typical baseboard heaters found in many houses operate from this simple principle where a current is passed through a long, thin heating element with a high electrical resistance to maximize heat dissipation.

In the case of the soft robotic hand, the stiffness of the joints is controlled by altering the individual joint temperatures. This localized heating can be easily achieved using the Joule heating principle. Nichrome is a high resistance metal that is often used for heating elements. The joints can be heated individually by passing current through Nichrome wire that is wrapped around insulated Nitinol, Field's metal, or PCL joints.
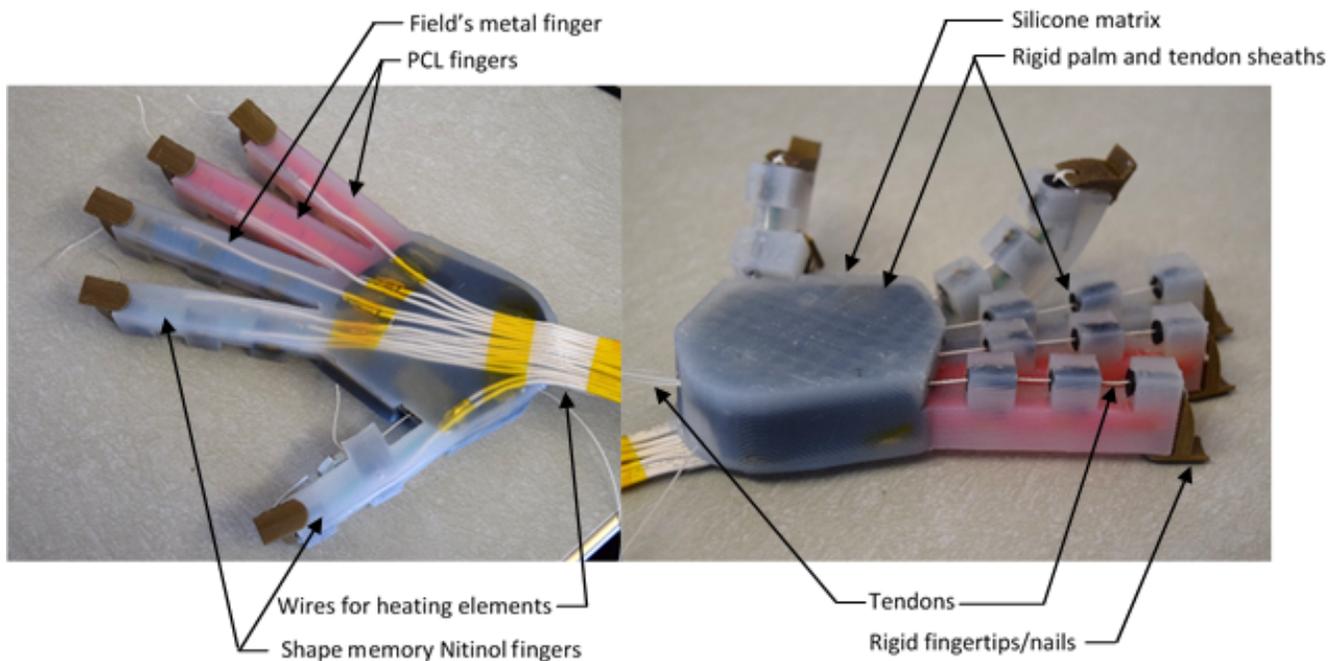
3. SOFT ROBOTIC HAND

Figure 7: Soft robotic hand featuring multiple smart materials.

The soft robotic hand is designed to mimic cunning biological features such as tendons, bones, and flexible tissue. Figure 7 shows the design of a simple soft robotic hand. Each of the engineering principles discussed above (stress, strain, bending moment, moment of inertia) are factors that play into the functionality of the design.

3.1 DESIGN FEATURES

Similar to the human hand, the soft robotic hand is capable of curling and extending the fingers with enough force to grasp items with dexterity and precision. The fingers demonstrate 3 different smart materials that can be used to achieve the desired strength and joint controllability. The hand is designed to be light, soft, and safe with no sharp edges or pinching hazards. The fingernails and grippy silicone allow it to grasp items of various shapes, sizes, and textures.

The palm is 3D printed with ABS filament to maintain rigidity and support each of the fingers and corresponding tendons. The human hand utilizes two major sets of tendons to control the finger movements; one set of tendons curls the fingers and the other straightens them. The use of Nitinol, Field's metal, PCL, and Silicone in the soft robotic hand allows for complete control of the fingers using just one set of tendons.

The fingers curl when the tendons are pulled and the finger joints are held at the appropriate temperature to allow bending at the joints. A Nitinol thumb and index finger extend from the palm, providing strength at high temperatures and flexibility in the joints at low temperatures. The middle finger consists of a Field's metal rod that can be melted at the joints to allow the finger to curl when the joints are held at a high temperature. The ring and pinky fingers are comprised of PCL rods that may be melted at the joints to allow bending. Any of the fingers may be curled by pulling the corresponding tendon and holding the joints at an appropriate temperature to achieve flexibility in the particular smart material.

Unlike the human hand, which requires a second set of tendons on the back of the hand to straighten the fingers, the fingers in the soft robotic hand straighten themselves with the appropriate temperature stimulus. Since the Nitinol is a shape memory alloy, the thumb and index finger return to their original (straight) shape when the Nitinol is heated above the critical temperature and the tendon tension is released. The Field's metal and PCL do not exhibit the shape memory effect, but their flexibility in the liquid state allows them to straighten without actuation. Because the silicone rubber is cast with the fingers straight, the elasticity of the silicone causes the middle, ring, or pinky finger to straighten when the Field's metal or PCL is melted at the joints and the tension in the tendon is released.

The ABS 3D printed rigid links mimic the bones of the fingers, preventing bending of the Nitinol rods except at the joints. The middle, ring, and pinky finger do not need rigid links to prevent bending between the joints because the heating elements are located only at the joints and do not melt the PCL or Field's metal except at the joints, so the fingers remain rigid between joints. The tendon sheaths prevent the tendons from tearing through the silicone and hold the tendons at an offset from the Nitinol rods to increase the bending moment applied by the cable tension. The entire assembly is encased in silicone to protect the components and replicate the texture of the human hand. The silicone is notched at the finger joints to decrease the bending inertia and the friction on the tendons. The fingertips/nails aid in the grasping of objects and also provide a tying location for the ends of the tendons. This helps distribute the load from the tendons across the surface of the finger tips.

Localized heating of the smart materials at the finger joints is achieved by passing electrical current through Nichrome wire wrapped around the smart material at the joints. Because Nitinol and Field's metal are conductive materials, a thin layer of insulation prevents direct contact between the Nichrome and the smart material. Since the Nichrome has a high electrical resistance, the current would prefer to pass through the Nitinol or Field's metal (lower resistance) if given the chance. The insulation prevents the current from traveling through the Nitinol or Field's metal, forcing it to flow through the higher-resistance Nichrome wire which dissipates much more heat to stimulate the temperature-induced transformation of the Nitinol or Field's metal.

The pointer finger is wired with separate heating elements for each joint so that the joints may be controlled individually. The thumb is equipped with two tendons so that it may be moved in two different directions, hence the thumb link with two separate tendon sheaths. For simplicity, the last three fingers have only one heating element per finger that heats all 3 joints with only one connection to the power supply. Thus, the 3 joints in the middle, ring, and pinky finger can only be moved in synchrony. Wiring these joints

with separate Nichrome elements would allow individual joint control but would require more wires and added complexity.

The movement of the hand may be controlled by manually connecting the heating elements to the power supply and pulling on the tendons by hand. Alternatively, for more advanced control, a control system may be implemented to pull the tendons with servo motors and heat the joints to desired temperatures via relay switches that modulate on/off when based on feedback from temperature sensors near the joints.

4. HAND ASSEMBLY

4.1 NECESSARY EQUIPMENT

- 3D printer (Minimum 6.125"x6.125"x1" build volume)
- Wire cutters
- Hand drill with drill bits
- Calipers
- Heat gun
- Pump and vacuum chamber (optional)
- Pointed tweezers
- Power supply (2 A, 20 V) with alligator leads

4.2 MATERIALS

- Ninjaflex filament (Ø3mm)
- ABS filament (Ultimaker Ø3mm)
- 3 ft PCL filament (FILAMENTS.CA's 2.85mm Low Temperature PCL Filament)
- 6" Nitinol wire (Ø1.91mm, shape memory)
- 2lb package of Silicone (Dragon Skin, 20 medium cure time)
- Nichrome 80 wire (32 AWG)
- 14g Field's metal (Roto144F Low Melt Fusible Ingot Alloy (Field's Metal))
- 15 ft Insulated copper wire (24-26 AWG, single strand, 105°C)
- 14 Molex female crimp terminals (18-24 AWG)
- Wire shrink insulation 2:1 heat shrink tubing (Ø1mm, Ø2mm, Ø4mm)
- Kapton tape or other electrical tape
- 6 ft Braided fishing line (Ø0.46mm, 100lb)

4.3 3D PRINTING

We will be using Cura to print the parts for the hand. Cura is an open-source software for "slicing" 3D models into many two dimensional slices for layer by layer printing on our 3D printer. As Cura supports many 3D printers with custom profiles, the instructions included here can be applied to most other machines.
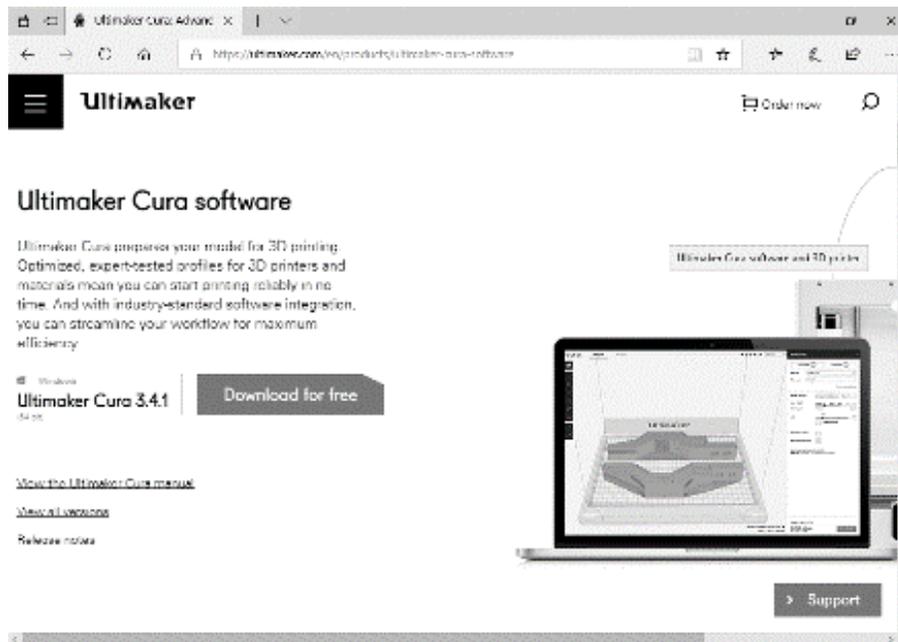
4.3.1 Printer Setup

1. Download and Install Cura

Figure 8: Download Cura, an Open-Source Slicer, from the Official Website

Navigate to : `https://ultimaker.com/en/products/ultimaker-cura-software` and click "Download for free". Once downloaded, proceed to install the software on your computer. When prompted to choose components, leave the default options selected, and click Install.

2. Profile Setup

(a) **(b)**
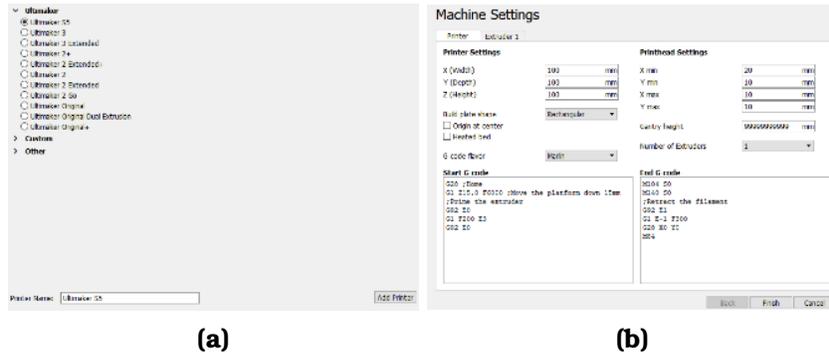
Figure 9: Default Profiles (a) & Manual Configuration (b)

In your first startup of Cura, you will be prompted to select your 3D Printer Profile. These profiles contain settings tailored to your specific printer, generally by the manufacturer, and contains sub-profiles for commonly used materials.

If you are using a printer currently listed in in these profiles, select it and click Add Printer then skip to step #4. Otherwise, select the Custom, click on "Custom FDM Printer". When prompted for Machine Settings, click "Finish"

3. Installing the latest Prusa i3 MK3 Profile
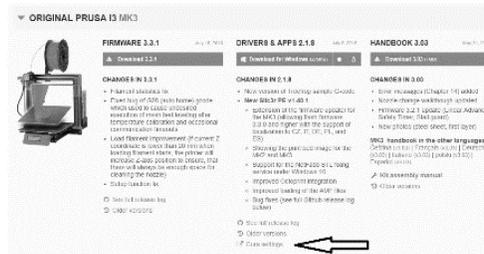
Figure 10: Install the latest Prusa MK3 profile

As the Prusa i3 MK3 does not currently have a default profile, we will need to download and manually install the latest profile. Prusa has created a step by step guide for this process. Navigate to `https://www.prusa3d.com/drivers/` and click on "Cura Settings", following the procedure to install the printer, layer height, material, and background profiles. Note that while we are provided with a profile for ABS, PLA, and PET, there is not one for NinjaFlex. We will have to create that profile manually later.

4. Learning to use Cura

   There are numerous resources available for learning the basics of Cura. If you have experience using other slicing software already, then the quick start guide available from Ultimaker is a good starting point. If this is your first time using a slicer and 3D printer, then their master guide is worth a read. This guide will assume from here on that you have familiarized yourself with Cura.

   Quick Start Guide:
   `https://ultimaker.com/download/24530/Cura%20quick%20start%20guide.pdf`

   Mastering Cura:
   `https://ultimaker.com/en/resources/21932-mastering-cura`

4.3.2 Printing the Components

1. Palm

(a) The Palm   **(b)** Palm Settings
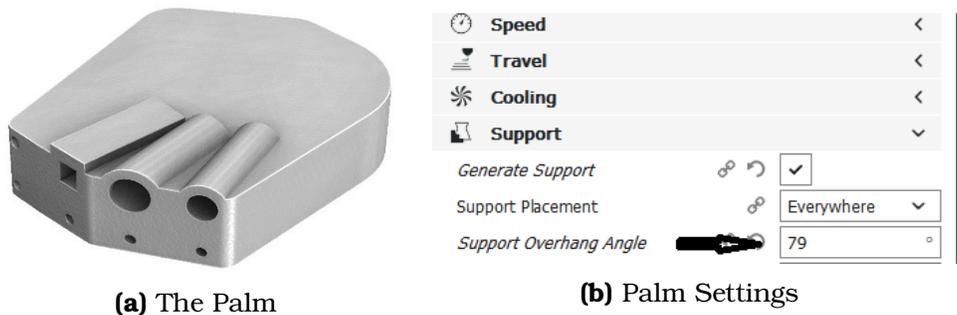
Figure 11: Palm & Print Settings

The palm, shown above in Figure 11a, is a single part which contains internal channels for tendons to pass through, along with inserts for the nitinol, fields metal, and PCL. Two of these inserts will require supports to ensure dimensional accuracy.

Select the following default profiles:

- Material Profile:

   `Prusa ABS`

- Layer Profile:

   `MK3_0.15_Optimal`

Enable custom settings and scroll to "Support", changing "Support Overhang Angle" to 79°, as shown in Figure 11b. This will only print supports where required and minimize post print cleanup. The Palm is now ready to print, and once done, the supports can be removed with a pair of tweezers or pliers.

2. Links & Sheaths

The parts most likely to fail to print are the links and sheaths. These components have very small areas with which to adhere to the print bed. Therefore, we will print these components in batches, reasonably close together, and use brims instead of the default skirts.

Load up one of each Link, and Sheath, then right click on each component and select "multiply". You will need to print **2** *Rigid End Caps*, **2** *Rigid Links*, **9** *Tendon Sheaths*, and **1** *Thumb Link*.

Select the following default profiles:

- Material Profile:

    `Prusa ABS`

- Layer Profile:

    `MK3_0.1_Detail`
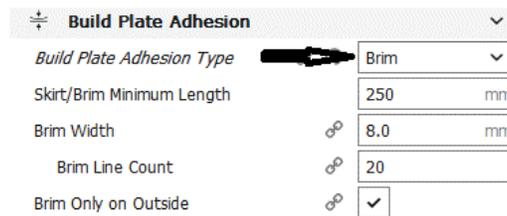
Figure 12: Build Plate Adhesion Settings

Enable Custom Settings, and scroll to "Build Plate Adhesion", changing "Build Plate Adhesion Type" from Skirt to Brim. Leave all other settings as their defaults. Once the parts have been printed, the brim can be peeled off from each part, and a light sandpaper can be used to smooth out any rough edges.
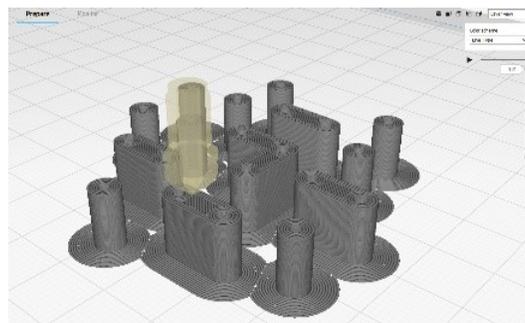
Figure 13: A tight placement will reduce print time & failures

Arrange the parts on the print bed so that they are close to one another, but not overlapping. You can have Cura auto arrange, which will use the build plate adhesion settings from Figure 12 to set initial placements, then shift them closer together manually, if necessary. You should have a build placement similar to that shown in Figure 13.
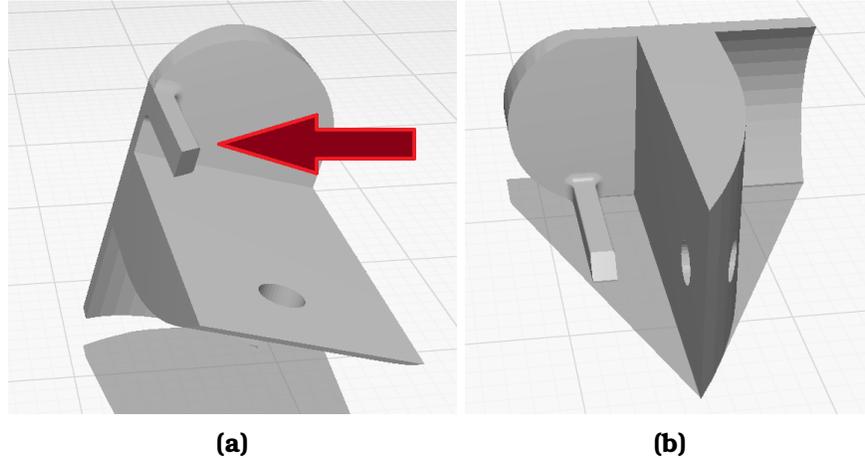
3. Finger Tips

Figure 14: Incorrect Orientation (a) & Correct Orientation (b)

Import the finger tip model, and ensure that the model is oriented as shown in Figure 14b. Multiply the model until you have **5**. We will use the same settings from the previous step, but placement of the models does not need to be packed as before.

When removing the finger tips from the print bed, it is possible that the small clip, indicated by the arrow in Figure 14a, will break off if too much force is used in removal. To ensure the best chance of a successful removal, wait for the print bed to completely cool first. The bed, having been heated during the printing process, will naturally contract as it cools, and the parts are easier to remove as a result. Print extra finger tips if needed to replace broken ones.

4. Silicone & Field's Metal Molds
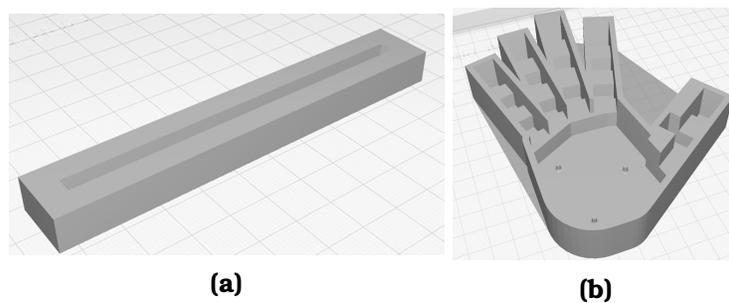
Figure 15: Field's Metal Mold (a) & Silicone Hand Mold (b)

Both molds used in the construction of the hand are going to be printed out of a TPU material known as Ninja-flex. On a printer such as the Prusa, we cannot print the material as quickly as ABS, because it is easily deformed at low pressures, such as being forced through a nozzle.
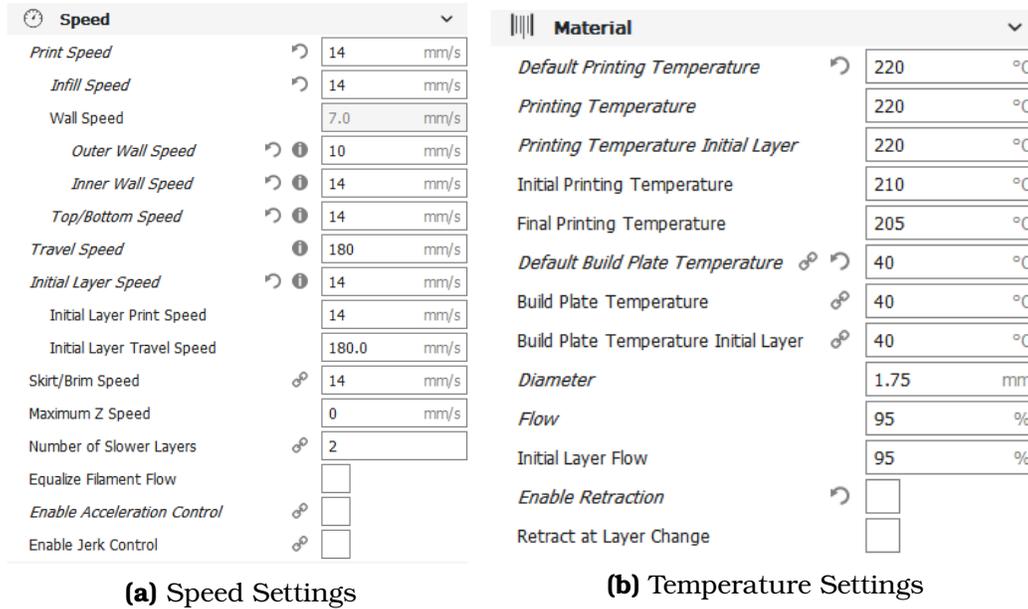
(a) Speed Settings   **(b)** Temperature Settings

Figure 16: Mold Print Settings

Select the following default profiles:

- Material Profile:

  Prusa ABS

- Layer Profile:

  MK3_0.1_Detail

Change the print speed settings to those shown in Figure 16a. This will increase print time, but reduce peak pressure being exerted on the filament.

The temperature in the default profile for ABS is too high, as the printing temperature for NinjaFlex is about 220C. Set the temperatures as shown in Figure 16b; additionally, disable retraction.

Disabling retraction means that the printer will never try to pull the filament back out when it is changing layers or passing over empty space or another part of the object. By default, the profile does not pass over printed areas of the object. The molds are mostly stacked walls, therefore there is little need for travel across large open spaces.

With this filament, we do not want to use a brim, skirt, or raft as these supports are very difficult to separate from the main body. Under "Build Plate Adhesion", seen back in Figure 13, change the type from skirt or brim to None.

4.4 ASSEMBLY INSTRUCTIONS

1. Print palm, rigid links, rigid end caps, thumb link, thumb end cap, tendon sheaths, Field's metal mold, and silicone mold according to 3D printing instructions above.

2. For the PCL fingers, cut 3 strands of PCL filament to 2.74" each for the pinky finger and 5 strands to 3.09" each for the ring finger. Heat the strands with a heat gun until they soften and become slightly translucent. Roll the strands together by hand on a flat surface until the filaments merge together to form a uniform cylindrical rod for both fingers.

3. For the Field's metal middle finger, heat about 14 g of Field's metal with a heat gun or on a hot plate just until completely melted. Pour the liquid metal into the Field's metal mold until filled and allow to cool. Remove from the mold once cooled and inspect for air bubbles. If substantial voids exist, melt the rod and repour it in the mold until a uniform rod is formed.

4. For the Nitinol fingers, cut one length of Nitinol wire to 3.16" for the index finger and one length to 2.61" for the thumb.

Table 1: Material lengths for fingers.

Finger	Material	Exposed Length	Total Length	Insulation Length & [Quantity]
Pinky	PCL (3 strands)	2.14"	2.74"	0.34"(Ø1mm)[x4]
Ring	PCL (5 strands)	2.49"	3.09"	0.45"(Ø1mm)[x4]
Middle	Field's metal (0.16x0.16" rod)	2.77"	3.37"	0.55"(Ø1mm)[x4] 2.87"(Ø4mm)[x1]
Pointer	Nitinol (Ø0.075")	2.26"	3.16"	0.41"(Ø2mm)[x3]
Thumb	Nitinol (Ø0.075")	1.71"	2.61"	0.54"(Ø2mm)[x2]

5. Cut insulation sleeve segments to the lengths listed in the right column of table 1.

6. Insert fingers into the printed palm. Note that some of the holes in the palm go all the way through; these holes are for the tendons. The smart material rods should fit into the holes that go about 1 inch deep into the palm. Since 3D printer tolerances may vary, the rods may not fit in these printed holes. If needed, drill the holes out with a hand drill to enlarge the holes. Use a #48 drill bit for the Nitinol fingers, #9 for the pinky, and #1 for the ring finger, being careful not to drill deeper than $\frac{3}{4}$ inch. The ends of the PCL fingers may also be softened with a heat gun prior to insertion in the palm for a snug fit.

Place the palm with smart material fingers into the silicone mold to make sure the fingers are exactly the right length. The ends of the fingers should almost touch the inside of the mold with the palm positioned as shown. If needed, recut the Nitinol fingers or melt and remove material from the PCL or Field's metal fingers to make a good fit in the mold.
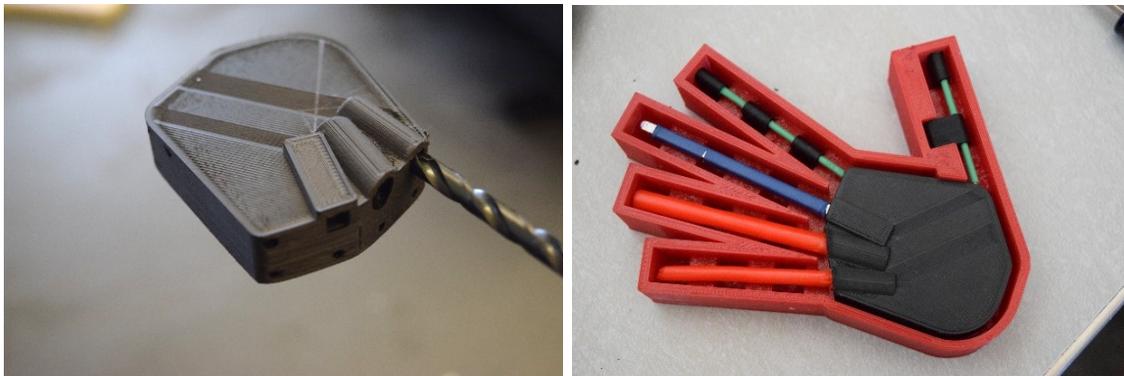
7. Slide the Ø4mm insulation sleeve over the exposed portion of the Field's metal rod being sure to cover each of the joint sections of the finger. The insulation should fit snugly over the rod.
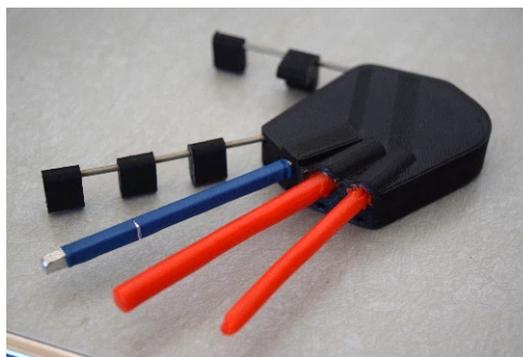
8. Slide the rigid links and insulation sleeves onto the Nitinol fingers in an alternating pattern as shown. For the index finger, begin with insulation, rigid link, insulation, rigid link, insulation, and end with a rigid end cap. For the thumb, start with insulation, thumb link, insulation, and end with a rigid end cap. Again, the holes in the rigid links may need to be drilled out with a # 48 drill bit to fit the Nitinol, depending on the printer tolerances.
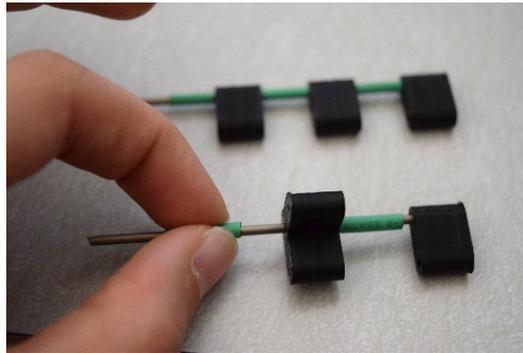

9. Use the heat gun to shrink the insulation sleeves around the Nitinol. This will also help hold the rigid links in place.

10. Cut the insulated copper wire into 14 1-foot segments. Strip the insulation with a pair of wire strippers of pliers to expose ¼" of bare wire at each end of the wire segments.

11. Cut the Nichrome wire into 3 6-inch segments (for the index finger) and 4 1-foot segments (for the remaining fingers).

12. To wire the thumb, Connect the stripped end of a 1-foot copper wire segment to the end of a 1-foot segment of Nichrome wire by crimping a Molex terminal at the junction as shown below in Figure **??**.
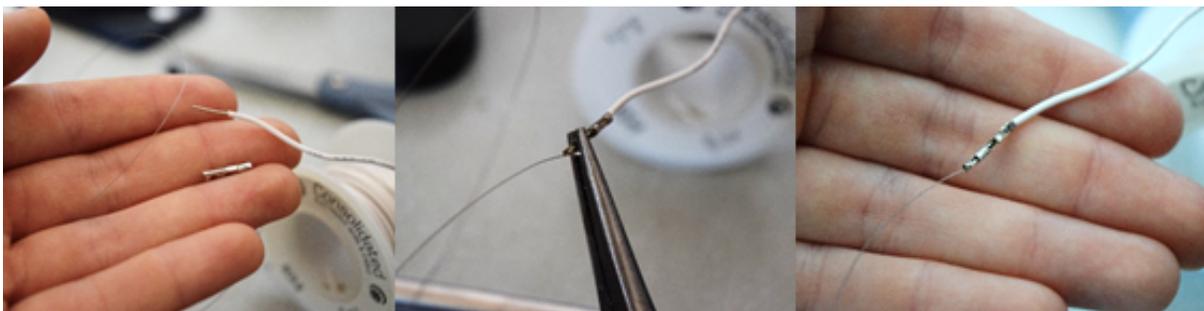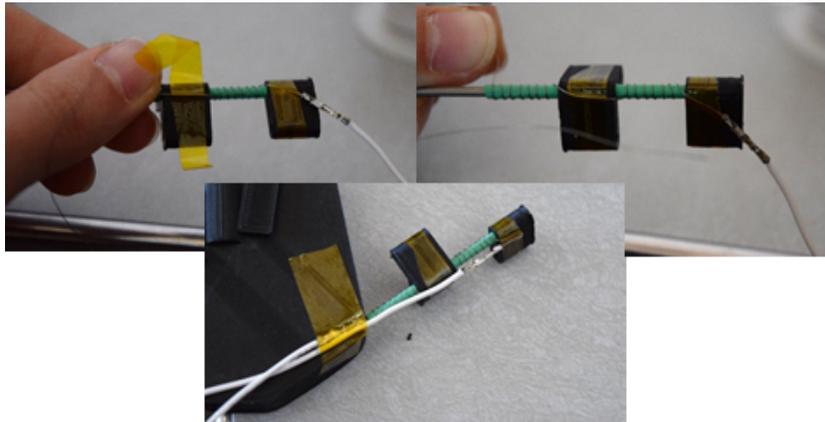

Tape the Nichrome wire at the base of the junction to the side of the rigid link at the fingertip as shown in Figure **??**. The tape will secure one end of the Nichrome so that the wire may be wrapped tightly.

Begin snugly wrapping the Nichrome around the first joint being careful to space the wraps evenly so that the wire never overlaps with itself. Overlapping the wire at any point would cause the current to short and skip heating a section of the wire.
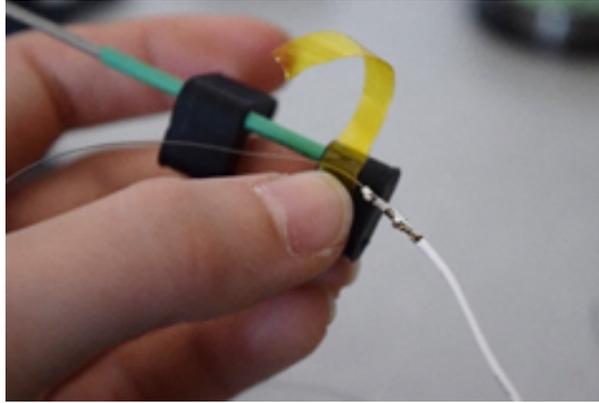
Aim for 5-6 full wraps around each joint and be consistent with the wrap spacing. At the end of the joint, pull the wire taught and tape it to the next rigid link. Wrap the next joint in the same manner until arriving at the palm.

Using a Molex connector, connect another 1-foot segment of stripped copper wire to the Nichrome at the base of the finger and tape down to the palm as shown below. Trim any excess Nichrome wire that extends beyond the Molex connector.

13. The joints in the index finger are wired individually. To wire the index finger, connect a 6-inch Nichrome segment to a copper wire segment with a Molex connector. Tape the wire to the rigid end cap and begin wrapping the distal joint exactly the same as the thumb, but stop after wrapping one joint. Connect another copper wire segment with a Molex connector and tape the connector to the nearest rigid link. Repeat this procedure for the remaining index finger joints so that 6 copper wire segments are connected to the index finger.

14. Place the hand assembly into the mold and mark the locations of the joints on the Field's metal and PCL fingers with a pen as shown. Remove the hand from the mold.


15. For the middle finger, slide the 4 previously cut 0.55" x Ø1mm insulation sleeves (from step 5) onto one of the 1-foot Nichrome wire segments. Use the heat gun to shrink 2 of the sleeves. Slide the 2 unshrunk sleeves over the 2 shrunken sleeves to double the insulation and shrink the sleeves together with the heat gun as shown. The two doubled-up insulation segments should be able to slide along the Nichrome wire.
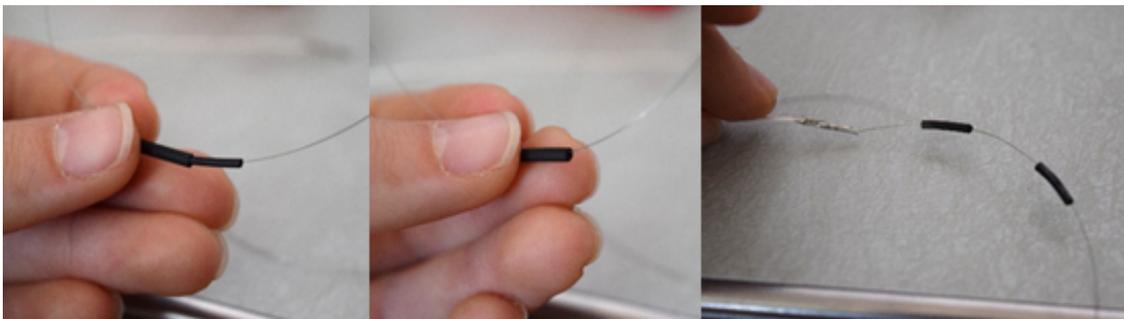
Connect a copper wire segment to the Nichrome wire with a Molex connector as shown in step 12.

16. Tape the Nichrome wire to the end of the Field's metal finger at the marking where the distal joint begins. Wrap the wire tightly around the insulated Field's metal rod with evenly spaced wraps. At the end of the joint (marked in pen), slide one of the doubled-up insulation sleeves up to the rod and tape the insulation segment to the rod in between the joints.

    The insulation around the Nichrome should span the distance between joints to prevent the element from heating the Field's metal in between the joints. Wrap the remaining joints in the same way, referring to the photos. Upon arrival at the base of the finger, connect another copper wire segment with a Molex connector and trip any excess Nichrome wire.
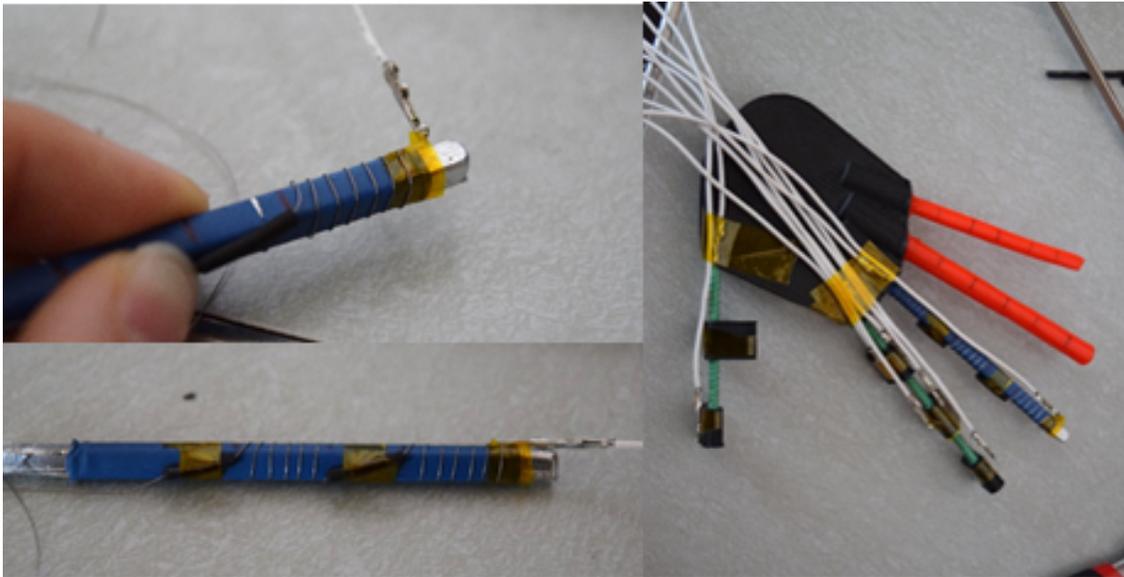
17. To wire the ring and pinky fingers, repeat step 15 using the remaining wire segments and the insulation segments cut for the pinky and ring fingers. Tape and wrap the wire in the same way as the middle finger, being careful to situate the insulation segments between the joints as shown.
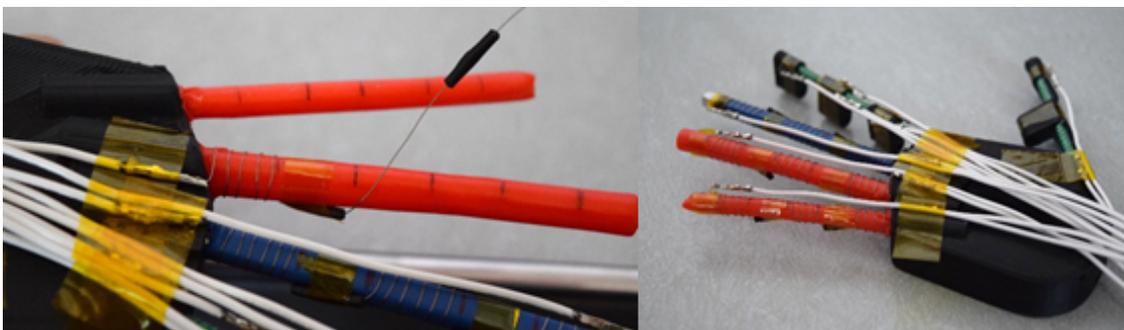
18. Verify that the wired hand matches the photo below with the same number of wires and connection locations.


19. Press the tendon sheaths into the silicone mold as shown for the middle, ring, and pinky fingers. Position the sheaths with tweezers so that they are centered in the slots and do not quite touch the bottom of the mold.
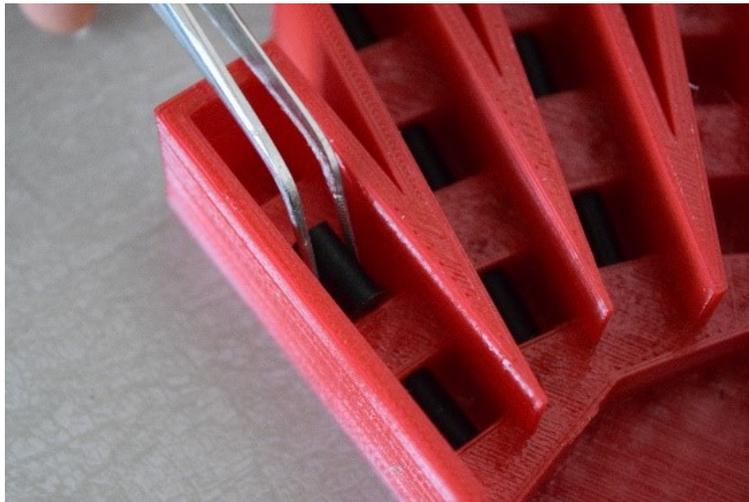
20. Fit the wired hand into the mold. Rearrange any wires that are in the way and position the palm as shown. Use the tweezers to straighten the rigid links in their slots. A narrow gap should exist between the mold and the base of the palm as shown below.

21. Mix up about 1.5 cups of silicone according to the directions on the package (3/4 cup each part). De-gas the mixture in a vacuum chamber if possible. Pour liquid silicone on and around the palm and fingers, taking extra time around the edges of the palm to allow the silicone to flow beneath the palm. Tap the mold on the table top to coax the silicone to flow under the palm. Fill the mold to the brim. As bubbles emerge, the silicone level will drop slightly; add more silicone if needed. Allow silicone to cure for at least 4 hours before removing it from the mold.
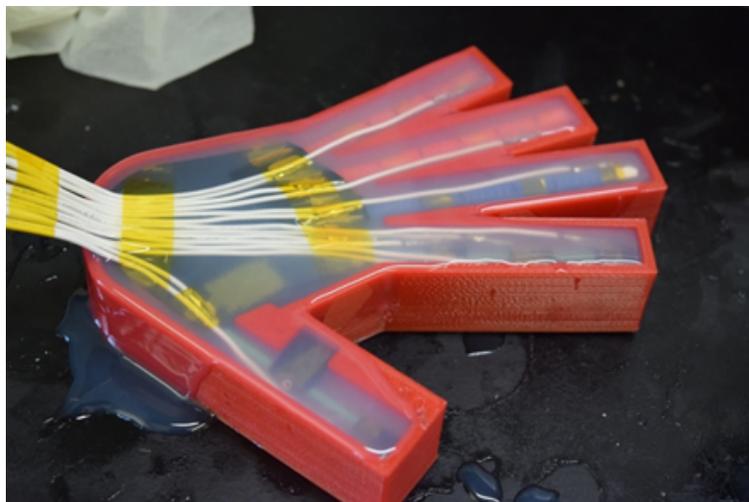
22. Clear the tendon paths by cutting away silicone with a utility knife and removing plugs from holes with tweezers as shown.


23. Feed 1-foot segments of fishing line through the tendon path for each finger (2 separate tendons for thumb). Use tweezers to feed the line through sheaths if needed.


24. Tie the ends of the tendons through the holes in the printed finger tips using a square knot as shown below. Tie the end of the secondary thumb tendon through the holes in the thumb end cap.
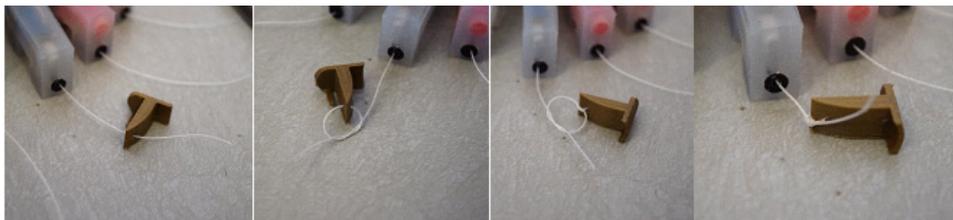
25. Using a pin or a pair of pointed tweezers, pierce a hole in the silicone at the tip of each finger for the prong of the 3D printed finger tips. Line up the printed finger tip to find the correct location to pierce the silicone.
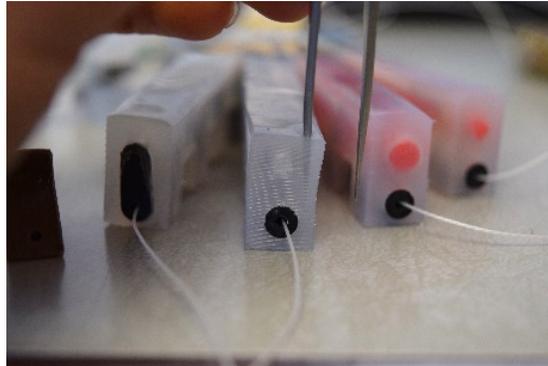
26. Insert the prong of the finger tips into the pierced holes and pull the tendons taught. If desired, tie loops in the other ends of the tendons to make them easier to pull by hand.
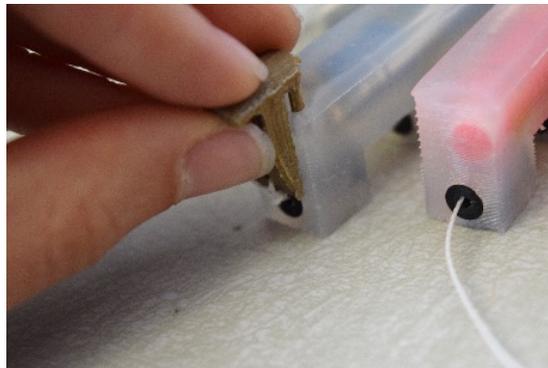
27. The soft robotic hand is now fully assembled and ready for manual operation.

5. CONTROLLING THE HAND

5.1 SETUP

Attach lanyards or carabiners to the ends of the tendons to make them easier to pull. Connect alligator leads to the power supply for easy connection to the heating wires.

5.2 NITINOL THUMB

The thumb demonstrates multi-directional movement capabilities because it is equipped with 2 tendons that actuate movement in different directions. The shape memory effect of the Nitinol actuates the straightening of the thumb, allowing it to straighten decidedly when heated.

Pull the primary tendon to curl the thumb in toward the palm. Pull the secondary tendon to pull the base of the thumb sideways toward the fingers. Release either or both tendons and apply up to 1 amp of current through the thumb heating wires to straighten the thumb in either or both directions. Varying the relative tensions in the thumb tendons allows for control of the direction of thumb movement.

5.3 NITINOL INDEX FINGER

The index finger demonstrates individual joint controllability because the heating element at each joint is wired individually. The shape memory effect of the Nitinol actuates the straightening of the index finger, allowing it to straighten decidedly when heated.

Pull the tendon with all joints cooled to curl the entire finger. Joints may be heated individually by passing up to 1 amp of current through the individual joint heating wires. Heating a joint causes that joint to straighten or remain straight while other (cooled) joints can bend when the tendon is pulled. Release the tendon tension and heat all three joints to straighten the entire finger.

5.4 FIELD'S METAL MIDDLE FINGER

The middle finger features Field's metal, a low melting temperature metal to achieve stiffness control. For simplicity, all three joints are heated simultaneously, meaning that the joints cannot move individually in the middle finger.

Apply up to 1 amp of current through the heating wires for the middle finger until the metal at the joints is melted, then pull the corresponding tendon to curl the finger inward. The finger may be allowed to cool and solidify in this position. Reheat/melt the joints and release the tendon to allow the finger to straighten.

5.5 PCL RING FINGER

The ring finger demonstrates another smart material that may be used for stiffness variability. Similar to the Field's metal, the PCL also softens and melts at a low temperature. For simplicity, all three joints are heated simultaneously, meaning that the joints cannot move individually in the pinky finger.

Apply up to 1 amp of current through the heating wires for the ring finger until the PCL at the joints is melted, then pull the corresponding tendon to curl the finger inward. The finger may be allowed to cool and solidify in this position. Reheat/melt the joints and release the tendon to allow the finger to straighten.

5.6 PCL PINKY FINGER

The pinky finger uses the same PCL material as in the ring finger, but in a smaller quantity. The PCL rod embedded in the pinky finger is thinner than the rod in the ring finger, illustrating a noteworthy tradeoff: using a thinner rod makes the finger weaker overall but allows the joints to melt faster (less heat is required to melt a thinner joint). For simplicity, all three joints are heated simultaneously, meaning that the joints cannot move individually in the middle finger.

Apply up to 1 amp of current through the heating wires for the pinky finger until the PCL at the joints is melted, then pull the corresponding tendon to curl the finger inward. The finger may be allowed to cool and solidify in this position. Reheat/melt the joints and release the tendon to allow the finger to straighten.

5.7 ADVANCED CONTROL

For more advanced control, a control system may be implemented to pull the tendons with servo motors and heat the joints to desired temperatures via relay switches that modulate on/off when based on feedback from temperature sensors near the joints.

LIST OF FIGURES

LIST OF TABLES