PURPOSE

This document serves as a guide for the construction and assembly of the NAU Biomechatronics Lab's OpenExo Hip Device. Pictures and supplemental videos are provided to help visualize the steps required to manufacture every component and fully assemble the device. In addition to this documentation, we have provided a complete Bill of Materials (BOM) with information on where to purchase the needed parts (and expected cost), and SolidWorks design files for all the needed components.

Table of Contents

PARTS/MATERIALS REQUIRED

This build contains 3D printed parts, machined carbon fiber and aluminum parts, a prefabricated hip belt, and various electrical components including motors, wiring, and a custom printed circuit board (PCB, information on which is include in **supplemental documentation**). A bill of materials (BOM) is provided which outlines all the necessary materials and fasteners (tools not included). The BOM also specifies the price of every component at the time of purchase, as well as where each component was purchased.

Worth noting in the BOM are the carbon fiber plates and tubing. These materials do not need to be purchased directly if you wish to have a third party manufacture them for you. In our case, we manufactured these components ourselves. If you would like your own tools for fully manufacturing all the components, you will need a CNC, a 3D printer, a drill press, and a Dremel.

Also worth noting are the three items under "Externally Manufactured Parts." These include aluminum adduction/abduction blocks (made of 7075 aluminum), which serve to allow out-of-plane motion on the hip belt, as well as a custom PCB used to control the exo. Information on where these were externally manufactured are available later in this document and in the BOM.

TOOLS REQUIRED

PPE

For certain aspects of this build, adequate personal protective equipment (PPE) will be necessary. Below is a list of the minimum required PPE.

1) Safety glasses
2) Respirator with P100 Filters (for machining carbon fiber)
3) Long sleeve shirt (for working with carbon fiber)
4) Ear protection (earmuffs or earplugs)
5) Heat resistant gloves (for thermoforming)

General Tools

1) Metric nut driver set
2) Metric hex keys
3) Torx drivers
4) Drill or drill press with drill bits
5) A set of files or sandpaper
6) Dremel with cutting disks
7) Tile saw (a table saw, circular saw, or jig saw also works) – for cutting carbon fiber
8) Tape (gorilla or something comparable)
9) Scissors
10) CNC (optional if parts are externally manufactured)

Tools for Electrical Components

1) Soldering iron
2) Solder
3) Heat gun
4) Wire stripper
5) Wire cutter
6) Utility knife
7) Crimping Tool
8) Helping Hands
9) Tweezers

PRINTING REQUIRED PARTS

Filament Used

The filament we use is Markforged's Onyx. For all printed parts, we used the Markforged Desktop Series. If you do not have access to one of these (or a similar type of printer), Protolabs is a company that can print them for you. Important to note though is that some of the printed parts include carbon fiber reinforcement (listed below), which at the time of writing this document, is not an option with Protolabs. The carbon fiber reinforcement is not required for the function of the device, but its absence may reduce the durability of those parts.

Carbon Fiber Reinforcement

Many of the printed parts in this build use carbon fiber reinforcement to increase strength while minimizing weight. These parts include:

- thighCuffFront.SLDPRT
- cuffSliderTop.SLDPRT
- cuffSliderBottom.SLDPRT

Further specification of the CF reinforcement will be provided in the "Thigh Cuffs" section.

List of all Printed Components

Below is a list of the printed components used in this build, as well as how many of each you will need. These components are contained in the "Part Files for 3D Printing" folder. Prior to printing components which have carbon fiber reinforcement, review the "Quad Cuffs" section where a guide for how much reinforcement to use is provided.

- **(1x)** electronicsBoxBackPlate.SLDPRT
- **(1x)** electronicsBoxBatteryCover.SLDPRT
- **(2x)** cuffSliderBottom.SLDPRT
- **(2x)** cuffSliderTop.SLDPRT

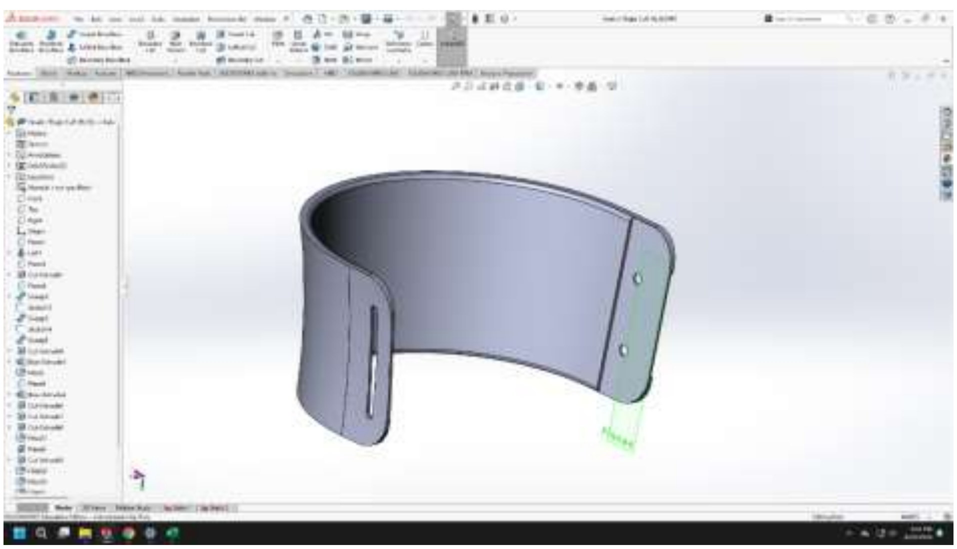
- **(4x)** heelPuck.SLDPRT
- **(1x)** holeTemplateForStrut.SLDPRT
- **(2x)** boltSpportForStrut.SLDPRT
- **(2x)** motorToStrut.SLDPRT
- **(1x)** electronicsBoxControlPanel.SLDPRT
- **(2x)** thighCuffBack.SLDPRT
- **(2x)** thighCuffFront.SLDPRT
- **(2x)** electronicsBoxStrainReliefRight.SLDPRT
- **(2x)** electronicsBoxStrainReliefLeft.SLDPRT

Thigh Cuffs

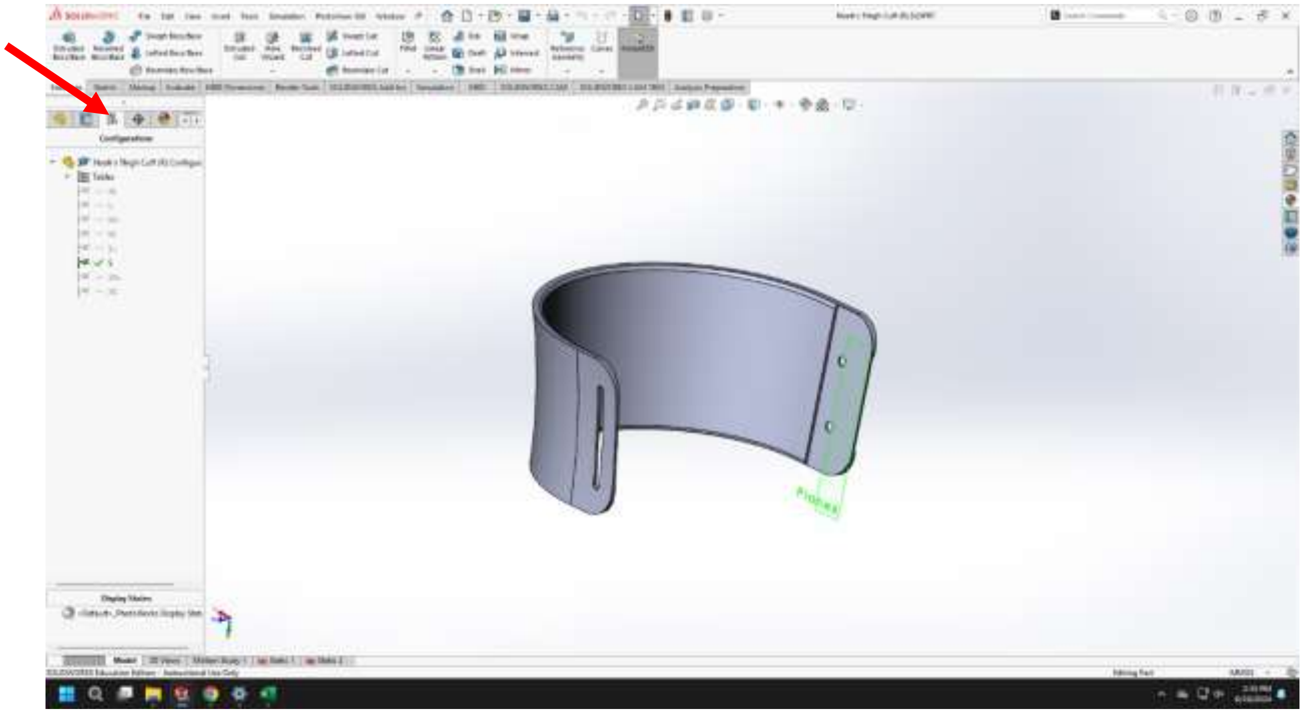
The thigh cuffs are the components of the build that interface with the users thighs, allowing for the transfer of assistance from the motors to user. These cuffs can be sized differently to fit a variety of potential users. Below is an outline of how to size, print, and assemble these components.

1. Sizing

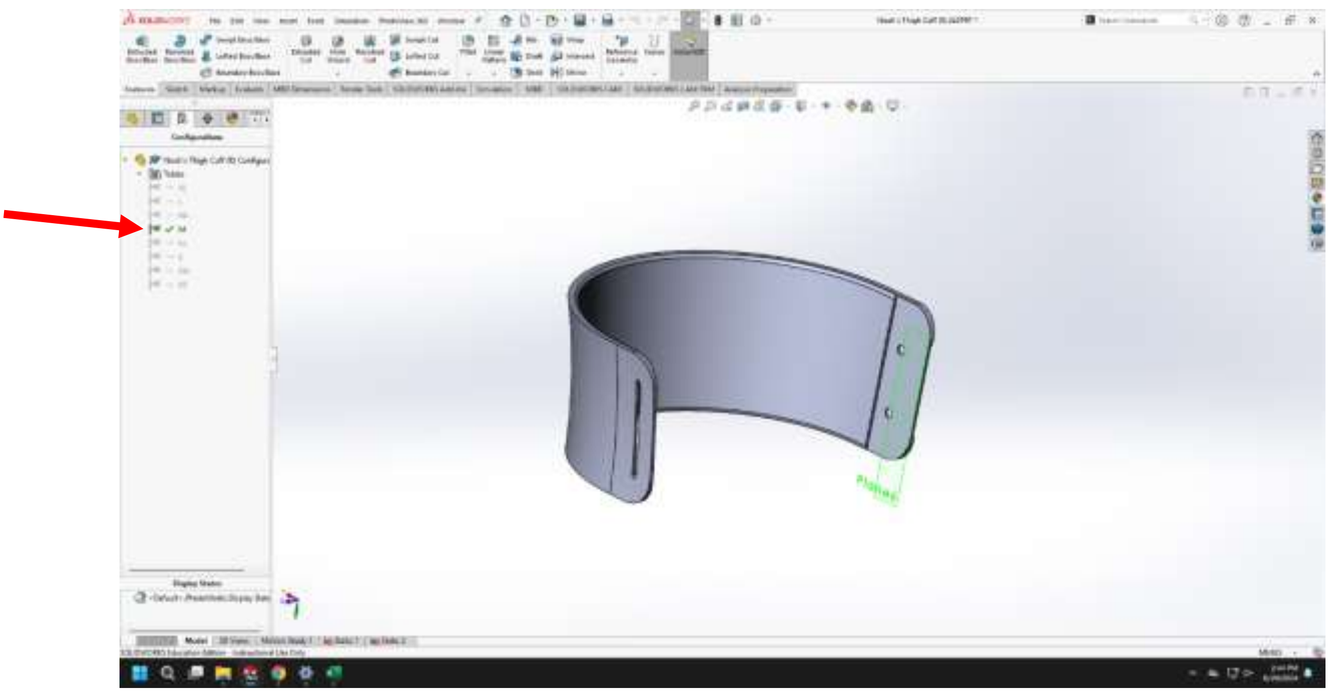
a) To size these components, open the thighCuffFront.SLDPRT file in SolidWorks.



b) Navigate to the Configuration Tree.

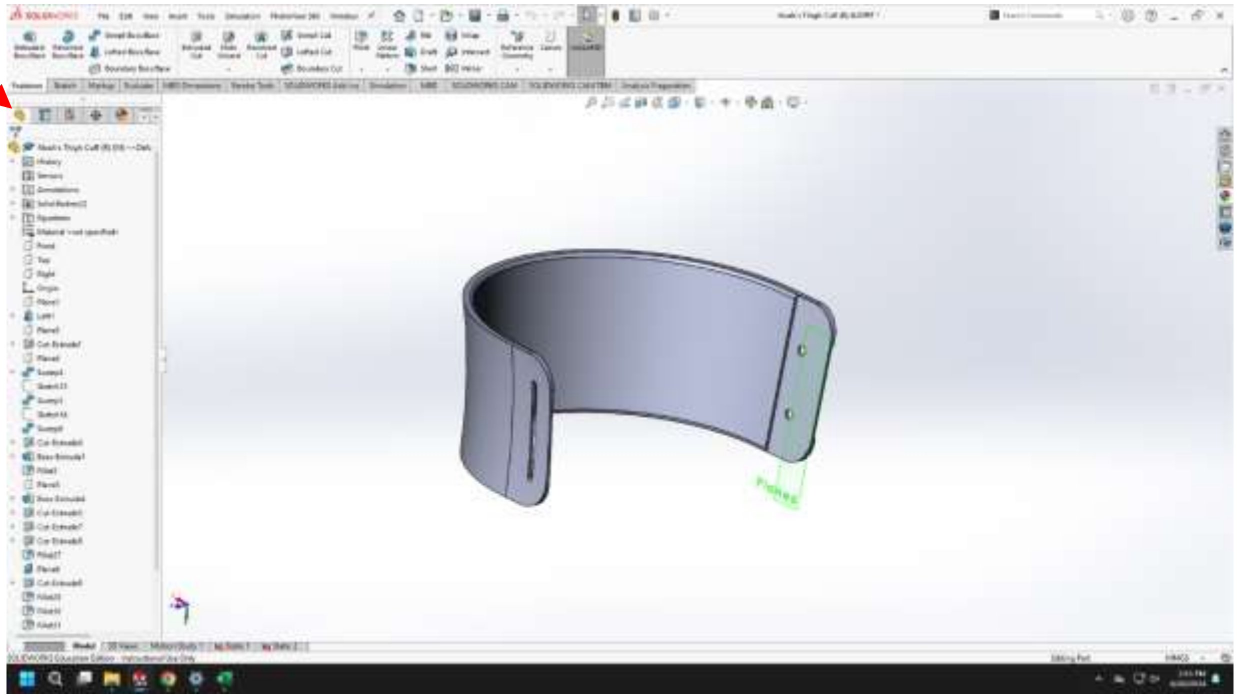


c) Select the desired size. The small size will fit a slim athletic build, while the medium will comfortably fit those with a larger build. The dimensions can be checked in SolidWorks and compared with physical measurements of the user's thigh to get a good match.

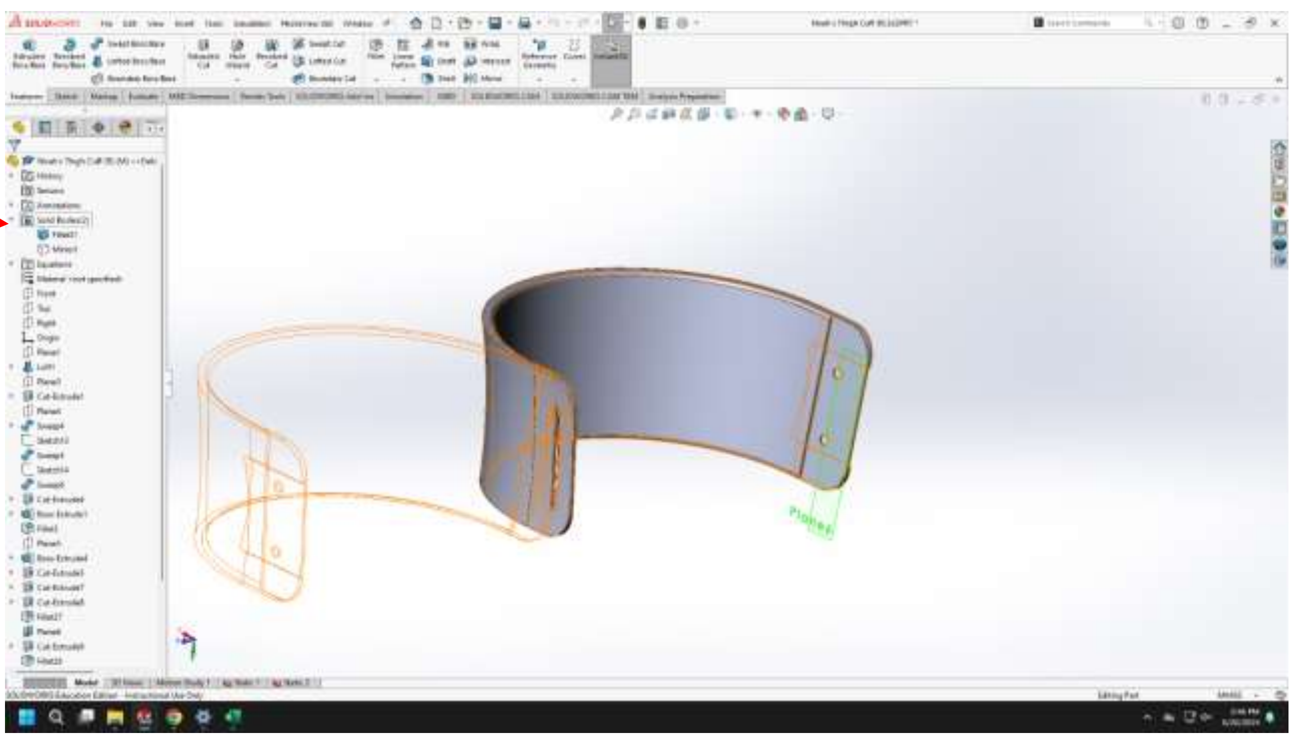


d) You can now save this as an independent file such as "XXSizeRightSide.SLDPRT" for ease.

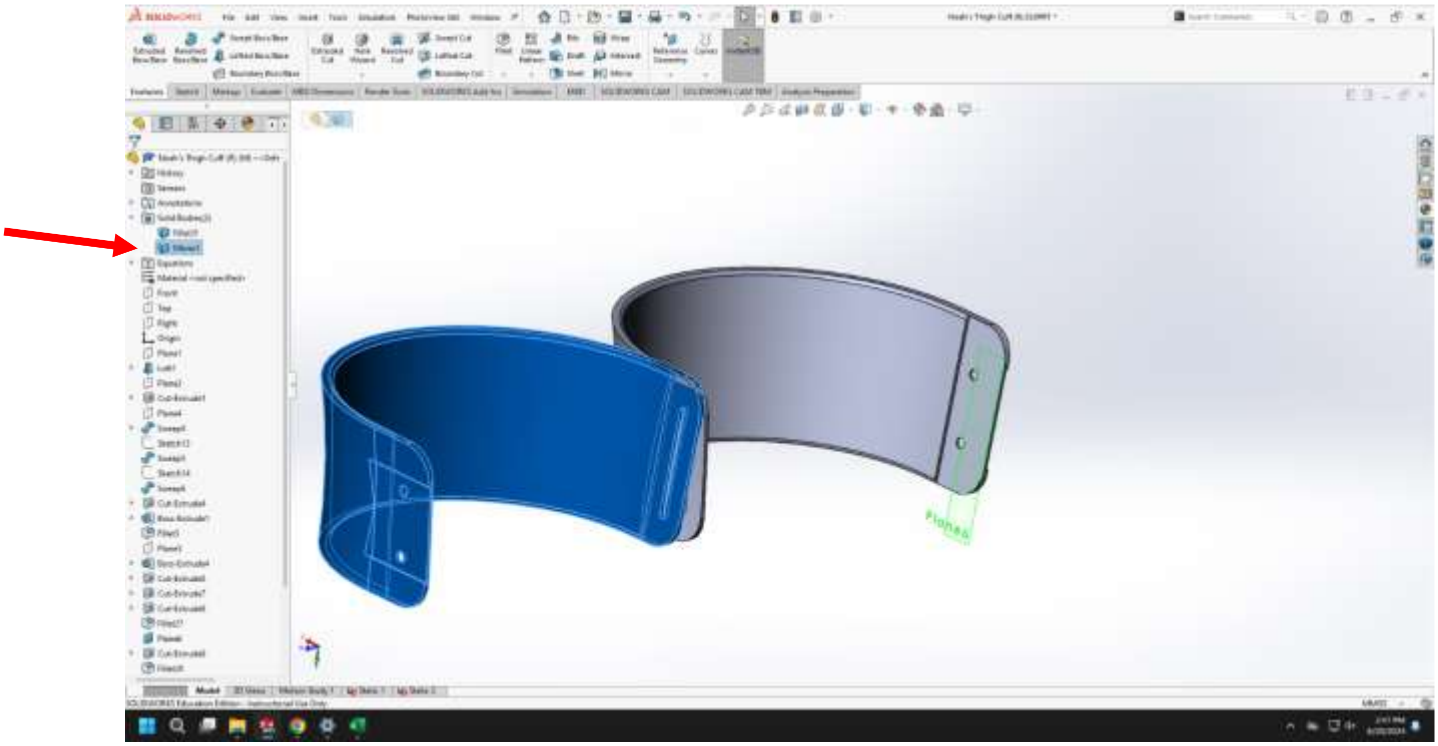
e) Next, we'll save the mirrored version for the other side of the leg. Save another copy of the part under the name "XXSizeLeftSide.SLDPRT." Ensure that this is the file you're now editing and navigate back to the feature tree.



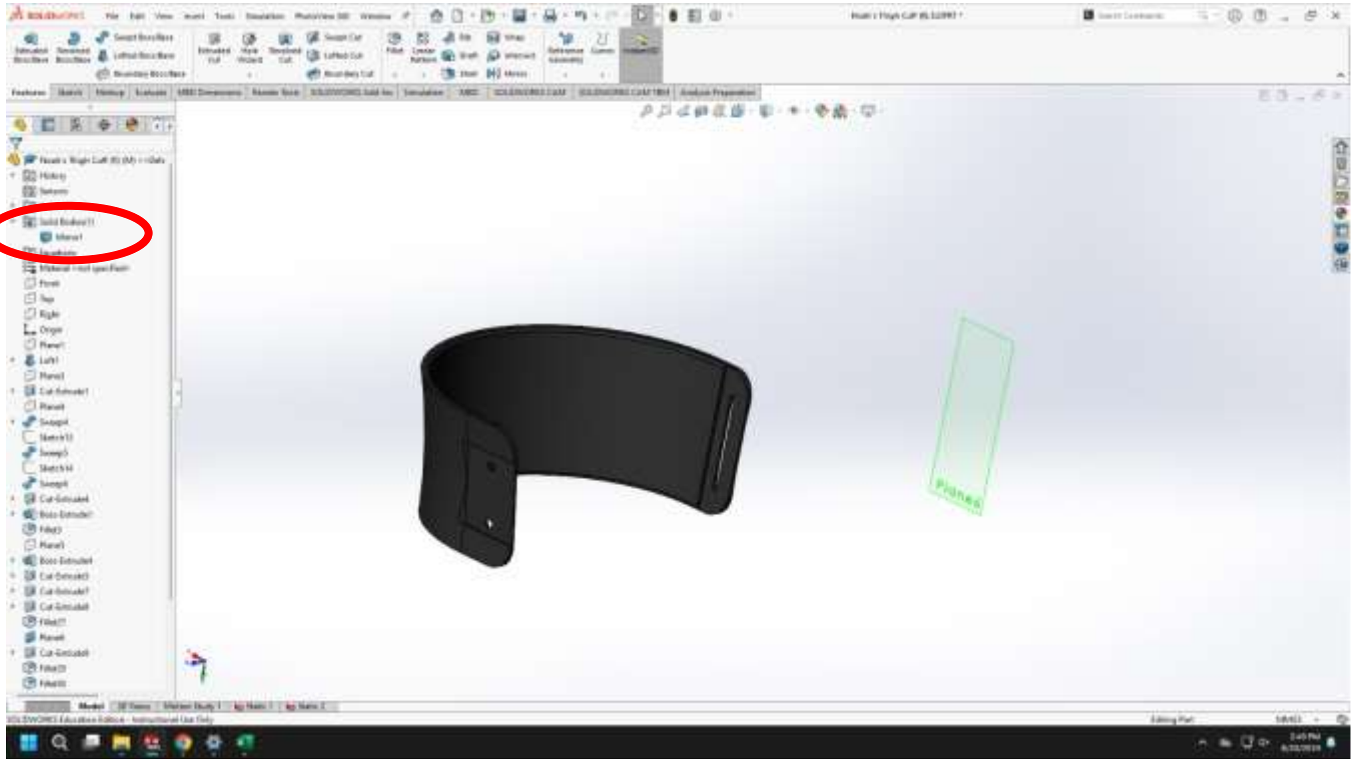
f) Now open the Solid Bodies dropdown.



g) Reveal the hidden solid body titled “Mirror1.”



h) Now delete the first body by right clicking on it in the “Solid Bodies” dropdown and selecting “Delete/Keep Bodies.”



i) Now that this is done, again ensure that you're editing "XXSizeLeftSide.SLDPRT" and save.

j) You now have part files of the cuff for both sides of the leg.

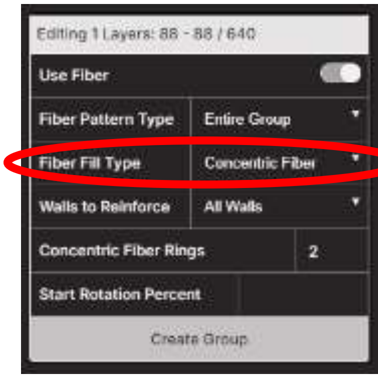
2. Printing

These components are reinforced with carbon fiber.

- thighCuffFront.SLDPRT
- cuffSliderTop.SLDPRT
- cuffSliderBottom.SLDPRT

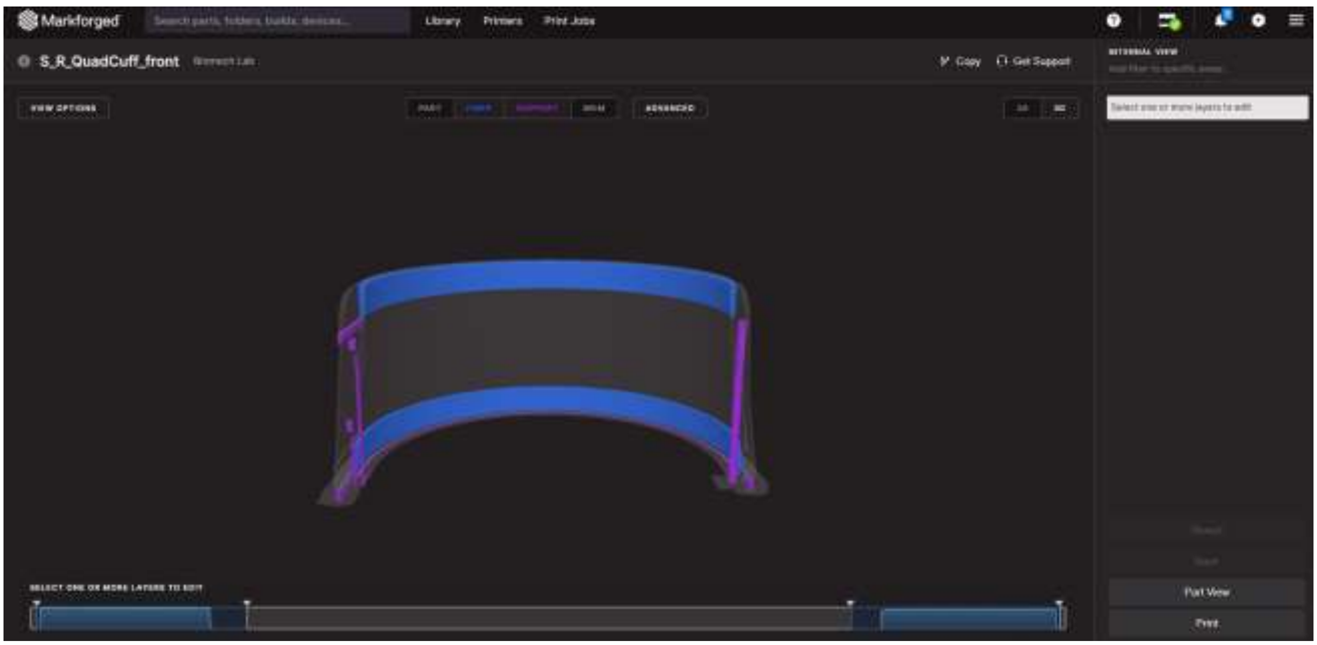
As mentioned above, if you are having a third party such as [Protolabs] print them for you, you will not be able to print with carbon fiber reinforcement, which may decrease the durability of the parts but should not prohibit function.

If you have access to your own printer, we have outlined the locations and quantities of CF reinforcement that you should use below. When you add the CF reinforcement, ensure that for each section you set the reinforcement geometry to "concentric."

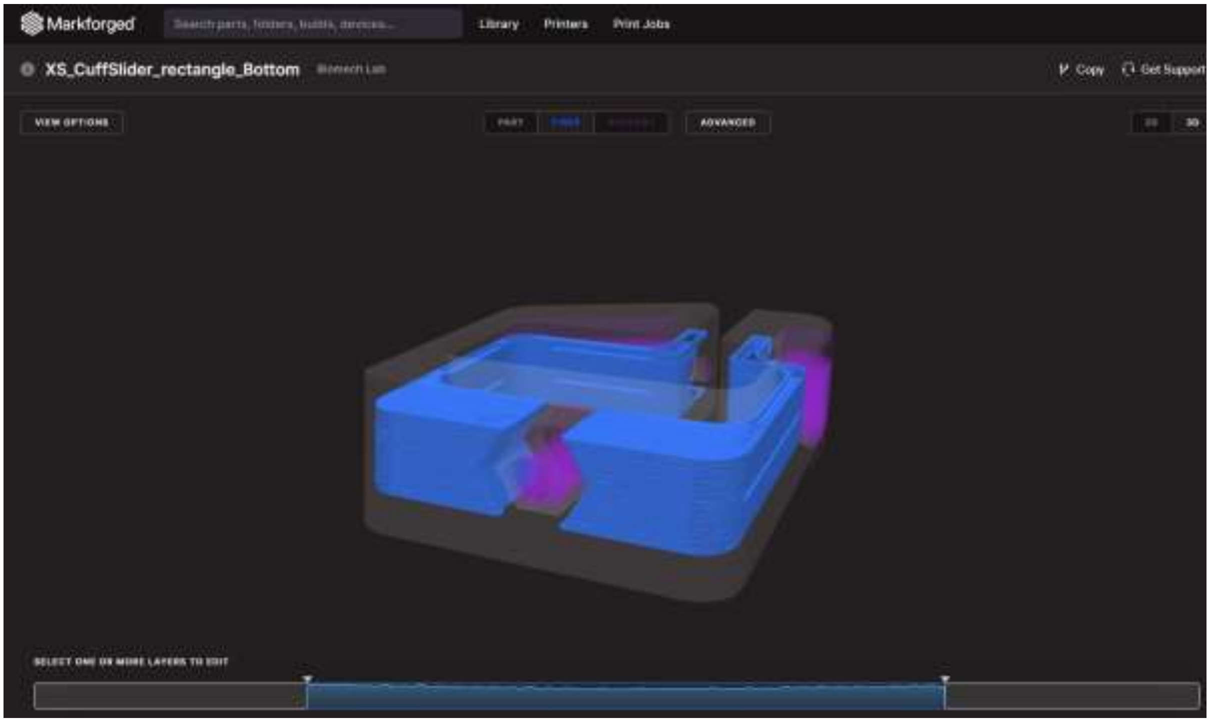


This can be done by selecting each blue segment in the slider at the bottom of the screen (seen below).

Thigh Cuff:



Cuff Slider (top and bottom):



fab

3. Assembly

a) Gather necessary components.

1x	XXSizeLeftSide.SLDPRT
1x	XXSizeRightSide.SLDPRT
2x	cuffSliderTop.SLDPRT
2x	cuffSliderBottom.SLDPRT
2x	thighCuffBack.SLDPRT
2x	ThighCuffReinforcement.SLDPRT
1x	Fabric (3 mm)
1x	Velcro with Adhesive Backer
2x	Velcro Strap
2x	Cam Handle
4x	M3 Lock Nut
2x	M3X16 Button Head Screw
4x	M5X12 Button Head Screw
4x	M5 Lock Nut
4x	M5 Washer
1x	Silver Sharpie
1x	Scissors
1x	Superglue
1x	Drill Press or Hand Drill with 5mm Diameter Bit

b) Use superglue to fasten the ThighCuffReinforcement.SLDPRT to the XXSize[Left/Right].SLDPRT. We recommend clamping/securing these parts together and letting sit until dry (we typically let it sit overnight, but two hours should suffice if needed sooner).

c) Once the glue is dry, cut small, rectangular, sections of the hook side Velcro and stick them to the inside of XXSize[Left/Right].SLDPRT in the manner shown below.

d) Now we'll create the padding to the cuff. Insert the fabric into the cuff and align it to fill the space. Make sure to leave the space with the slot open as this is where the strap to fasten the cuff will be fed through. Using a silver sharpie create an outline of the cuff on the fabric. Take a pair of scissors and cut the fabric along the outline. Attach the fabric to the cuff via the Velcro.

e) Place hook-side Velcro on the inner side of the thighCuffBack.SLDPRTs in the manner shown.

f) Cut and fasten a piece of fabric to the Velcro to be used as padding, similar to what you did for the front side of the cuff.

g) Algin the loop-side Velcro on outer side the thighCuffBack.SLDPRT in the manner shown. Cut out that section and attach to the outer side of the back cuff.

h) Cut the buckle off of the Velcro strap so that it looks similar to the strap below

i) Place the strap in line with the the two M5 holes in the XXSize[Left/Right].SLDPRT. Make sure that the strap extends a bit past the holes into the cuff. Using the silver sharpie, mark the hole locations on the Velcro strap as shown below. These will be where we secure the strap to the cuff.

j) Use a 5 mm diameter drill bit to cut out the holes you just marked on the Velcro Strap

k) Slide the Velcro strap through the thighCuffBack.SLDPRT as shown below, with the Velcro facing the outside of the cuff.

l) Press the M3 Lock nuts into their respective slots in the cuffSlider[Top/Bottom].SLDPRT.

m) Insert the CAM lever into the cuffSliderTop.SLDPRT and a M3X16 screw into the cuffSliderBottom.SLDPRT. [Note: The cuffSliderBottom.SLDPRT has the larger (thicker) base]

n) Press M5 lock nuts into their respective slot on the cuffSlider[Top/Bottom].SLDPRTs.

o) After placing M5 washers on each, press two M5X12 button head screws through the two holes in the cuff as shown.

p) Slide the two holes in the Velcro strap over these screws, with the strap being on the outside of the cuff

q) Fasten the cuffSliderTop.SLDPRT and cuffSliderBottom.SLDPRT to the cuff as shown (make sure to pay attention to which leg you are on).

r) The finished product is shown below. The cuff is now ready to be attached to the carbon fiber uprights once the exo is ready. When placed on, they should slide onto the upright until at a comfortable height, at which time the Cam Handle can be used to tighten the upper cuff slider, securing the cuff to the upright and preventing motion.

MAKING YOUR OWN INSOLES (optional)

To operate the exoskeleton with intended control scheme, you will need to secure FSRs to your insoles (to be detailed later). This process can damage your insoles when trying to remove the FSRs from them. As a result, we recommend buying shoes/insoles dedicated to use with the exo, or making custom insoles to interface with the device. Additionally, if you have multiple people using the exo, it will be easier and less expensive to make a variety of insole sizes than it would to purchase multiple shoes. We have outline the steps needed to make your own insoles below.

a) Gather necessary components

1x	6 mm Foam
1x	Insoles (left and right) from your own shoes
1x	Sharpie
1x	Scissors

b) Place the left and right insoles on the foam and trace their outline.

c) Cut out the traces you made using scissors.

d) Put the pieces of foam into your shoes to check the fit. Trim if necessary. When you are done, store these for now. The FSRs will be fastened to them during the “Electrical Components” section.

PREPARING THE HIP BELT

The first step in this exoskeleton build will be manufacturing the components to interface with the waist belt. Here we will be preparing the hip belt to accept the motors as well as modifying the belt to accept the casing for the battery and PCB.

Making the Mounting Plates

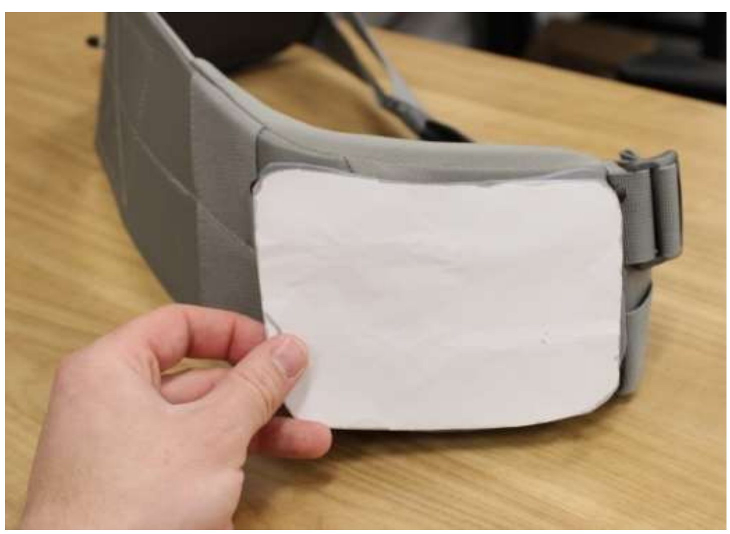
To mount the motors to the belt, pieces of thermoform plastic must be shaped to match the belt's contour. This process is outlined below. **A video of this process is provided** here, which may be easier to follow than the written instructions.

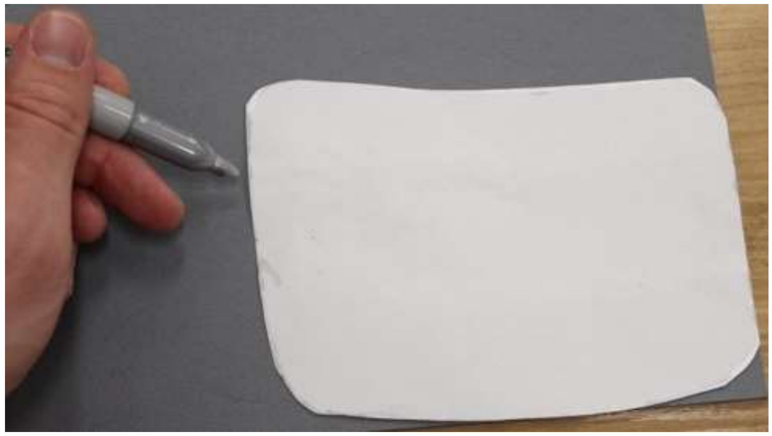
1. Cutting the Plastic

a) Gather necessary components.

1x	Hip Belt
2x	Blank Paper
1x	PVC/Acrylic Plate (thermoform plastic)
1x	Sharpie
1x	Dremel with Cutting Bit
1x	Eye Protection
1x	Respirator

b) Use a piece of paper and a sharpie to trace the outline of the belt section on which you intend to place the interface. You will want as much surface area as you can get for the mounting holes. Generally, the outline should span from top to bottom of the belt and go from the front edge of the belt back to the diagonal fabric pattern on the belt (see image).





c) Transfer this outline to the piece of plastic stock that you'll be using. Use a Dremel with a grinder bit (or any other suitable tool) to cut out the shape just traced. **Wear PPE (Respirator/Eye Protection) during this step** as the plastic will melt and release fumes as it is cut.

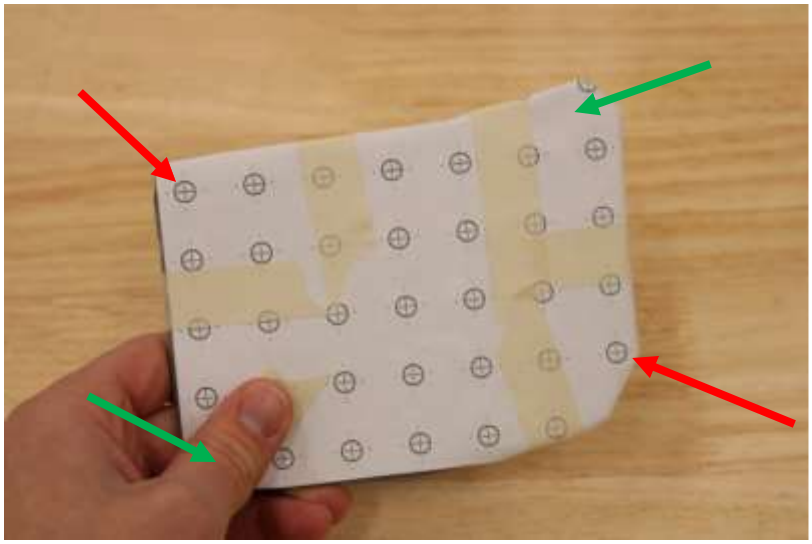
d) Repeat for the other side of the hip belt. The template you made with the blank paper will work for the other side of the hip belt but ensure that you mirror the orientation of the paper to reflect the flipped contour of the belt.

2. Drilling Mounting Holes

a) Gather necessary components. This includes printing two copies of the hole pattern template (PlasticMountTemplate.pdf)

1x	Drill with 5.9mm Diameter Bit (or similar size)
2x	Cut Mounting Plates (from previous step)
2x	Printed Copy of PlasticMountTemplate.pdf
1x	Tape
1x	Scissors

b) Place and position the hole template onto the cut piece of plastic so that you have as many holes as possible on the plastic. An additional, important, requirement is to have a hole near each corner so that you can use bolts to fasten it to the belt (holes will be drilled into the belt later). If the markings on the template line up well with the four corners of the plastic, then they can be used for mounting (red arrows). If this is proving challenging, space it so that the four corners have some spacing around it and then drill similar holes in those spots (green arrows = where holes for mounting would be drilled).



c) Tape the template onto the plastic.

d) Following the template, drill the holes through the plastic mount with a 5.9mm diameter drill bit.

e) Repeat for the other piece of plastic.

3. Thermoforming

a) Gather necessary components.

1x	Heat Resistant Gloves
1x	Heat Gun
1x	Hip Belt

b) Put the Hip Belt on. This will ensure that the plastic is thermoformed to the proper shape.

c) Put on the heat resistant gloves and start the heat gun. Use the gun to heat the plastic to the point where it is easy to deform.

d) Press the plastic onto belt such that it conforms to the contour of the belt. Hold in place until plastic cools enough to be stiff. Assess and adjust via reheating as needed.

e) Repeat for the other side.

4. Mounting the Plates to the Belt

a) Gather necessary components.

1x	8mm Nut Driver
1x	Sharpie
2x	Mounting Plates
1x	Hip Belt
8x	M5x22mm Button Head Screw
8x	M5 Nut
8x	M5 Washer
8x	M5 Screw Cap
1x	Drill Press or Hand Drill (6mm bit)

b) Place the motor mounting plates onto the belt in their desired positions and use a sharpie to mark the places where mounting holes will be drilled into the belt. These should be in the four corners of the plate.

c) Use the added belt markings to drill holes into the belt. These holes should just be through the initial outer layer of the belt and should not puncture into the foam padding component. You should be able to reach into the inner part of the belt and feel the holes without having them go all the way through! (Note: It is advised to use a scrap piece of plastic or other material to prevent the drill from punching past the inner lining of the mounting area. This can be seen in the below image. If not available, just proceed slowly and try to avoid getting into the actual foam padding of the belt).

d) Once all the mounting holes are drilled, place washers onto the M5x22 bolts and insert them into the holes with the heads on the inside of the belt and the ends sticking through the belt as shown below.

e) Place the mounting plates onto the bolts and tightly fasten down M5 nuts using the driver. Once this is done, place the caps onto the bolts. The final product is shown below.

Repeat for other side.

Mounting the Battery & PCB Casing

Here we will be printing and mounting the Battery and PCB casing to the back of the belt.

1. Printing

These will be long prints. Thus, it is best to print only one or two parts at a time so that if the print fails at any point, less material is wasted. Start by printing the "electronicsBoxBackPlate.SLDPRT" located in the "Part Files for 3D Printing" folder.

2. Mounting

It is best to mount the Battery and PCB case before assembling the device.

a) Gather necessary components.

1x	electronicsBoxBackPlate.SLDPRT
15x	M3 Threaded Inserts
4x	M3x14 Button Head Screws
4x	M3 Washers
1x	Drill Press or Hand Drill (3mm bit)
1x	Sharpie
1x	Soldering Iron

b) Insert the threaded inserts into every hole of the 3D printed backplate. These will allow you to properly fasten the 3D printed part to the belt and to properly secure components (PCB, Strain Relief) to the casing. It should be noted that there are specific orientations that should be followed. The four that secure the casing to the belt should be inserted from the side the PCB would sit (front side, first picture, see red arrows). All other threaded inserts should be placed from the side that would face a person's back when wearing the hip belt (back side, second picture). This should be an easy convention to follow, as there are shoulders inside the through holes for the threaded inserts corresponding to this pattern. Threaded inserts can be placed by heating a soldering iron, placing its tip into the metal threaded insert, and slowly pressing (and twisting) the insert into the hole until the surface of the threaded insert is flush with the 3D printed material.

c) Take the back plate and align it centrally on the lower middle of the waist belt. Take a sharpie or pen and place the tip into the four centrally placed holes in the backplate (red arrows above) with the goal of marking those hole locations on the belt. These will be the points where we will secure the casing to the belt. Generally, you should have these as low as possible and as evenly leveled as possible.

d) Using a 3 mm diameter bit, drill through these marked locations on the belt. Make sure to puncture all the way through the material and the plastic, out onto the other side.

e) Press four M3 screws with washers on them the through the inside of the belt (Velcro side), as shown.

f) Attach the back plate onto the belt by aligning the four holes with the fasteners. Screw the fasteners into the backplate, securing it to the belt.

MANUFACTURING THE CARBON FIBER PARTS

Some components of the exo are made from carbon fiber (to retain strength while minimizing weight). If you have access to the necessary tools, this can be done in-house. Otherwise, there are plenty of third-party options online. **Importantly, when machining carbon fiber always ensure you are wearing a respirator and eye protection.**

All of the machined carbon fiber components can be found in Part Files for Machining > CF Machining.

1. Machining the Parts for Yourself

If you have access to your own CNC, it may be easier to machine these components yourself, as they are fairly simple geometries. Included are tutorial videos for how we machine our carbon fiber components using our in-house CNC. These may be of use for you, and can be found here.

Should you choose to machine these components yourself, ensure that you are protecting yourself from the carbon fiber dust while machining. The dust poses a serious health risk if ingested. **Wear a quality respirator and eye protection**. Covering as much skin as possible while machining is also recommended.

2. Third-Party Machining

If you do not have the ability to machine these parts yourself, third-party manufacturers, such as Xometry can do so for you. They can cut contours into carbon fiber plates, which is what you'll need for the following components, all of which are contained in the CF Machining folder:

- hipAdapterOuter.SLDPRT
- hipAdapterInner.SLDPRT
- motorBracketSpacer.SLDPRT
- motortoStrutSupport.SLDPRT
- thighCuffReinforcement.SLDPRT

There is another carbon fiber component that you'll need to have manufactured for you (carbonFiberStrut.SLDPRTs). These are one-foot-long pieces of rectangular carbon fiber tubing which serve as the main interface to help transfer motor torque to the wearer. For the carbonFiberStrut.SLDPRT, you'll need **two** carbon fiber tubes cut to a length of one foot. Once you have the tubes, three mounting holes need to be drilled. For this, a drill press is best, but a hand drill and a fair amount of diligence can suffice as well. The process for doing so is outlined below.

3. Drilling Mounting Holes into the Carbon Fiber Tubes

a) Gather necessary components.

2x	1' Carbon Fiber Tube
1x	Drill Press or Hand Drill with 5mm Diameter Bit
1x	Silver Sharpie
1x	holeTemplateForStrut.SLDPRT

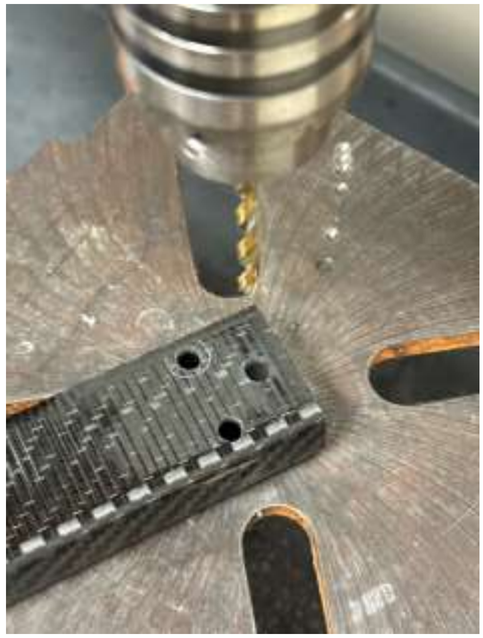
b) Slide the holeTemplateForStrut.SLDPRT onto the carbon fiber tube.

c) Using the sharpie, mark the positions where the holes will be drilled. If you're using a drill press, you only need to mark one side. If you're using a hand drill, it's best to mark both sides of the upright and drill both sides independently for the best accuracy.

d) Drill the holes.



e) The carbon fiber tubes are now ready to serve as the uprights for the exoskeleton.

OBTAINING THE MACHINED ALUMINUM PARTS

We do not manufacture the aluminum abduction/adduction parts in-house due to their complexity. Like the carbon fiber components, it is easy to have a third-party manufacturer do so for you. We have previously used UPTIVE to manufacture them for us. The part files are provided in the Aluminum Machining folder. The material used for these parts is 7075 Aluminum.

ASSEMBLING MACHINED COMPONENTS

1. Motors onto Belt

Here, we will be using the plastic mounting interfaces, the carbon fiber components, and the externally manufactured aluminum components to attach the motors onto the belt.

a) Gather necessary components.

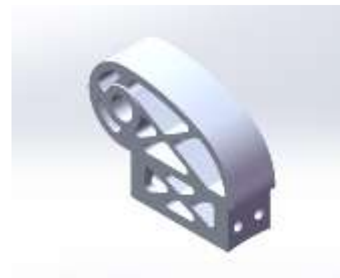
1x	Belt Assembly
4x	Ball Bearings
4x	M6 Washers
2x	6mm x 25mm Shoulder Screw
2x	M5 Lock Nut
8x	M5x14 Button Head Screw

8x	M5 Nut
18x	M3x4 Socket Head Screw
8x	M3x6 Button Head Screw
2x	AK60v1.1 Motor
2x	hipAdapterInner.SLDPRT
2x	hipAdapterOuter.SLDPRT
2x	adAbductionBlockHipSide.SLDPRT
2x	adAbductionBlockLegSide.SLDPRT

HipAdapterInner.SLDPRT

HipAdapterOuter.SLDPRT

adAbudctionBlockHipSide.SLDPRT



adAbudctionBlockLegSide.SLDPRT

b) Remove thermoformed interface from belt.

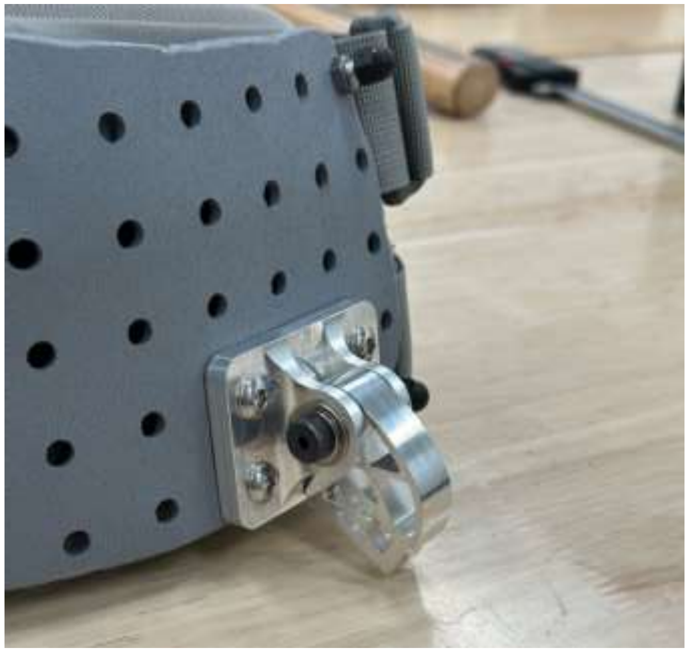
c) Press the bearings into the hip side abduction/adduction block.

d) Fasten the hip side abduction/adduction block to the thermoformed interface using the M5 x 14 bolts and M5 nuts. You may need to bend the plastic mounting plate to get this to properly fit and, on some occasions, the holes in the mounting plate may need to be slightly expanded to ensure proper fitting (can be done by sanding them).

Side Note: An important thing to consider is where in the mounting plate grid this abduction/adduction block should be placed. We first recommend having the intended user wear the belt with the empty mounting plates (no aluminum blocks) on it. Once this is accomplished, have the top of the belt aligned with the top of their iliac crest and the fronts of the belt's padding equally aligned with their left and right ASIS while snug on the user. From there find their greater trochanters and then identify the hole patterns in the mount that are in-line with the greater trochanters. It's possible, depending on the belt used, that this won't be possible, at which point we would recommend finding a different belt size that will allow for this alignment. Once this hole pattern is identified, fasten the abduction/adduction block to the mounting plates at these locations as described above. Generally, we have used the bottom row of holes for this (as shown in the image) so that the center of the motor is most in-line with the hip joint, but this may need to be adjusted depending on the user. While this generally fitting approach is our recommendation (it seems to be the easiest way to get consistent fitting across users), feel free to explore other potential fitting approaches as you see fit.

e) Once the abduction/adduction block is secure to the mounting plate, refasten thermoformed mounting plates to the belt.

f) Fasten the leg side of the abduction/adduction block to the hip side using the 6mm Diameter x 25mm Length Shoulder Screw, M6 Washers, And an M5 Lock Nut.



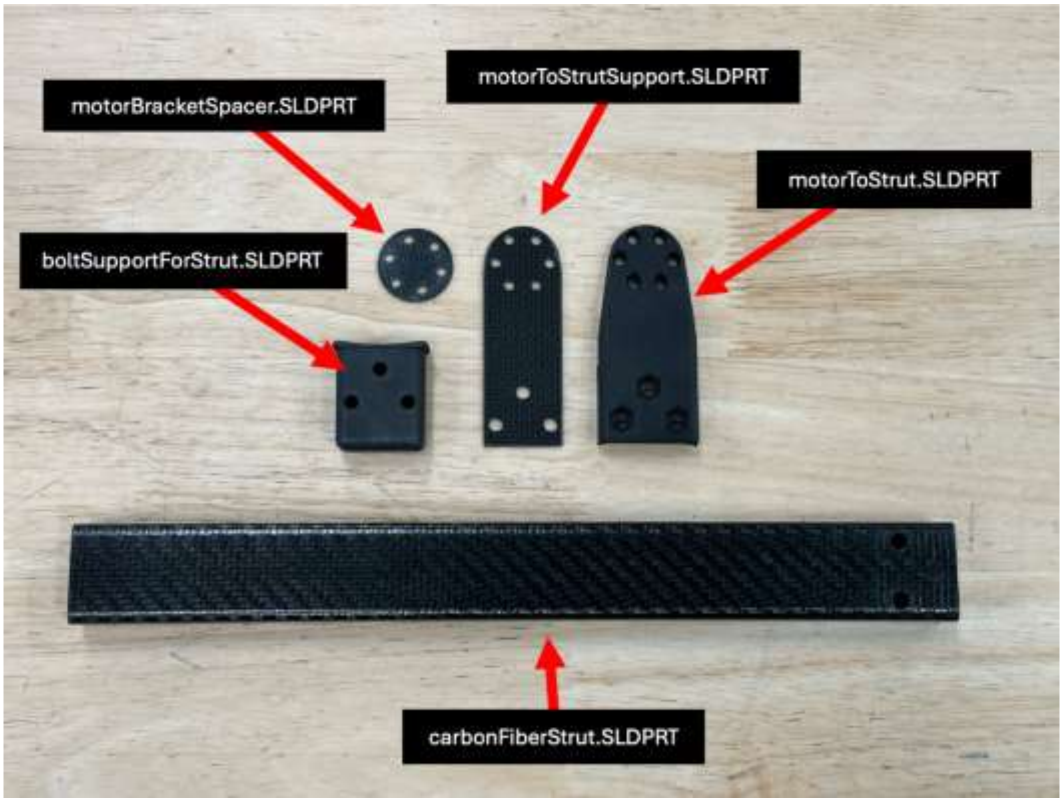
g) Fasten both the inner and outer carbon fiber Hip Adapters to the AK60v1.1 motors using a total of nine M3x4 bolts for each. **DO NOT OVER TIGHTEN** as this may puncture the motor, damaging them and leaving them non-functional. When fastening, ensure that the longer side of the **Inner** Hip Adapter is facing the **back** of the belt when the motor is mounted, as shown in the right image below.

h) Fasten the motors onto the aluminum block interface using four M3x6 button head screws for each motor (red arrows). We recommend using Loctite during this step to avoid the chance that the screws back out.

2. Attaching the Uprights to the Motors

a) Gather necessary components.

2x	motorToStrut.SLDPRT
2x	motorToStrutSupport.SLDPRT
2x	motorBracketSpacer.SLDPRT
2x	boltSupportForStrut.SLDPRT
12x	M3x10 Socket Head Screws
6x	M5x30 Button Head Screw
6x	M5 Washers
6x	M5 Nuts
2x	carbonFiberStrut.SLDPRT



b) Fasten the motorBracketSpacer, motorToStrutSupport, and motorToStrut to the motor with six M3x10 screws. Once again, **do not over tighten** as this may puncture and damage the motor. The motorBracketSpacer should be the only part that touches the motor. The motorToStrutSupport should sit inside the motorToStrut. This may require you to press the part in or to do some minor sanding to the spacer to get it to sit properly within the 3D printed spacer. The screws will ensure all the parts are fastened to the center of the motor. [**Note: The hip belt is oriented upside down in the following image to provide the clearest view of the assembly].**

c) Insert the boltSupportForStrut into the carbon fiber strut and ensure that the holes of the bolt support align with those in the strut.

d) Place the Carbon Fiber Strut onto the motorToStrut, aligning the three M5 holes.

e) Use three M5x30 bolts, M5 washers, and M5 nuts to fasten the strut onto the motorToStrut.

This Completes the Hardware Assembly

ELECTRICAL COMPONENTS

In this section we will outline the process of making all the electrical components involved with this device. This includes the creation of the CAN communication wiring to facilitate communication between the PCB and the motors, the FSR wiring to facilitate the connection between these external sensors and PCB, and the power cables connecting the battery to the PCB and the PCB to the motors. At the end of this section, an outline for where all the wires should be connected is provided.

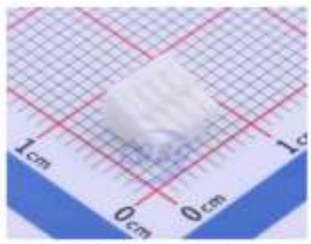
1. Assembling the CAN Wire

a) Gather necessary components.

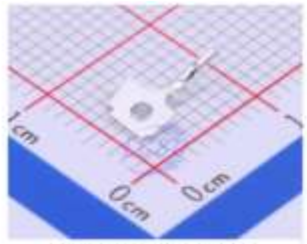
1x	Motor-to-Board CAN Wire
2x	CJT Connectors – Motor End
4x	CJT Pins – Motor End
4x	MOLEX Pins – Board End

2x	MOLEX Connectors – Board End
1x	Crimping Tool
1x	Wire Strippers/Cutters
1x	Utility Knife
1x	Heat Shrink


Motor-to-Board CAN Wire



CJT Connector - Motor End



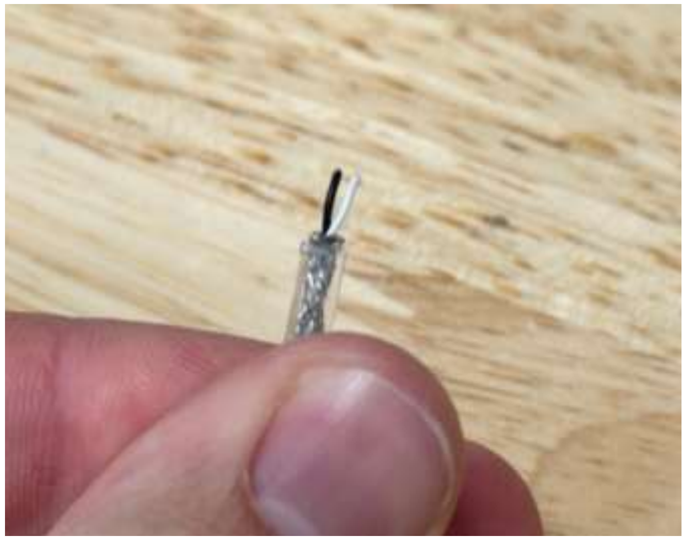
CJT Pin – Motor End


MOLEX Connector - Board End


MOLEX Pin – Board End

b) Cut the Motor-to-Board CAN Wire to the required length. 40 cm should be adequate, but double check whether this is enough for your belt (Make sure they can reach from the motors to the PCB while someone wears the belt). We use and recommend a specific CAN wiring but feel free to swap out with some alternative if you would like.

c) Strip roughly 1 cm of the outer cable on both sides of the wire, revealing the two inner wires. We typically use a box cutter for this step, carefully cutting off the outer shell without cutting into the inner wiring. When you do this, you will typically still get some of the gray inner lining material left around those wires. We recommend peeling this off and trying to cut as much of it off to leave only the wires exposed (see image below).



d) Strip the very ends of these inner wires on both sides to prepare them for crimping. Only a little bit of the inner wire needs to be exposed, so try to strip off as little as possible.

e) Cut two pieces of heat shrink and slide them onto the middle of the cable.

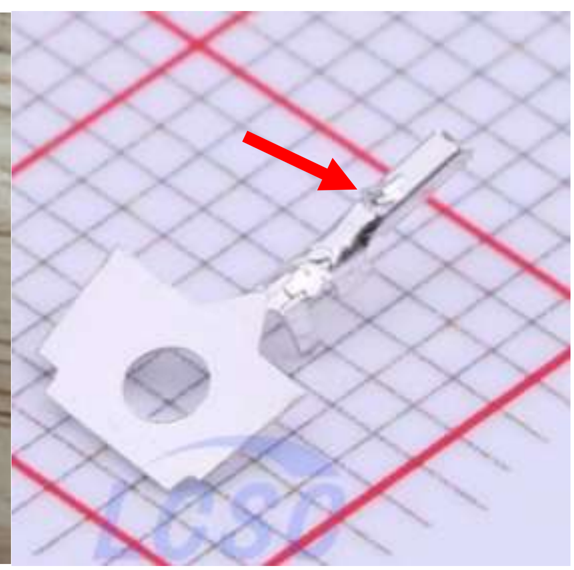
f) Carefully crimp the Molex pins onto one end of the wire (one for the black cable and one for the white cable on the same end of the cable).

g) Crimp the CJT Pins on the other end of the wire.

h) Using the continuity check feature on a multimeter, ensure that the connection between each end of the wire is good. To do this, tap each end of the jacks of the multimeter to the opposite end of the same color wire. For example, touch one jack to the CJT pin on the black wire and the other jack to the Molex pin on the black wire. If there is a connection, the multimeter should make a beeping sound. Now, keeping one jack on the black pin, switch one end to the white wire (e.g., move from the black Molex to the white Molex while keeping the other jack on the black CJT pin). No beeping should be coming from the multimeter. If beeping does occur, that means there is a short in the wiring which can create problems and it is likely best if the wire is remade. Repeat this process with the opposite-colored wire (e.g., white).

i) Insert the Molex pins into the Molex connector. Orient the Molex connector such that the tabs side is facing up (see image below). Once the connector is oriented this way, insert the wire connectors such that the **white** wire is on the **right** side and the black wire is on the left side, as shown in the image below. The pins should be oriented and slotted into the connector with their metal tab side facing up (red arrow). It may be helpful to have a pair of tweezers to aid in this step.


j) Insert the CJT pins into the CJT connector. Orient the CJT connector such that the tabs side is facing up (see image below). Once the connector is oriented properly, insert the wire connectors such that the **black** wire is on the **rightmost** hole and the while wire is in the hole immediately to its left. Ensure the tab on the CJT pin is facing upwards (red arrow) during this step.

k) Slide the heat shrink to the base of the connector on each side and then use the heat gun to shrink the material. It may be helpful to have a pair of tweezers available for this step as well. When completed, the two ends should look like the images below.

l) Repeat the continuity test with the multimeter (as described above) by sticking the tip of each jack onto the exposed metal component for each connector.

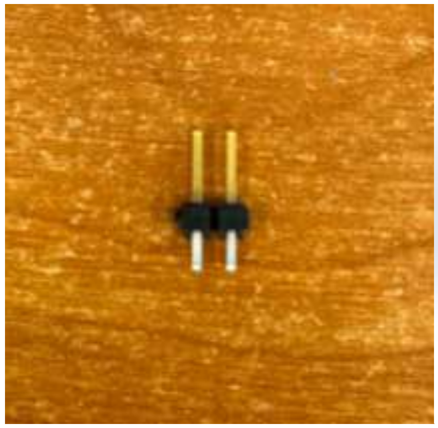
Note: If you are having issues with the pins becoming loose and sliding out of the connector, applying some hot glue on the ends of the connectors where the pins are inserted may help alleviate this problem.

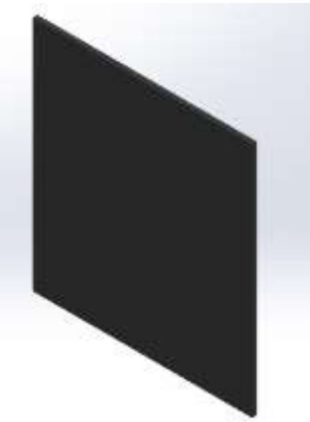
2. Preparing the FSRs

Here we will make the FSRs (external sensors that will detect heel and toe strike for control estimation). Prior to this, you will need to print four Heel_Puck.SLDPRTs, which are located in FILES FOR USERS/Part Files for 3D Printing.

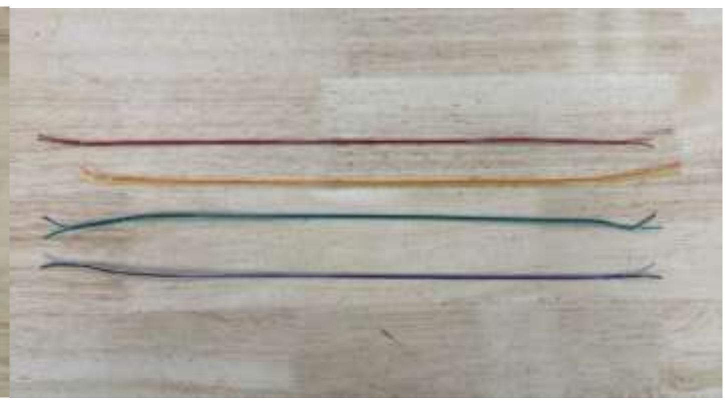
a) Gather the necessary components.

4x	Force Sensitive Resistors (FSRs)
1x	40cm Length Ribbon Cable
4x	Pairs of Male Pin Connectors
1x	Heat Shrink (you will need a smaller and larger size)
1x	Soldering Iron
1x	Solder
1x	Heat Gun
1x	Tweezers
1x	Wire Strippers
2x	Insoles
4x	Heel_Puck.SLDPRT
1x	Gorilla Tape (or something comparable)


Male Pin Connector Pair


heelPuck.SLDPRT

b) Take the ribbon cable, cut it to a length of 40cm. Then split the ribbon cable into separate pairs of two. To split the connectors, we use the edge of a box cutter to get started and from there peeled them apart. You should do this until you have 4 pairs of two wires. From there you should separate both edges of each wire as shown in the images below.

c) Strip all the ends of each wire and then coat each end with solder

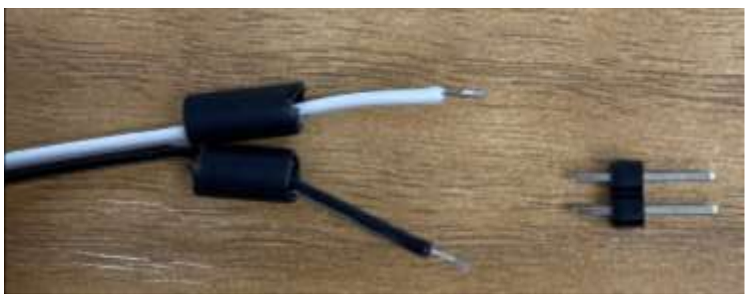
d) Slide the smaller diameter heat shrink over each individual wire on one end of the cable. Do **not** use the heat gun to shrink the material yet.

e) Take the FSR and coat the two exposed metal ends in solder in the same way you coated the ends in the step above.

f) Solder one end of the wire (both components of that end) to the two exposed metal ends for the FSR. Then slide the heat shrink over each soldered end and use the heat gun to shrink them. Be careful not to apply too much heat to the metal connectors of the FSRs as this may cause them to become dislodged, ruining the sensor. Once completed, the FSR should look as below.

g) Slide heat shrink onto the other side of the wires.

h) Solder these wire ends to the short end of the pair of male pin connectors. Prior to soldering it may be helpful to coat the short end of the male connector in solder. Once soldered together, slide the heat shrink over the soldered connections and use the heat gun to shrink them.



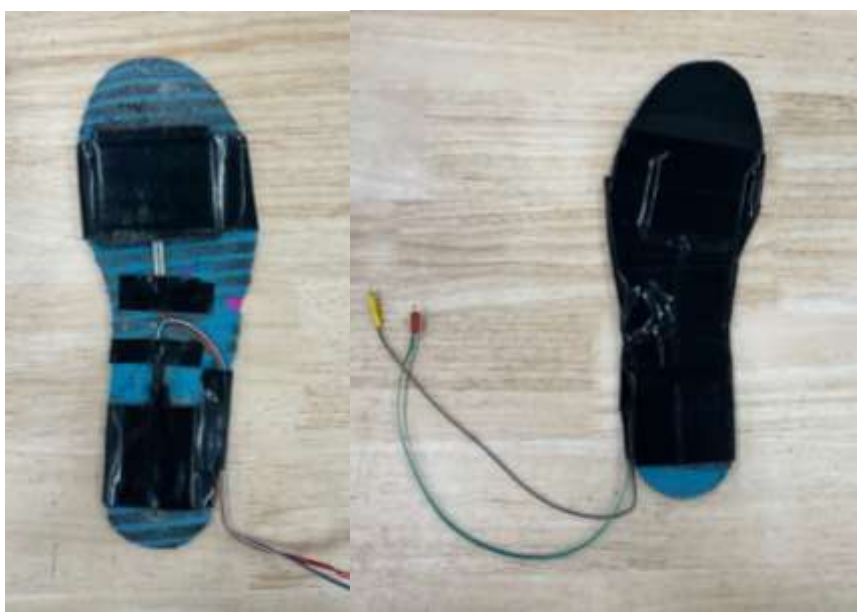
i) Slide the larger in diameter heat shrink onto the end just soldered and shrink onto the base of the pin connector and the wires. This will serve as extra protection as well as a handle (see left image below). The entire FSR should look similar to the image below (right)

j) Now we'll need to secure the FSR to the heelPuck.SLDPRT. To do so, lay the footplate as shown below.

k) Taking your tape, completely wrap the FSR in order to protect it.

l) Tape the FSR to the bottom side of the shoe's insole about where the ball of your foot rests (as shown in the image below). Be careful not to confuse the orientation when flipping the insole upside down!

m) Place the second FSR at the heel and tape down as well. Ensure that the wires are coming out on the external side of the foot close to where your ankle would be, this will make it easy for the wires to exit the shoe without interfering with movement. It is helpful to guide the wires to the edge and then tape them together along the edge to keep them secure. **During this step, make note of which wire is for the toe FSR and which is for the heel FSR.** We suggest placing a label or wrapping a piece of tape around one of the wires to help differentiate them.



n) Place the sole back into the shoe and repeat for the other side.

3. Wires for Connecting the FSR to the PCB

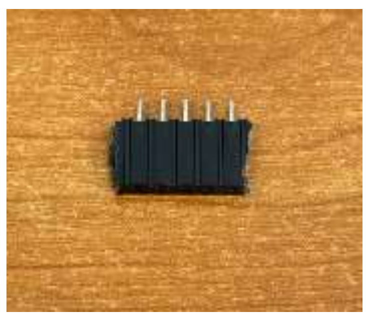
Here, you will be making the cables that connect the FSRs to the PCB. You will need two of these wires, one for each leg. As a result, the process outlined below will need to be repeated an additional time!

a) Gather necessary components.

1x	FSR-to-Board Connecting Cable
1x	Heat Shrink
1x	Ribbon Cable Header for Board
2x	1X5 Female Pin Connectors
1x	8-Wire Ribbon Cable
1x	Soldering Iron
1x	Wire Strippers
1x	Solder
1x	Heat Gun

FSR-to-Board Connecting Cable

Ribbon Cable Header for Board



1X5 Female Pin Connector

b) Cut 120 cm of the FSR-to-Board Connecting Cable. This is the black cable with four wires inside, as shown above.

c) Strip roughly 2 cm of the outer cable off both ends of the cable. This will leave the insides exposed which consists of the four wires and inner insulation/sheathing. Remove the inner sheathing/insulation as best you can (we try to twist it off to the side and cut away as much of it as possible with wire cutters/scissors/box cutters).

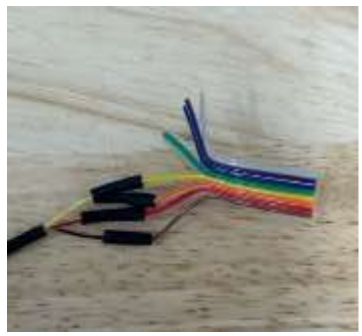
d) Strip the ends of the four inner wires, on both sides, to prepare for soldering. You only need to strip a small portion off each end.

e) Cut ~4 cm of ribbon cable, ensure it has 8 wires (you can always get a bigger one and remove a few if needed).

f) Separate four of the wires on only one side of the ribbon cable and strip them to prepare for soldering. [Left Image: Four Separated – Brown, Red, Orange, Yellow; Right Image: Four Stripped – Brown, Red, Orange, Yellow]

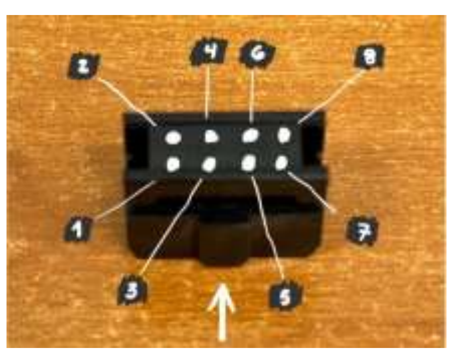
g) Cut small sections of heat shrink and slide it over those four wires. Then, solder the four ribbon cable wires to the FSR-to-Board Connecting Cable. Once soldered use the heat gun to shrink the heat shrink around the soldered connections. **It is important to take note of the order you solder these wires.** That is, keep note of what color of the FSR wire is soldered to what color of the ribbon cable. We recommend the following convention (assuming colors align on both the ribbon cable and the FSR wire):

- FSR Black -> Ribbon Cable Brown
- FSR Red -> Ribbon Cable Red
- FSR White -> Ribbon Cable Orange
- FSR Yellow -> Ribbon Calbe Yellow



h) Now we'll solder the other end of the FSR-to-Board Cable to the 1x5 Female Pin Connector. **Order is important here**. First, some background information. Below is a diagram indicating the order of the wires in relation to the ribbon cable header that we will eventually place on the ribbon cable we just soldered. The inclusion of this diagram is to make clear the logic behind the order that you will solder wires to the 1X5 Female Pin Connector. Once connected to the PCB, the board will read the wires as follows:

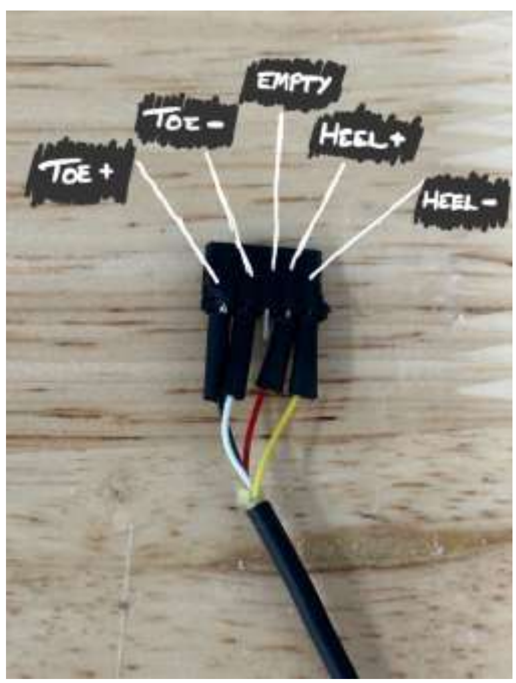
- 1: FSR Toe + (Ribbon Cable Brown -> FSR Black)
- 2: FSR Heel + (Ribbon Cable Red -> FSR Red)
- 3: FSR Toe - (Ribbon Cable Orange -> FSR White)
- 4: FSR Heel - (Ribbon Cable Yellow -> FSR Yellow)
- 5-8: Unutilized pins for additional sensor (e.g., torque transducer)



Note the orientation of the ribbon cable header in the photo, with the top (solid side) facing upwards and the tab facing towards you. The bottom, with the actual holes is facing down onto the table, we have drawn in the orientation of the holes onto the figure to aid in clarification of the order. The arrow indicates the direction that the ribbon cable will be inserted into the connector. As such, the four leftmost wires of the ribbon cable will be the ones that need to be connected to the FSRs. The other four are available for an additional sensor type (e.g., torque transducer, angle sensor) but for the purposes of this guide we will ignore (but are the reason we have 8 wires for the ribbon cable instead of just isolating to the 4 utilized). [Side Note: If you were to use the remaining four pins for a new sensor type, you would need to change the "Board.h" file in the software as those pins are currently assigned to torque transducers)

When soldering to the 1X5 female pin connector, there will be one extra pin. This is to allow for adequate spacing when connecting the FSRs. This extra pin should be in the middle. You should solder the connections to the female pin connector in the following order:

- Left Most -> Toe + (FSR Black)
- Second Left Most -> Toe – (FSR White)
- Middle -> Empty
- Second Right Most -> Heel + (FSR Red)
- Right Most -> Heel – (FSR Yellow)



i) Slide larger heat shrink over both ends that you just soldered to enclose the wires. Apply heat to shrink them as a protective covering.

j) Press the 2X4 8-Pin Connector onto the ribbon cable in the orientation shown. This is with the connector holes oriented up and the tab should face towards the main body of the wire. With this orientation, the white (non-connected) side of the ribbon cable should slide into the left side of the connector and the brown (connected) side of the ribbon cable should be on the right side. Once properly oriented, press the two sides of the ribbon cable connector down until firmly pressed together (the two ends should meet). Note that the correct orientation is necessary for proper function of the cable. This should leave you with one cable to connect the PCB to the FSRs in the shoe/insole.

REPEAT THESE STEPS TO MAKE AN IDENTICAL WIRE FOR THE OPPOSITE LEG

4. Wiring the Power Switch

a) Gather necessary components.

1x	XT30U Male Connector
1x	XT60E1 Male connector
1x	Power Switch
NA	Heat Shrink
2x	16AWG Wire (one red, one black)
2x	16AWG Nylon Quick Disconnect Female Terminals
1x	Large Crimping Tool
1x	Wire Strippers/Cutters
1x	Soldering Iron
1x	Solder

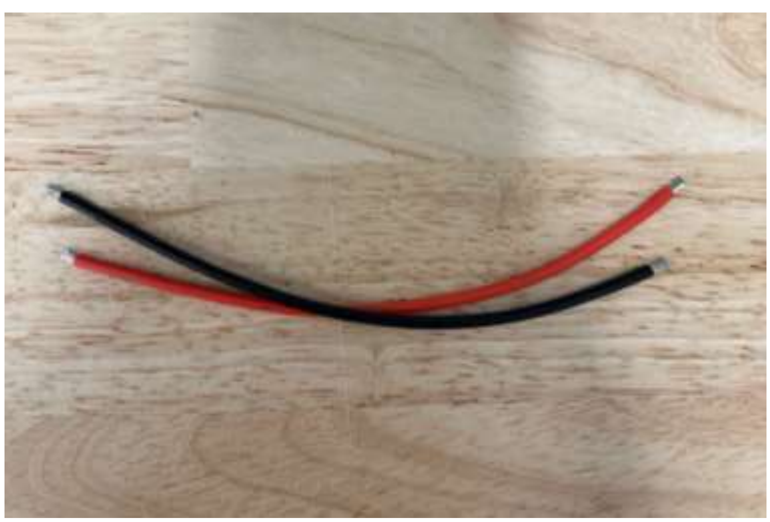

XT30U Male Connector


XT60E1 Male Connector


Power Switch


16 AWG Nylon Quick Disconnect Female Terminal

b) Cut 10 cm of both the positive (red) and negative (black) wires and then strip the ends for soldering.



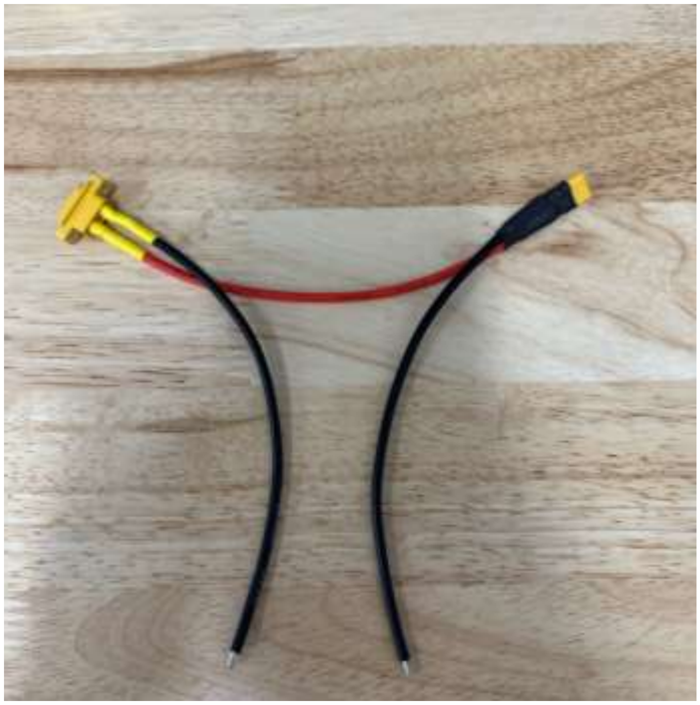
c) Solder the wires to the XT60E1 Male Connector and apply heat shrink over the connections.

d) Slide another piece of heat shrink over the positive (red) wire (to cover the connection you are about to solder).

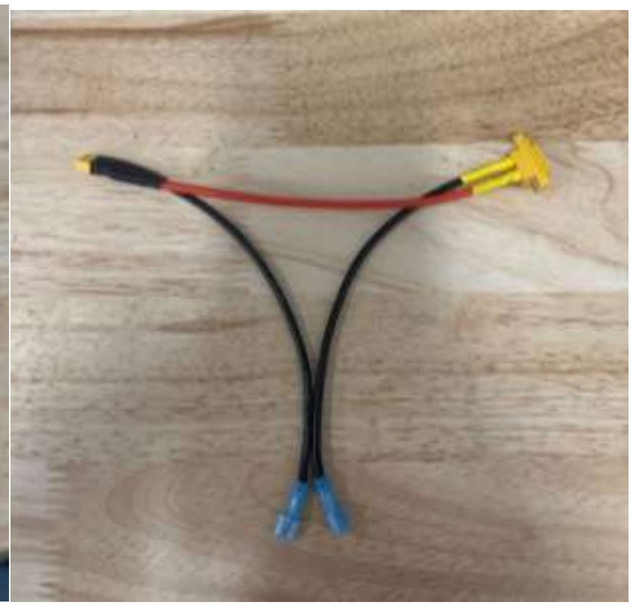
e) Solder the positive wire (red) that extends from the XT60E1 Male Connector to the positive terminal of an XT30U Male Connector. Using the heat gun, shrink the heat shrink you slid on to cover the connection.

f) Cut another 10 cm length of black wire and strip both ends.

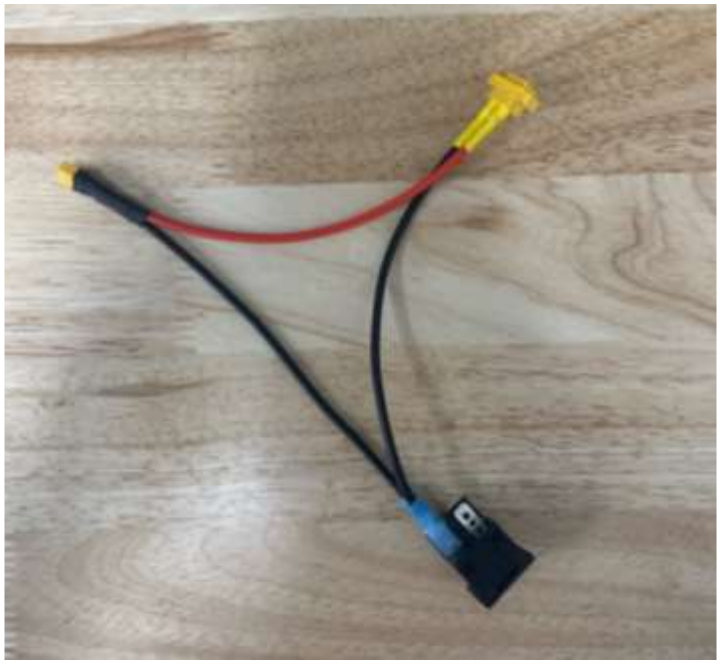
g) Solder the wire you just prepared to the negative terminal of the XT30U Male Connector. Apply heat shrink to cover the connection. Then cover both connections over this end with a larger heat shrink. Use the heat gun to shrink it down, giving you a firm base to plug/unplug the wire from the board.



h) Crimp the 16AWG Nylon Quick Disconnect Female Terminals onto the two remaining exposed ends of wire. To do this, slide the terminals onto the wiring and use a crimper to squeeze down on the middle portion of the connector.



i) Attach the Power Switch to the two female terminals as shown in the image below. Make sure these two ends are attached to opposite sides of the same horizontal component rather than right next to each other.



5. Tapping Holes for the Battery Connector

Here, we'll tap the holes in the PCB cover's backplate so that we can fasten the battery connector of the power switch in place.

a) Gather necessary components.

1x	Hip Belt w/ Electronics Box Back Plate attached
1x	M2.5X0.5 Tap
2x	M2.5X10 Screw

b) Use the tap to thread the two holes in the battery compartment of the electronics box. You may need a tap wrench for this stage.


c) Screw the battery connector of the power switch into place using two M2.5X10 screws.

6. Soldering the Status LED

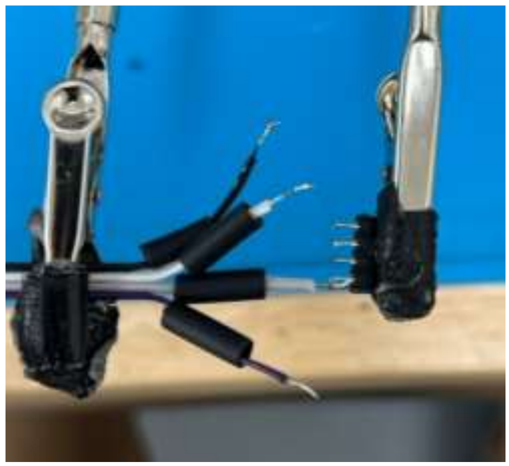
a) Gather necessary components

1x	RGB LED
1x	Ribbon Cable
1x	1x4 Female Pin Connector
1x	Soldering Iron
1x	Solder
1x	Heat Gun
1x	Wire Strippers/Cutters
NA	Heat Shrink

b) Isolate about 20cm of four wires of the ribbon cable and separate the ends as shown.

c) Strip the ends of the wires on both sides to prepare for soldering.

d) Cut pieces of heat shrink to size and slide over the wires. After soldering, these will be shrunk to protect the connections.



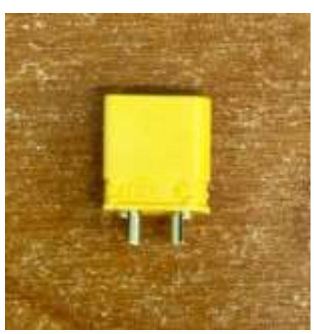
e) Solder the wires to the 1X4 female pin connector and shrink the heat shrink. Order does not matter in this step.

f) As done before, cut to size and slide heat shrink onto the other ends of the wires and solder to the LED. Order only matters in the sense that the wires are soldered in the same sequence as before (i.e. purple is still next to gray, which is still next to white, which is still next to black).

7. Making the Battery-to-Motor Power Cable

a) Gather necessary components

4x	16 AWG Wire
2x	XT30U Male Connector
2x	XT30U Female Connector
1x	Wire Strippers/Cutters
NA	Heat Shrink
1x	Heat Gun
1x	Soldering Iron
1x	Solder



XT30U Male Connector

XT30U Female Connector

b) Cut roughly 40cm of the 16 AWG Wire for the positive and negative connection.

c) Strip both ends to prepare for soldering. Once stripped, it may be helpful to coat each end in a layer of solder to make that process easier.

d) Slide two pieces of heat shrink over both wires on both ends (four total) to protect the solder.

e) Solder the male XT30U to one end and the female XT30U to the other. Cover both ends with a larger piece of heat shrink to help with easy attachment/removal of the wiring.

8. Configuring the Motors

a) Gather the necessary components.

1x	R-LINK Module
2x	AK60v1.1 Motor
1x	Battery-to-Motor Power Cable (from prev. step)
1x	Power Switch Cable (from earlier step)
1x	Battery
1x	USB Cable
1x	Computer with CubeMarstool_V1.32.exe Installed (located in the same folder as this document)

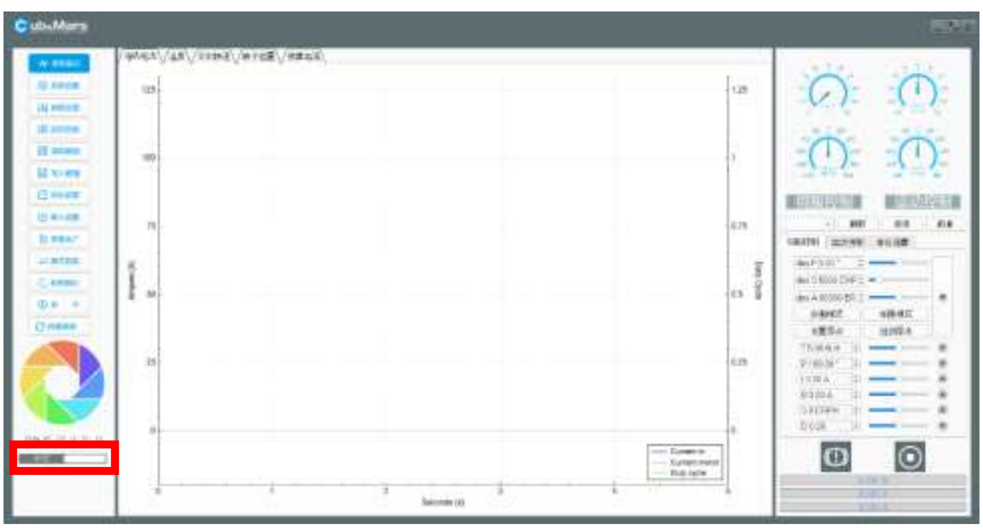
R-Link Module

Battery-to-Motor Power Cable

Power Switch Cable

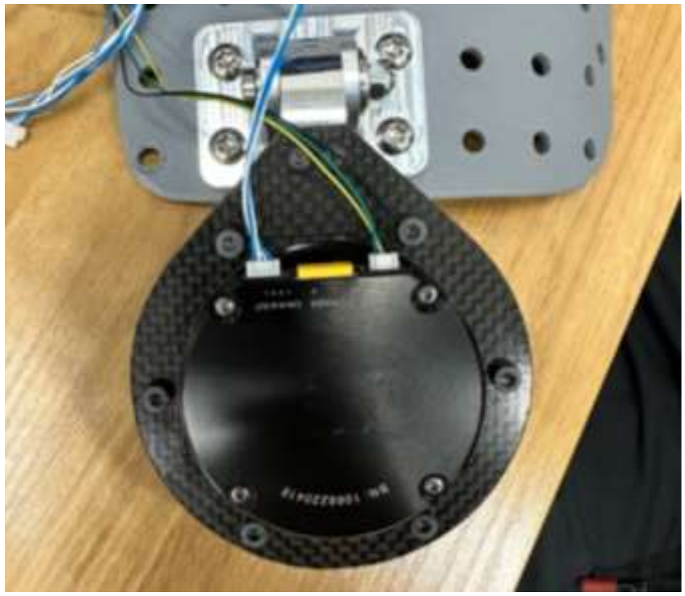
b) Open the CubeMarstool_V1.32.exe software.

c) Once the software opens, use the switch on the bottom left of the window to switch the language to English, as shown below.



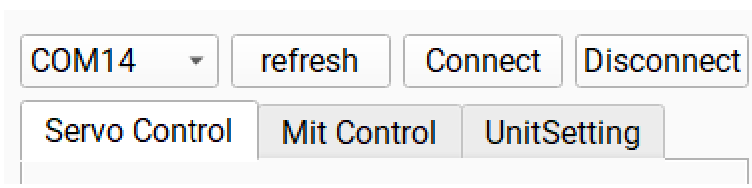
d) Connect the R-LINK Module to the computer with a USB cable.

e) Connect the 3-pin and 4-pin cables from the R-LINK to the motor, as shown in the image. The tabs on the connectors should face outwards.



f) Plug the battery into the motor via the battery-to-motor cable and the battery-to-switch connectors. Power on the motor.

g) In the CubeMarsTool window, press the refresh button. The software should auto select the correct COM port. If it does not, you can use the dropdown to select manually.



h) Click "Connect." A green bar like the one below should flash briefly at the bottom of the screen as confirmation.

i) On the right side of the screen, switch to MIT control. Click Debug.

j) Hold the motor such that it can spin freely. Go down to the bottom of the window and type in the command line "calibrate." **For this to occur, you will need to remove the upright configuration from the motor. It may be easier to do this step prior to placing the motors onto the belt.** Once the motor is done calibrating, you will be presented with commands that you can use, as below.

```
Commands:

run - Motor Mode

calibrate - Calibrate Encoder

setup - Setup the motor

encoder - Show encoder value now

origin - Set Zero Position

exit - Exit to Menu
```

k) Type "setup" in the command line. You will be presented with text similar to that shown below. Notice specifically the "prefix," "parameter," and "current value" sections [red boxes]

Configuration Options

prefix	parameter	min	max	current value
set_band_width	Current Bandwidth (Hz)	100	2000	100.0
set_can_id	CAN ID	0	127	0
set_master_id	CAN Master ID	0	127	0
set_current_limit	Current Limit (A)	0.0	60.0	0.0
set_fw_current_limit	FW Current Limit (A)	0.0	33.0	0.0
set_can_time_out	CAN Timeout (cycles)(0 = none)	0	100000	0

l) **<u>Configure the motor according to the settings in the image below</u>**. In order to do so, type the "prefix" for the setting (shown above and below, directly under the "Configuration Options" text), then separated by a space type the desired value. (Example: set_can_id 65). **<u>The one option you will need to change, depending on joint and leg you are targeting, is the CAN ID</u>**. Use the following convention:

- **Left Hip: 65**

- **Right Hip: 33**
- Left Knee: 66
- Right Knee: 34
- Left Ankle: 68
- Right Ankle: 36

So, for the hip device, you would want to set the CAN ID for the motor on the left side to 65 (as shown in the image) and to 33 for the motor on the right side! It may be helpful to place labels on the motors indicating which side and joint they are for during this stage in order to avoid confusion down the road.

```
Configuration Options

prefix                parameter                      min   max    current value

set_band_width        Current Bandwidth (Hz)         100   2000   1000.0

set_can_id            CAN ID                         0     127    65

set_master_id         CAN Master ID                  0     127    0

set_current_limit     Current Limit (A)              0.0   60.0   13.5

set_fw_current_limit  FW Current Limit (A)           0.0   33.0   13.0

set_can_time_out      CAN Timeout (cycles)(0 = none) 0     100000 0
```

m) Once the remaining "current values" are the same as ours, type "exit" in the command line.

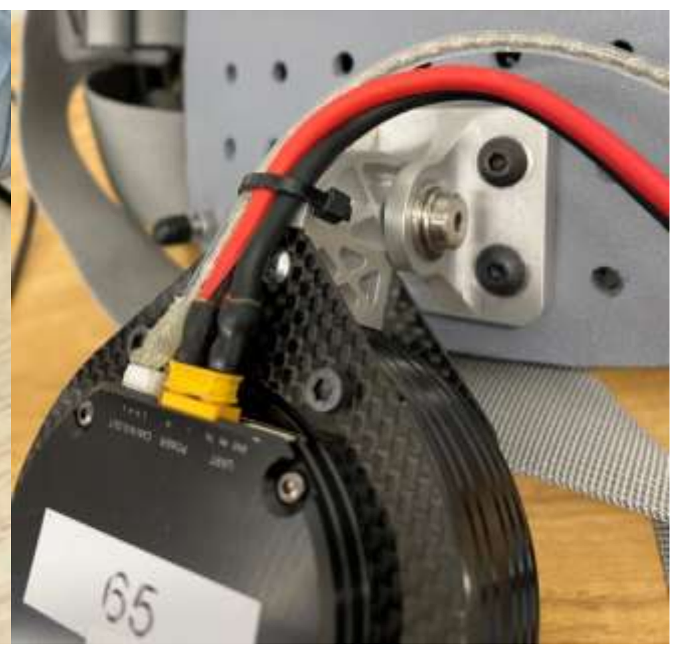
n) Click "Disconnect" and you are finished configuring the motor. Repeat for the other motors.

9. Making the Connections

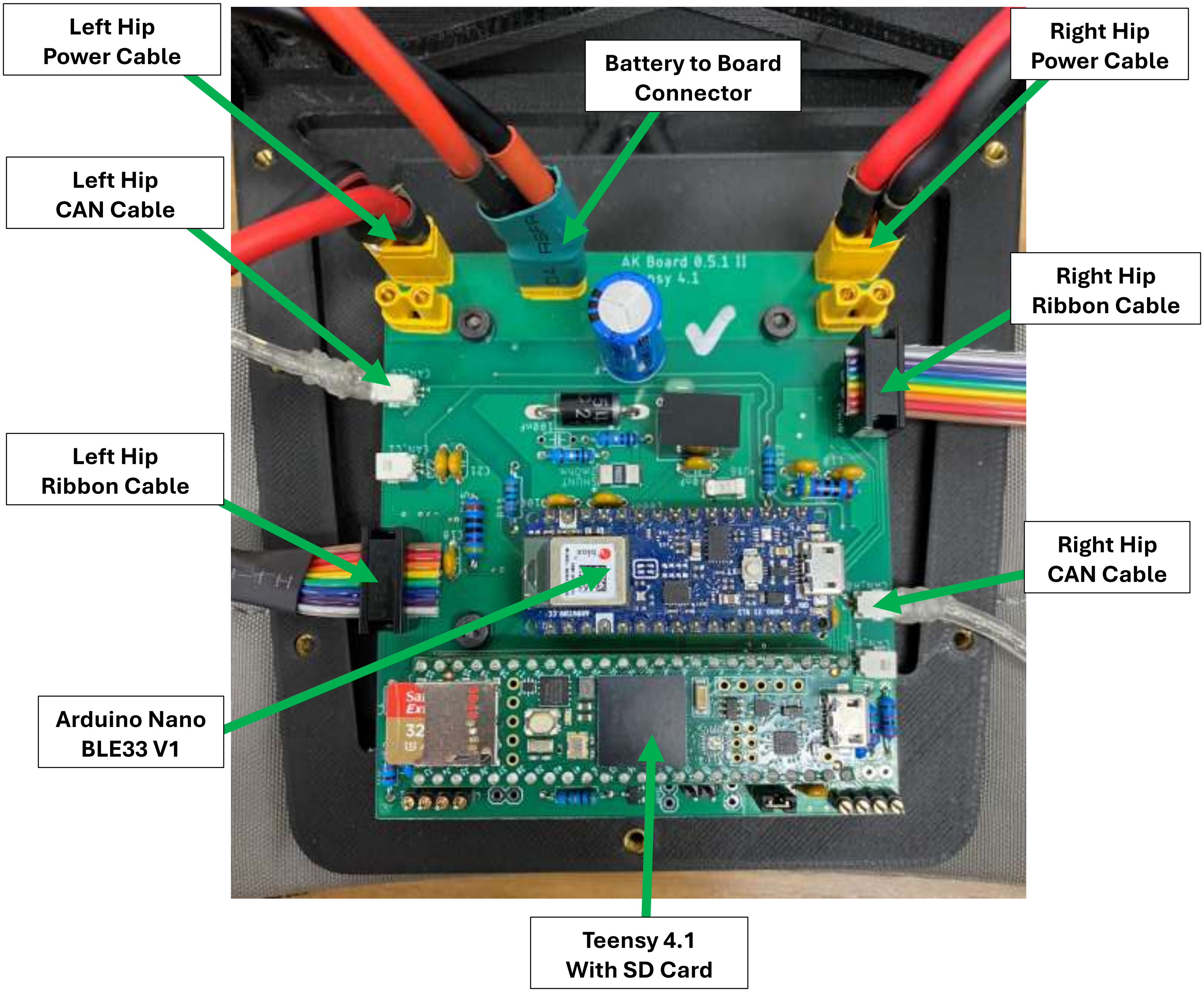
a) Gather the hip belt and all the wires you've made so far, as well as the electronicsBoxStrainRelief[Left/Right].SLDPRT.

b) Fasten the PCB to the electronics box back plate using the 3 mounting holes which have threaded inserts in them.

c) Connect power and CAN cables to both motors. The power cable goes in the power slot and the CAN communication goes into the connection with 4 pins. Labeled “CAN In & Out” on the side of the motor). Once connected, it may be helpful to add some strain relief in the form of a zip tie. This can be accomplished by zip tying the two cables onto the abduction/adduction block (right image below).

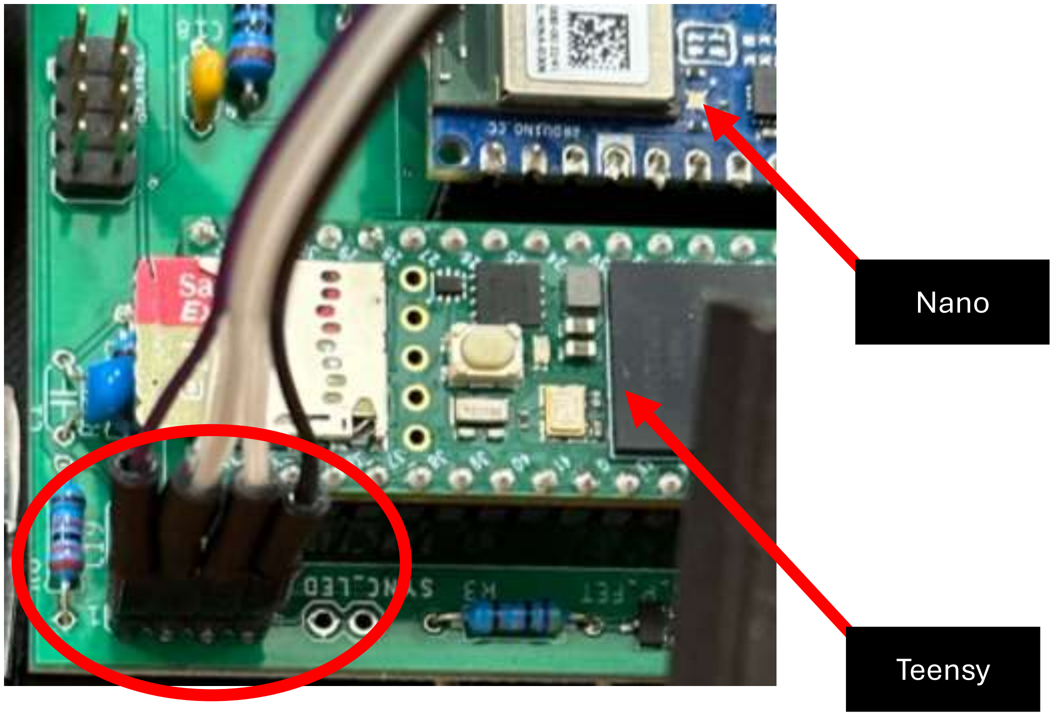


d) Connect all wires as shown in the image below. The ordering convention that we use, should you want to do multi-joint applications, is that the proximal joint goes in the top slots and the more distal joint goes in the bottom slot. In this case, the power cables go in the first power connector and the CAN communication wiring goes into the top ports on each side. Finally, make sure to plug in the battery-to-switch connector and the ribbon cables.

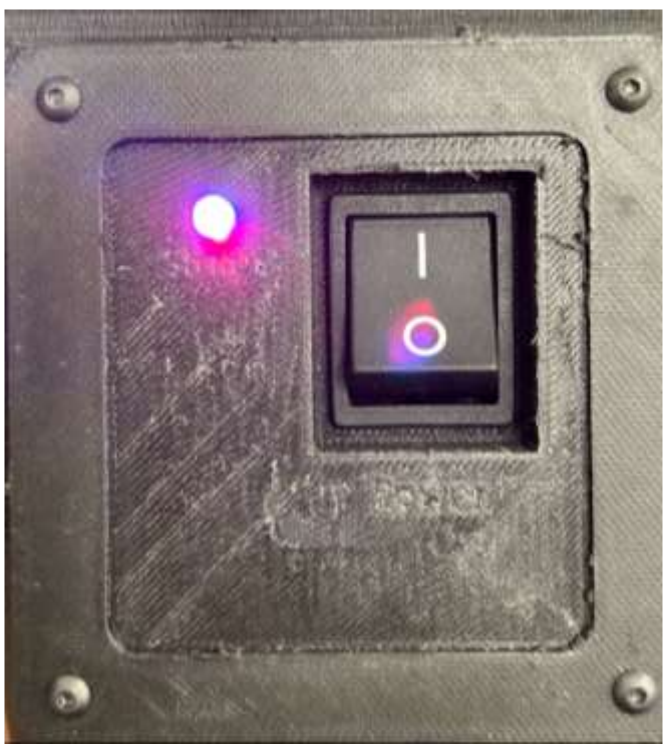


e) Fasten the strain reliefs to the board. Note that there is a left and right side; the slots in each strain relief correspond to the placement of the ribbon cable on each side of the board.

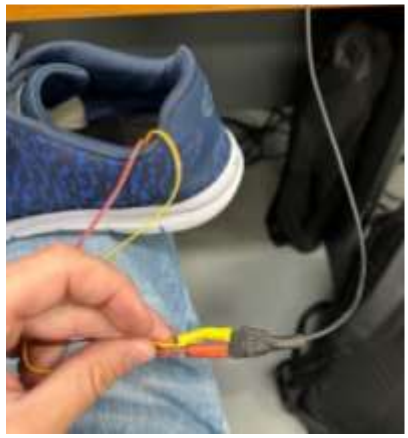
f) Connect the status LED to the board and slide into its respective hole in the panel containing the power switch.



g) Power the board on to ensure that the LED functions. If it does not, reverse the orientation of its connector and try again.



h) During this stage, you should also take the time to connect the heel and toe FSRs on both sides. If you aren't sure which wires correspond to the heel or toe, you can test to figure it out by pressing each sensor and reading the data. Generally, the shorter wire should belong to the heel since it is oriented away from the connection on the actual insole itself. It may be helpful to make a marking on the FSR connection cable indicating which side is the toe for future usage (one convention we have used is shading the Toe+ connection on the female header a white color to make it stand out).



ASSEMBLING THE PCB COVER

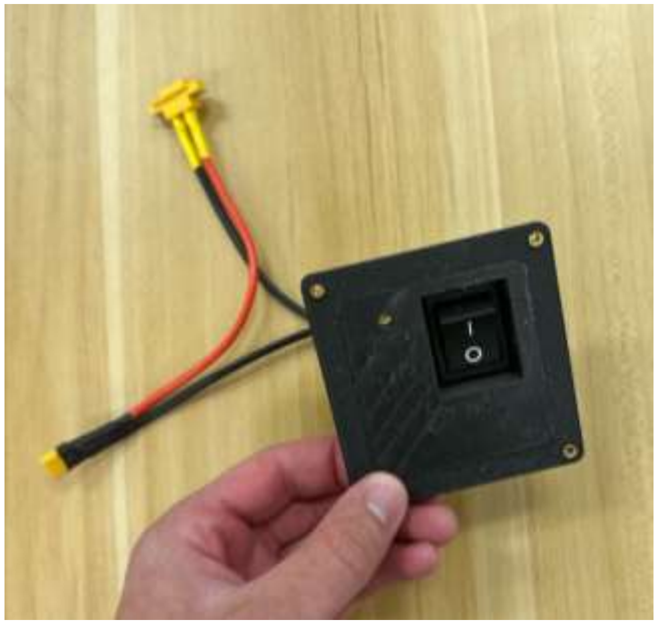
Now that the wiring is complete, we can assemble the rest of the PCB casing. You'll need to gather all of the components you've printed for the PCB cover.

a) Gather necessary components.

1x	Hip Belt (as left off in the previous section)
1x	electronicsBoxBatteryCover.SLDPRT
1x	electronicsBoxControlPanel.SLDPRT
1x	electronicsBoxStrainReliefLeft.SLDPRT
1x	electronicsBoxStrainReliefRight.SLDPRT
1x	electronicsBoxBody.SLDPRT
4x	M3 Threaded Inserts
1x	Soldering Iron
6x	M3X10 Screws

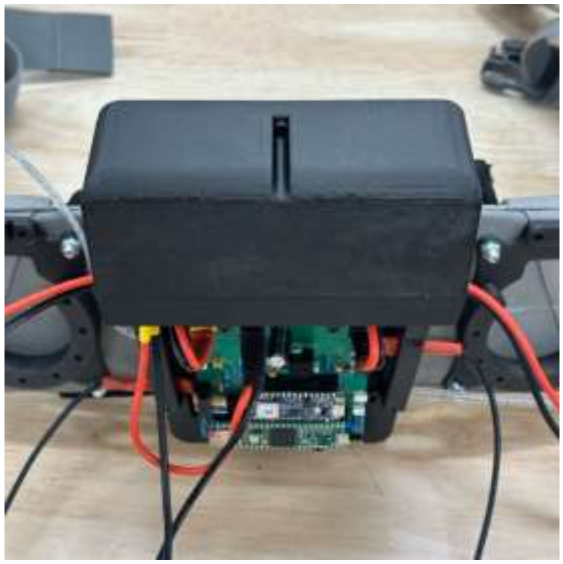
a) Use the soldering iron to place M3 threaded inserts into each of the four mounting holes.

b) Press the switch and LED into the electronicsBoxControlPanel.SLDPRT. (Note: The below images do not have the LED, but you should have it during this stage).



c) Place the battery into the top compartment of the electronics box backplate as shown below with the battery’s power wire protruding through the slot.

d) Fasten the electronicsBoxBatteryCover.SLDPRT over the battery with an M3X10 screw.



e) Fasten the electronicsBoxControlPanel.SLDPRT with the switch in it to the electronicsBoxBody.SLDPRT with four M3X10 screws.

f) Connect the switch to both the board and the battery and fasten the electronicsBoxBody.SLDPRT with the switch in it to the backplate.

PADDING FOR ADDITIONAL COMFORT

You may want to make a pad that fits onto the inner side of the hip belt for additional comfort (example below). These were made by making a pocket with two different fabrics. One softer and breathable for the side facing the user, and a tougher side to which Velcro is sewn. Foam was placed into the pocket (the same foam used for making the insoles) and the pocket was sewn shut. Alternatively, you could take a piece of foam and attach Velcro and that should work somewhat well too.