Force Sensor Protective Casing and System Design for a Lower Limb Exoskeleton

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BACKGROUND

The Locomotor Control System Laboratory (LocoLab) works solely with lower limb exoskeleton design for the purpose of rehabilitation. We aim to help the elderly, stroke patients, and the population needing partial assistance unilaterally (one leg) or bilaterally (both legs). Traditionally, exoskeletons on the market provide complete assistance. As in, a user in the exo will pre-choose the task they need to complete- say, going up the stairs- and the exosuit will move their limbs and complete the task. In this sense, the user has very limited freedom of movement. They are restricted to movement only in pre-defined modes dependent on the control panel. However, those requiring only partial assistance do not need to be so constrained, nor is the normal daily life of an able-bodied person so premeditated. Some Activities of Daily Living (ADLs, as the lab has defined them) include up/down stairs, incline/decline walking, and stand-to-sit. In a typical routine one may choose to combine, switch, reverse, or change tasks midway on a spur of the moment decision. Our lab focuses on giving that freedom back to our target audience.

Current development efforts are working on a controller for an efficient, backdrivable, task-invariant knee-ankle exoskeleton. Backdriveable, referring to the ability to “back-drive” a motor, specifies the ability of a user to provide the input motion on a motor, to drive the direction of the task. Task-invariant control refers to a controller that automatically senses and provides support for any ADL- regardless of the task the user chooses to perform. Through these specifications, we hope to reverse the controlling factor and return it back to the user. The target controller can continually listen to changes in motion, determine which task is going to be performed, and assist the user appropriately, and seamlessly switch between tasks.

MOTIVATION AND INTRODUCTION

The exoskeleton prototype used for testing depended on a footplate to determine the ground reaction forces. Measuring these forces from the ground is integral to the functionality as it defines a participant’s gait phase (step or swing). Simply put, force sensors would determine if there was a force from the ground (user is currently stepping on the foot), or not.

Figure 1: The original prototype exoskeleton used, dubbed ComEx1.

Through the Summer Undergraduate Research in Engineering Program, I assisted running experiments using this prototype during a control method verification study to confirm that the task invariant control system truly reduced the metabolic cost (amount of energy used) to perform three ADLs: stair ascent/descent, incline/decline walking, and sit-to-stand tasks [1]. As a volunteer subject myself, I became the youngest, only female participant in the experiment. I quickly learned that the current prototype was too big, and too bulky for smaller users. Specifically, the footplate was too large for my smaller size, and it caused more tripping, irregular walking, and noisier ground force reaction measurements, making task switching more difficult. All of these issues detracted from the overall goal of collecting metabolic data from the various ADLs, and made testing, as well as the eventual design of the exoskeleton, inaccessible to a larger participant pool.

In order to support the smoother collection of data for the main research being performed, and to push towards a more equitable exoskeleton design, I took on the project of designing a more flexible ground force reaction measurement system, through adjustable sensor placement underneath a research participant's foot.

REQUIREMENTS

A stakeholder analysis was conducted to understand the design context. Here, all groups connected to the work I am performing were considered, the opinions they may have, and constraints that may apply to my project were extracted.

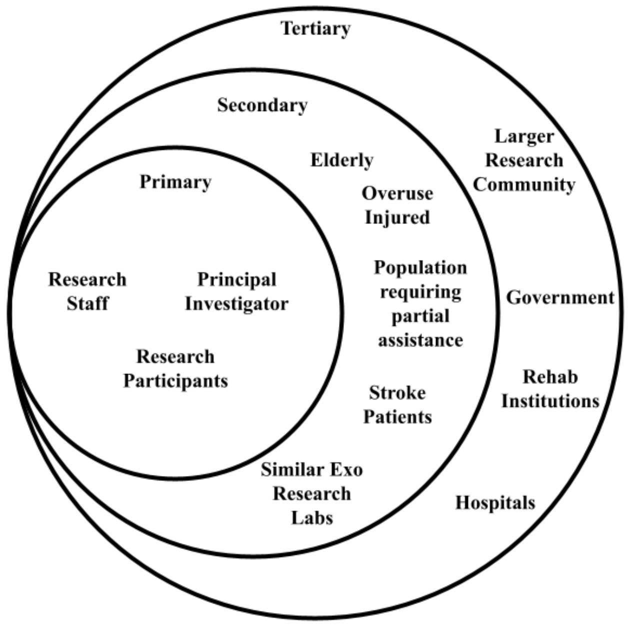

Figure 2: Stakeholder Analysis. Each larger circle represents an audience more distantly connected, who may still take interest in the problem.

A handful of engineering specifications were derived from the secondary and tertiary stakeholders. In order to accommodate for the largest pool of users, the system had to have size flexibility. This would allow for more widespread testing and larger amounts of data. The system also had to be as imperceptible as possible. An unobtrusive system would preserve the natural gait of the participant, allow researchers to work with accurate gait data, and help the exoskeleton to recreate a user's unique gait.

Most specifications were defined in tandem with the primary stakeholders. Constraints on the design problem included the materials already in the lab, the current exoskeleton wiring system, and overall price. Previous materials provided an initial wiring system, printed circuit board (PCB), and specified a force sensing resistor (FSR) to work with. Per discussions with my PhD research advisor, we decided the design must have a protective casing, securely hold the FSR, be easy to check for FSR quality and make replacements, and be securely attached to the foot. To minimize costs, the expensive high quality sensors needed to be protected from rips and scratches, constantly checked, and the number of sensors bought should be minimized. The correct FSR fit minimizes noise from rattling and prevents false measurements by ensuring the sensor is not pinched in the casing. Secure attachment was necessary to further protect the sensors, and to ensure the system's reliability in multiple trials and participants.

Table 1: All stakeholder requirements, summarized into a list.

Secondary Stakeholders	Size Flexibility
	Imperceptible
Local Stakeholders	Protective Casing
	Secure FSR Sensor Fit
	Easy to check quality and replace sensors
	Secure Attachment

PROJECT: FSR Casing

In the following sections I describe the FSR hard case system that was ultimately designed and completed. However, it did not take as long as anticipated and I will also briefly mention the secondary, revamped concept I began work on afterwards. Both are ongoing solutions to the initial problem described above.

CONCEPT GENERATION, DESIGN, AND PROTOTYPING

Concepts were brainstormed for a couple weeks before prototyping began, with me and my research advisor, while I began the initial designs for the sensor cover on Fusion360 (a CAD program) in tandem with securement discussions. The electrical wiring system and code was only developed after. Once the materials had all arrived, the design finalized, and the wiring and code were completed, the system was assembled and tested.

Securement Concepts

The first concept fully discussed was the idea of using cricket/golfing shoes with detachable spikes. By recreating the geometry of the spike attachment in 3D through a Computer Aided Drawing (CAD) program, the sensor protection design could be easily securely attached to the shoes. By utilizing the pre-made geometry, we could confirm that the attachment would be secure without creating an entirely new system. Size flexibility would come from buying three sizes of the shoes, from a women’s size 6 to a men’s size 9. However, there were many issues with this idea. It was very difficult to obtain a range of sizes for cricket shoes, and there did not seem to be a consistent design for cricket spike attachment. Most shoes cost >$300 per pair, were custom ordered, and would have to be shipped from across the world. Additionally, there was a very limited size availability: a majority of the options/ brands only sold shoes in men's sizes larger than size 7. There were very few women’s cricket shoes. Considering the time and money budget we had, there was no combination of various brands or sources that would allow all the shoes to arrive within a couple months, have the same attachment method, and cover the range of sizes we wanted to have.

The next idea explored for securing the sensors was to simply screw the designed case into the bottom of any shoe. The only constraint for this design was to have a foam layer taller than the screw length to protect the participants from the sharp points of a screw. This way, we could find a cheap mass produced sneaker that would provide the size range we needed and minimize shoe costs. After a quick test run with a physical shoe we determined this method would be secure enough for our purposes.

Figure 3: Validating the screw-in securement method with an initial design of the protective cover's base.

Sensor Design, Rapid Prototyping, and Manufacture

The sensor casing was designed through rapid prototyping: a quick turnaround between design, manufacture, and validation testing. The cycle time was approximately one day to edit the design, 3D print it overnight using a Markforged 3D printer with ABS plastic, test it with a sensor on a shoe, and have it checked by my advisor. The first printed design utilized the following features to satisfy the engineering requirements: 3D printed plastic material for protective properties, a twist cap for easy maintenance and removal, foam concentrator pucks to secure the sensor, and a domed cap to concentrate the forces to a single point of contact.

Through the various iterations, there were four features added to the first printed design. First, a locking mechanism. The caps were initially too easy to slide off, and would occasionally come off during tests. This lock was created through a notched extrusion on a wing. It provided a snap fit lock to the cap. Secondly, rubber grips to aid with traction when the pucks were added to the shoes. The original plastic combined with the domed cap led to a lot of slippage. Thirdly, a cover notch to aid with part orientation, and increase the ability to close the caps correctly. This feature was particularly hard to implement and took multiple iterations on its own. The amount of pressure applied on the resistor sensor could not be artificially created from the casing on its own, yet the sensor could not be loose enough to move inside. There was no analytical solution to this problem, and my advisor and I could only solve it experimentally. I iterated through many versions changing the internal height of the space inside of the case, printed it, and tested it on the system.

Electrical and Software System

The wiring system was pre specified by my mentor and consisted of two parallel wires running to a single PCB. From the PCB, which clarified the system output through onboard OpAmps and resistances, to be sent straight to a processing program. The difficulties in creating this came from the parallel wires. To minimize space, I decided to run the wires around the circumference of the shoe, and solder each sensor's tips to each wire. I spent days practicing soldering techniques, as it was the first time I had attempted to do a larger scale soldering project. However, the copper wire I chose was coated in a laminate that rejected the solder. The manufacturing plan was delayed while I slowly sanded down the laminate in the exact positions of each sensor. After being taught to use a Dremel for this task, I sanded down and soldered the copper wire, then electrically tested to ensure each connection was created correctly.

Arduino was used to modify the output to normalize to the voltages being read by the participant's weight. The code used is attached in the Appendix. The program felt very simple: a timed function to measure the participant's full weight, then a continuous reading loop that converted voltage outputs to the serial plotter, in % of full weight.

FINAL SYSTEM DESIGN

The final iterations of the protective base and cover, along with the wiring, are shown below. Notable features are:

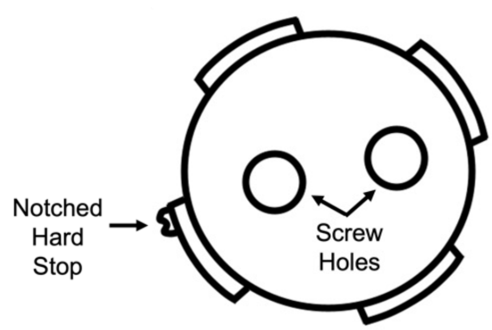

Figure 4: A labeled diagram of the final base iteration.

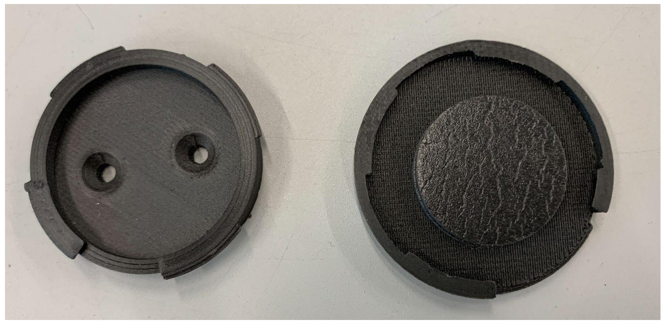

Figure 5: The case (left) and cover (right) with a foam concentrator. This is an image of the final design, including the notched hardstop, cover notch, and, not pictured, the rubber grip on the opposing side.

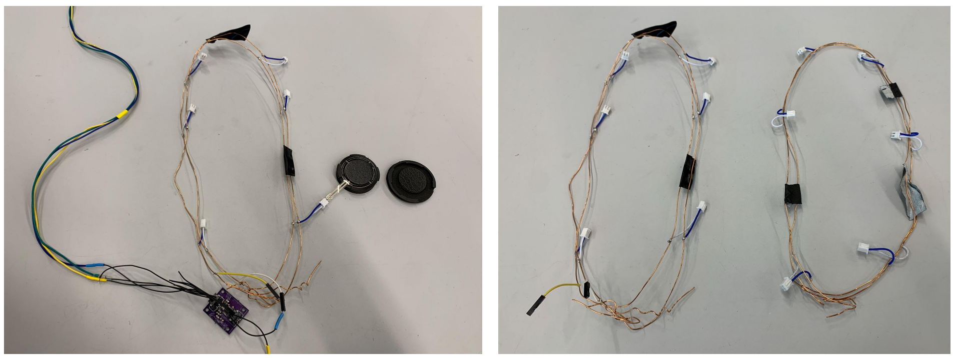

Figure 6: The electrical wiring system, without the shoes. The oblong shapes are the two copper parallels. Soldered around each edge are inserts for each sensor.

VERIFICATION AND VALIDATION

Verification testing was a series of tests pacing in a hallway. The system was fully assembled on a women's size 6 shoe, with five sensors in the casing screwed in an arrangement below the shoe. Three sensors and two sensors covered the toe and heel area, respectively. Everything was plugged into a laptop to see the software output on a constant running output through Arduino. A picture of a trial in progress is shown below.

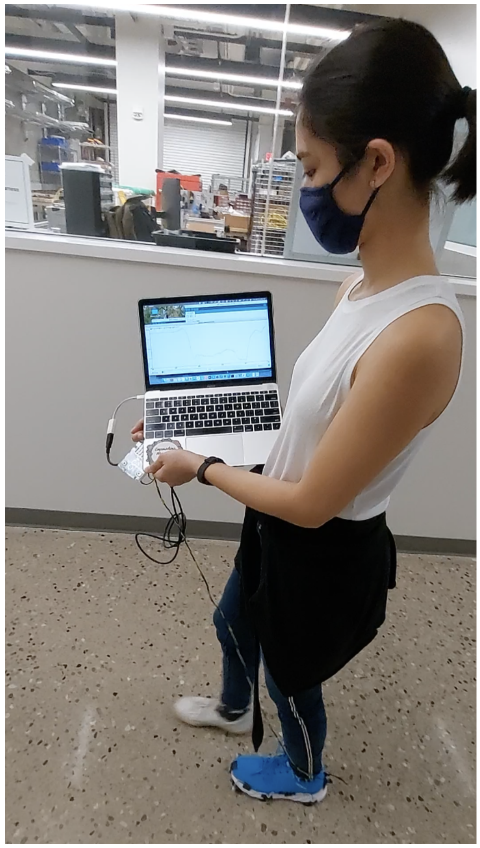

Figure 7: A snippet of a verification test. The entire system is fully assembled.

These tests confirmed that the designed system will output gait data similar to results that was seen with the original footplate on the first prototype. The gait data should look like a step function, outputting the force data as a percent of the participant's full weight. The results are pictured below, and validated to be correct by my advisor.

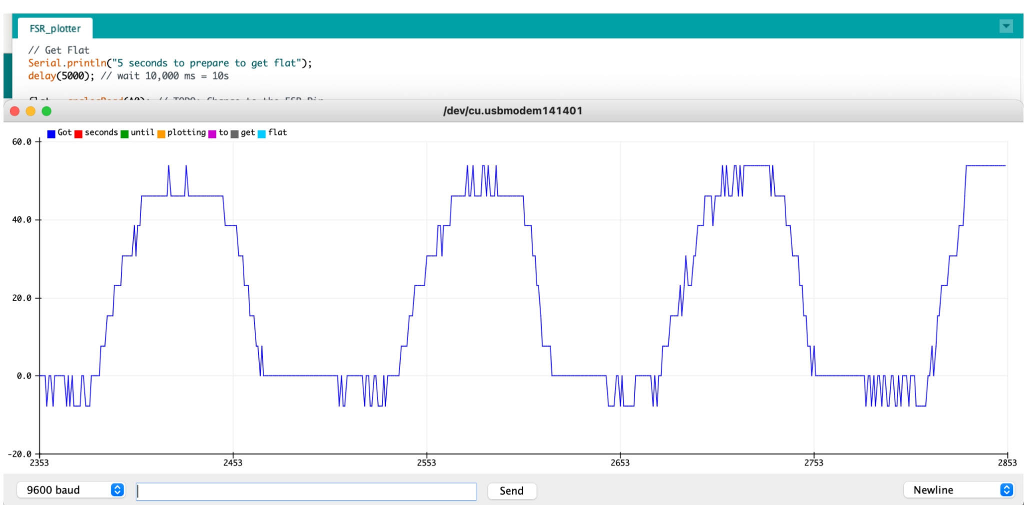

Figure 8: A snippet of the sensor output from walking along the hallway, showing the correct output.

My final validation meeting with my advisor confirmed that the finished project indeed completes the overall problem, that we created a more flexible system to measure the ground reaction forces for exoskeleton control. After these tests, the system was implemented with the exoskeleton control system, and was used to collect data for a couple weeks.

PROJECT: FSR Cover

After completing the casing system completely, I began work on a more simplified design, based on an initial concept from a Master's student working in the lab at the same time. His idea was to create a flexible cover system that would wrap around the participant's shoe. Retaining the participant's own shoe would further preserve their gait and allow for smoother testing, and pushed towards the larger goal of making a seamless exoskeleton support system- one that allowed the user to keep their normal shoes in the regular day.

CONCEPT GENERATION

Though all my concepts stayed theoretical, there were a handful of ideas that were being considered. The sensors could be attached two ways. Either through a fabric pocket sewn into the cloth covers, or through an easy on/off attachment method, such as velcro. Protection methods could be foam layers around the sensor, replicating a sole of a shoe, or a slim hard case around each sensor to again provide the foam concentrators to hold them secure. However, with each iteration of ideas, sensor protection, force concentration and wire control were all issues I had to address.

INITIAL PROTOTYPING

Due to the nature of the shoe cover the wiring system needed to be more flexible than the wire circuit surrounding the shoe. The parallel wiring system was originally designed to average the forces and resistances through the circuit, but averaging measurements could also be easily completed through the software. Therefore, I worked mostly on recreating the wiring system that was originally taken over through the PCB. Instead of controlling the averaged output voltages all at once with the OpAmps and resistors at the end with the PCB, it was routed through multiple OpAmps.

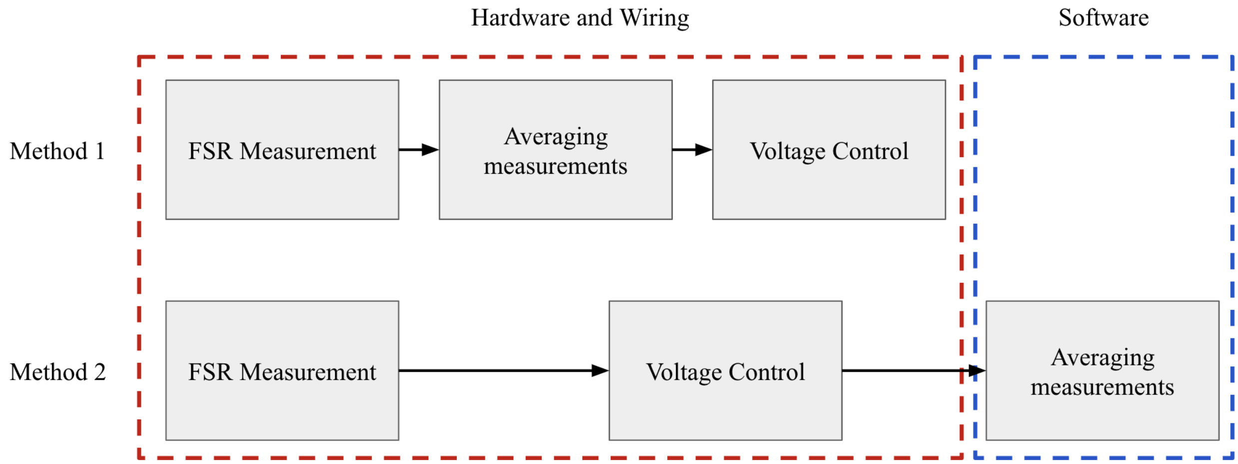

Figure 9: Differences between the two wiring systems. Blocks represent data and conversions.

The initial circuitry had been completed by the time the semester ended, but there were still unknown bugs with the system. The current wiring system is pictured below. The circuits were based on the FlexiForce Sensor's recommended circuit taken from their datasheet [2]. However, the following wiring should not be taken as completely correct, as there are still errors with the system.

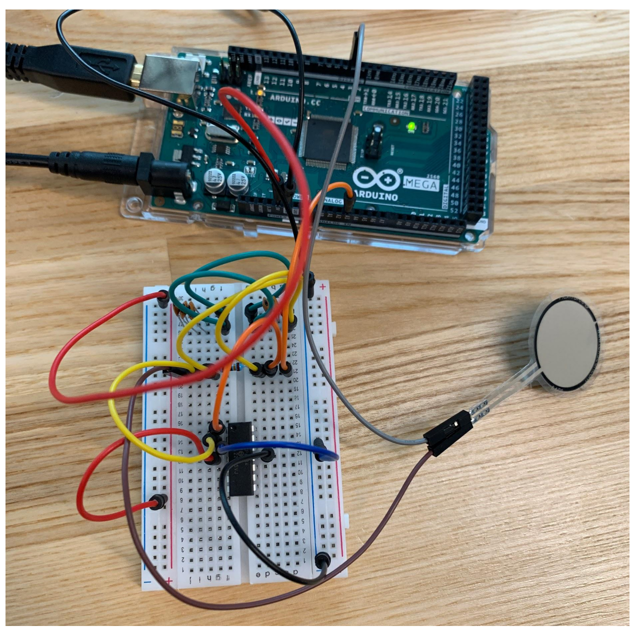

Figure 10: Current wiring system for an individual force sensor

DISCUSSION

The flexible ground force measurement system was successfully designed, created, experimentally validated, and implemented into research purposes. Below is a table showing the initial requirements and the features created to satisfy them. With the current design, further improvements can be made, as nothing has been hard integrated into the exoskeleton design.

Different iterations only need to keep the same data output to integrate with the rest of the system.

Table 2: Requirements and corresponding features created to satisfy them. The additional requirements found through rapid prototyping have been included.

Stakeholder/Source	Requirement	Feature
Secondary Stakeholders	Size Flexibility	Multiple shoe sizes
	Imperceptible	Height Minimized
Local Stakeholders	Protective Casing	ABS Plastic Used
	Secure FSR Sensor Fit	Foam Force Concentrators
	Easy to check quality and replace sensors	Twist-Lock Cap
	Secure Attachment	Screw Attachment
Rapid Prototyping Realizations	Non-Slip	Grip
	Cap Securement	Locking Mechanism
	Part Orientation	Cover Notch

Outside of the project completion, I learned to solder and learned a new CAD program for the first time. It is one of the few times I have applied wiring design and coding on a project outside of assigned coursework. It was exhilarating being able to work on all this on my own.

REFLECTION

If given more time to work on this project, I'd put more effort into fully completing the over-the-shoe cover system. I believe there is a lot of potential as a solution. The amount of flexibility that it would provide the participants and the accuracy in preserving the natural gait allows it the possibility of being the best solution to date. I'd also like to see if I can change materials for the original hard case system and make it even slimmer. Though it did not cause too much of an effect, the height of the case and cap did influence the walking patterns of the participants. I would also like to try iterations with a sliding cap, to minimize space but keep the same functionality of the easy removal of a cap.

REFERENCES

[1] Lin, Jianping & Divekar, Nikhil & Lv, Ge & Gregg, Robert. (2020). Optimal Task-Invariant Energetic Control for a Knee-Ankle Exoskeleton. IEEE Control Systems Letters. PP. 1-1. 10.1109/LCSYS.2020.3043838.

[2] TekScan, FlexiForce A301 Sensor. https://cdn.tekscan.com/sites/default/files/resources/FLX-Datasheet-A301-RevI.pdf.

APPENDIX:

Arduino Code for Plotting the FSR Response

```
float base = 0;
float flat = 0;

void setup() {
 Serial.begin(9600);
 pinMode(11, OUTPUT);
 digitalWrite(11, HIGH);

 // Get Base
 Serial.println("Send 0 when ready to Get Base");
 while (Serial.available() == 0){
   // waiting
 }
 base = analogRead(A5);
 Serial.println("Got Base: ");
 Serial.println(base);


 // Get Flat
 Serial.println("5 seconds to prepare to get flat");
 delay(5000); // wait 10,000 ms = 10s
  flat = analogRead(A5);
 Serial.println("Got Flat: ");
 Serial.println(flat);

 Serial.println("3 seconds until plotting");
 delay(3000);
}

void loop() {
 int FSR = analogRead(A5);
//  Serial.println(FSR);

 // Data Processing
 // Want to plot it as a % from 0% to 100%
 float percent = ( (FSR - base)/(flat - base) ) *100;
 Serial.println(percent);  // Plot the FSR signal
  delay(10); // Wait 100 ms
}
```