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Team 12

ME C178 / BioE C137 Final Project: FootSens

Introduction

In the course Designing for the Human Body, we were given a project through our client sponsor, Professor O'Connell. The task was to create a foot sensor to measure the forces on the foot during various activities. Knowing loading forces could be useful in diagnosing medical problems related to asymmetrical loading, which occurs when one part of the body carries a large and unequal amount of force compared to another part. This could cause long term health problems, such as arthritis and muscle fatigue. Current sensors are static, in that they do not move and adapt with the body while doing physical activities. After factoring in the most important aspects of our client's needs by using a Pugh Chart, the goal was defined as creating a modular, comfortable, dynamic, and easy-to-use foot sensor to measure forces during the user's day-to-day activities.

Anatomy

The anatomical parts most impacted by the design are the foot and ankle. The tibia and fibula bones of the leg are connected to the talus bones of the foot. The connection, the ankle, functions as a hinge joint that allows for plantar flexion and dorsiflexion of the foot joint. Plantar flexion is pointing the foot away from the body, while dorsiflexion is pulling the foot up towards the body. The other joint impacted by the design is the metatarsophalangeal joint of the big toe, which is located in the ball of the foot. Muscles in the foot are extensors and flexors that work together to stabilize and raise the foot. These will be impacted by sensor placement, as these are prevalent in the gait cycle. As a design constraint, we want to ensure the foot rests naturally at 90 degrees as it would if one were standing on the floor with no support. According to Allen Anderson in his article "Sports Medicine, Anatomy Ankle," with increasing plantar flexion, the bony constraints are decreased, and the ligaments are more susceptible to strain and injury. So in our design, we need to be sure that when the device is in use, the ankle does not rest at an angle significantly above 90 degrees. Our design incorporates a sock that will be worn on the foot. This will ensure that the foot naturally rests against the shoe and floor.

Brainstorming

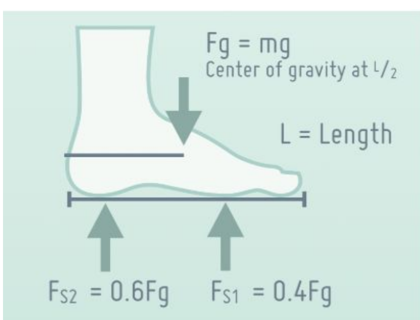
The most important aspects of the design were chosen using a Pugh Chart (Appendix B). After generating more than 20 ideas for the foot sensor, 8 were chosen and compared to each other using key criteria identified in the chart. The top two criteria our group focused on were modularity and robustness/durability. After completing the decision matrix, the top three ideas were: multiple sensors within the shoe, multiple sensors outside the shoe, and a memory foam insole with weight tracking software. Other ideas such as the solid sensor plate within the shoe were eliminated because they did not meet one of the top criteria of the design: comfort. Ultimately, the group chose the design of having multiple sensor points within a shoe because it best represented all of the top priorities of the design. It could be modular, robust, comfortable, cost effective, and easy to use.

After choosing the top design idea, our group then focused on sensor placement. At first, we proposed using at least 5 sensors in various places, but after meeting with our client and more literature search, two main points were chosen for efficiency: the ball of the foot and heel. According to Peter Cavanaugh's *Pressure Distribution under Symptom-Free Feet during Barefoot Standing*, it was found that "load distribution analysis showed that the heel carried 60%, the midfoot 8%, and the forefoot 28% of the weight bearing load."[1] Selecting the forefoot and heel helped to simplify our design for the purposes of this class and also yield significant results.

Estimated Joint/Tissue Loading

The assumptions of equal and concentrated force distribution are not entirely representative of the real forces acting on the foot. There is an unequal force distribution that acts on all points of the foot in contact with the ground. We needed to place our sensors in areas that these forces are mostly concentrated and find the load distribution there to see if they are in fact equal during static loading and walking.

Figure 1: FBD



In this FBD (Figure 1), it is assumed that there are two major stability points on the foot: the heel and ball of the foot, where the sensors are placed. Static loading is assumed. Taking the mass of a theoretical person to be 55.0 kg, the force of gravity is m*g.

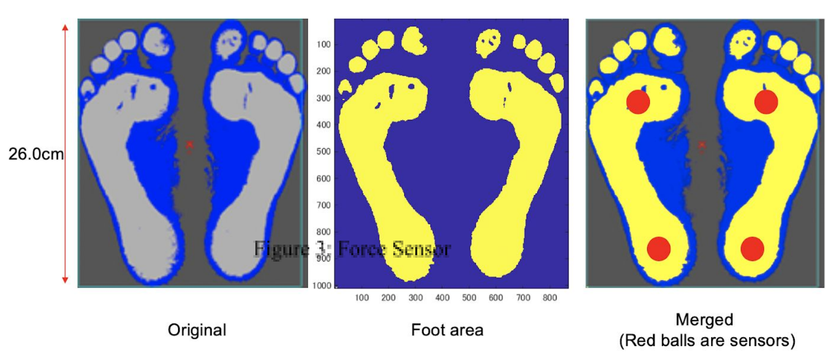
$Fg = 55.0kg * 9.8\frac{m}{s^2} = 539N$

Calculating the forces on the sensors:

$F_{s1} = 0.4 * Fg = 0.4 * 539N = 215.6N$

$F_{s2} = 0.6 * 539N = 323.4N$

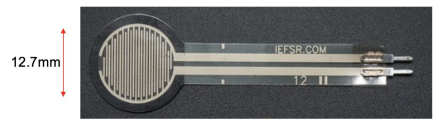
Figure 2: Contact Area



Another approach in the force analysis is to look at the pressure distribution across the foot during static loading. The normal force acts on the contact area of both feet. We estimated how much force acts on each force resisting sensor (FSR) under a normal standing condition. For simplicity,

we assumed that the pressure distribution of the contact area is uniform.
The contact area can be calculated using dimensions in Figure 3[4].

Figure 3: Force Sensing Resistor



- Body weight: $M = 55.0\ kg$
- Foot contact area: $S = 2.11 \times 10^{-2}\ m^2$
- Sensor's diameter: $D = 12.7\ mm$
- Sensor's active area: $s = 1.27 \times 10^{-4}\ m^2$
- Gravity acceleration: $g = 9.81\ \frac{m}{s^2}$

Given that the body load is distributed equally onto the contact area, the pressure P can be calculated as follows.

$$P = \frac{Mg}{s} = 2.55 \times 10^4\ [Pa]$$

Therefore the magnitude of force that acts on each foot sensors is

$$F = P \times s = 3.24\ [N]$$

During the gait cycle, the magnitude of force acting on one sensor varies according to the change of the contact area on the sensor. As the force sensitivity range of this sensor is 0.1N~100N, this base value is suitable for measuring a wide range of values during the gait cycle[4].

Some potential modified loads include standing on one leg, lifting weight, standing on tiptoes (plantar flexion), or rocking back and forth. Two major concerns are the weight capacity of the sensors — overloading may give erroneous data — and that only two sensors may not be enough to account for all of the changing forces.

Prototyping

When developing the looks-like prototype, fabric selection was a significant factor in how the final prototype would feel. Because we wanted to have a durable prototype, a thick sock was selected, then taken apart to sew in non-stretchable fabric in order to keep the sensors in place. The "sensors" were created out of cardboard and duct tape, cut to the dimensions of the FSR itself. Then, the prototype was stitched together using a sewing machine to get a good grasp on how the fabrics would interface. It was also a practice of assembling the final prototype.

In testing, the test subject (whose foot was notably larger than expected) noted that there was mild discomfort in the regions where the unstretchable fabric was stitched to the stretchable fabric. Furthermore, the unstretchable fabric prevented the prototype from conforming to the test subject's foot. Based on this information, we concluded that the final prototype would need to increase in both comfort and modularity, so as to be able to fit larger foot types without compromising comfort. We also found that having a precise sensor placement (a set distance from the tip of the toe to the sensor, and the edge of the heel to the sensor) was not very important when considering a wide variety of foot shapes and sizes, so the stiff fabric was removed altogether.

Sensors that fit the use and budget were necessary for the works-like prototype. The Round Force-Sensitive Resistor (FSR) Interlink 402 was chosen because it fit our size constraint and was compatible with the Arduino Uno already supplied in class. Two FSRs were wired to the Arduino, with appropriate circuitry, and the device was connected to MATLAB to read voltage values. On MATLAB, the voltage outputs transmitted from the sensors are converted to force values and are shown in graphs and a heat map in real time, and saved as an .avi file. In addition, the values and the frame rate of the measurement are stored in the workspace in order to be analyzed later on. The initial works-like prototype was developed using a wired connection to the Arduino from the computer. When this prototype was tested, it was found that it was functional; however, the values would appear to peak at an unexpectedly low force. Upon consultation with the client, we determined that the given calibration (from Adafruit) would not be sufficient, and custom calibration testing would need to be conducted with the embedded sensor and padding in place. This resulted in the following calibration curve (Figure 4).

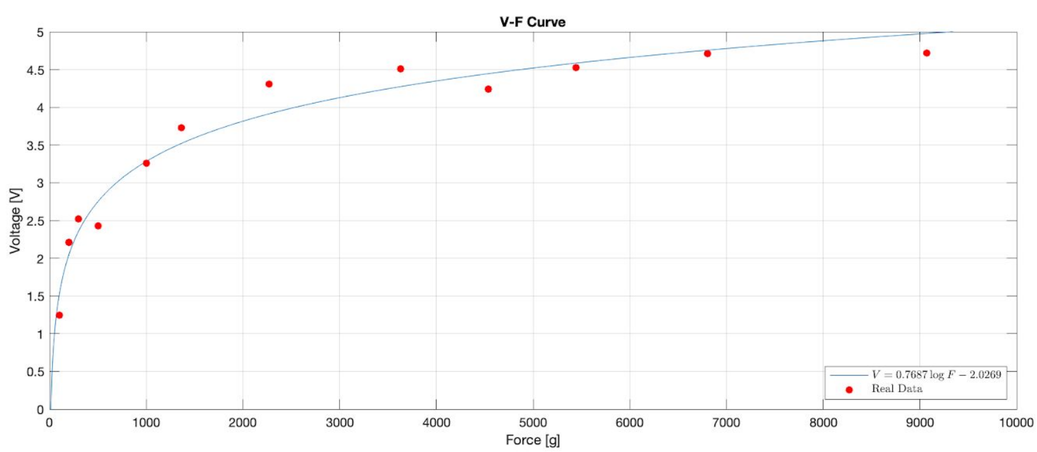


Figure 4: Voltage to Force Calibration Curve

For the final prototype, the works-like model added a Bluetooth module to wirelessly transmit data, so that the user was not constricted by a short radius.

While CAD modelling was not used in this project, several iterations of design sketches were done, as shown in Figure 5.

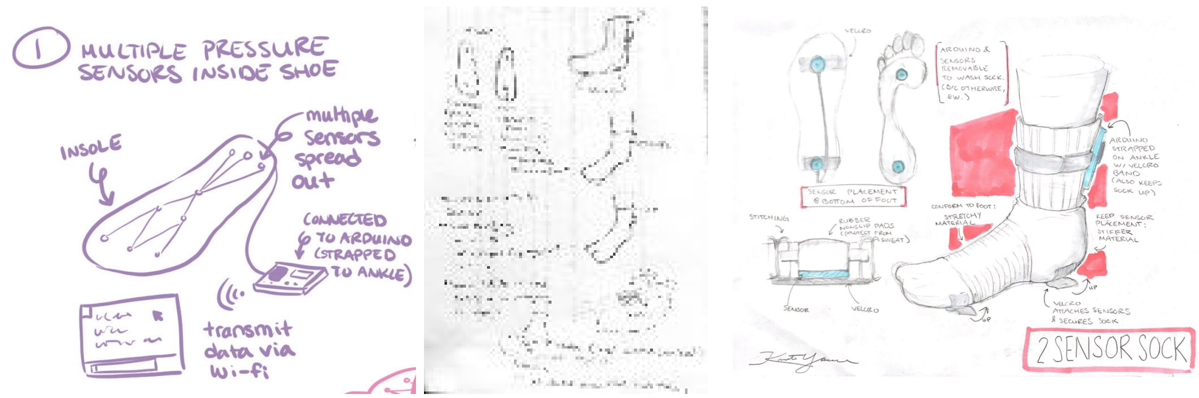


Figure 5: Design Sketches of FootSens

The final prototype, shown in Figure 6, combined the works-like and a new iteration of the looks-like prototype, such that the sensors are embedded in the sock and the Arduino is strapped around the ankle.

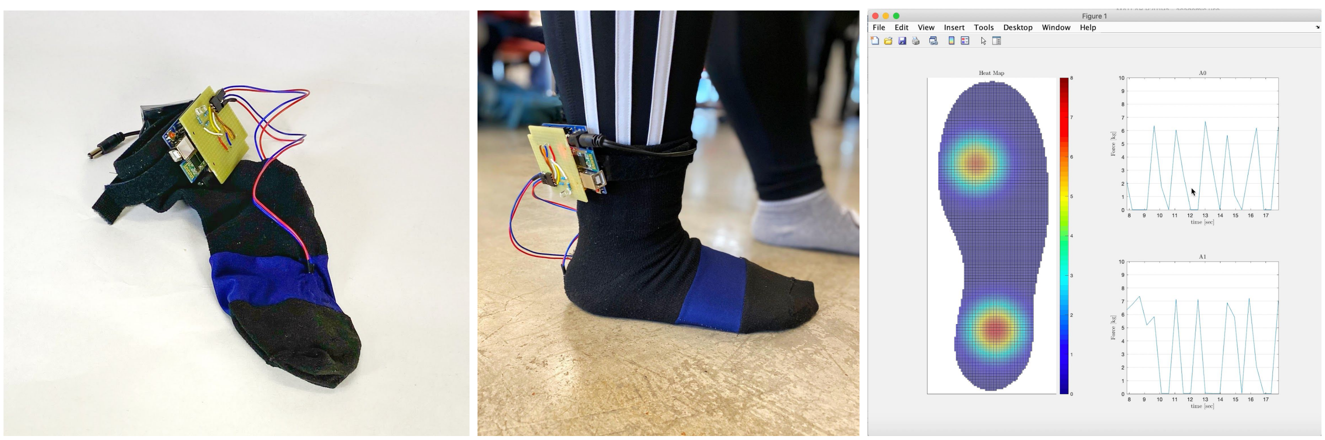


Figure 6: From left to right, standalone prototype, prototype in testing, and heat map/results.

Assessing the Design

The force sensors that we used produced a lot of noise in the data and did not always read the measured weights accurately. Additionally, the force sensors used were not rated for a typical human's body weight. In an effort to simplify the design for prototyping, we only took measurements at two points, but to get an accurate reading of loading on the body, we need to look at a variety of points across the foot.

When testing our initial prototype on a test user, we noticed that the sock itself may not fit all users, given that the stitching was tight on the user's foot. Disregarding the size of the sock, however, the wires, sensors and Arduino were virtually imperceptible to the user. According to the user, the prototype was comfortable enough to wear for an extended period of time while performing normal household tasks. Our concern was that the wires might get caught on something as the user walked around, which would hinder device performance. As such, our final prototype took sock size, lack of elasticity, and wire placement into account.

We determined that our prototype closely met our top design criteria, given that we prioritized modularity and durability. The sock design allows the prototype to fit a wide variety of foot sizes, and the fabric chosen enables the user to wear the sock for an extended period of time without extensive wear to the device.

After presenting our prototype to our client sponsor, she suggested that we try calibration testing on our own for the sensors that we integrated. The existing calibration curve did not extend to bigger weights, so we were not able to accurately gauge the voltage that corresponded with various loads based on the given calibration curve. She also encouraged us to test the sock while wearing a shoe to see if that affected data collection in any way.

There are a number of existing products that are similar in design. Several insoles intended to measure loading on the foot exist on the market, including loadsol, iShoe, and the Pressure Profile Foot Mapping System. Compared to our design, loadsol[5] is an insert, not a sock; therefore each piece is likely not modular, and the user would have to purchase a separate insert for different shoe sizes. Unlike our current design, the loadsol insert is available in four different sensor layouts, so that the user can capture different subareas of the foot. However, similar to our design, the loadsol has an app that enables the user to see the foot loading force values in real time. Our design has Bluetooth capability that allows us to see the readings on a computer, but in future iterations, we'd like to move towards an app as well.

Conclusion

We created a modular and comfortable device that can measure loading in different areas of the foot. Our idea is novel in that we enhance modularity by working with socks which tend to be one size fits all. Through preliminary testing and prototyping, we demonstrated a proof of concept and hope to continue further testing and development to create a more robust tracking system. Some future steps may include integrating more sensors, experimenting with different types of sensors, as well as developing a mobile app that can help users track their own loading and provide suggestions on precautionary care.

References

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Appendix A.

Tiana Johnson-Kidd: Tiana worked to design the prototype, contributed to report writing, and helped with planning testing. She gathered data for works like prototype.

Radhika Mardikar: Radhika worked to design the prototype, contributed to report writing, and helped with planning testing. She gathered data for works like prototype.

Keitaro Murakami: Keitaro worked to build the prototype, contributed to report writing and helped with planning testing. He gathered data for works like prototype.

Revati Thatte: Revati worked to design the prototype, contributed to report writing, and helped with planning testing. She gathered data for works like prototype.

Kristin Yamane: Kristin worked to build the prototype, contributed to report writing and helped with planning testing. She gathered data for works-like prototype and looks-like prototype.

Appendix B

ME C178 / BioE C137	CONCEPT SELECTION									
Group members: Radhika, Revati, Tiana, Kristin, Keitaro										
Key Criteria	**Weight**	Sensor plate inside shoe	Sensor plate outside shoe	Mutliple pressure sensors inside shoe	Multiple pressure sensors outside shoe	Anklet with EMG	IMU	Memory foam with weight tracking software	Insole with Springs	Color changing sensing material
Modularity	0.3	2	1	5	2	4	3	4	3	4
Cost	0.05	4	4	3	3	1	1	1	4	2
Data transmission	0.1	3	3	4	4	1	3	3	2	4
Robustness/durability	0.2	3	3	4	4	2	4	2	3	2
Ease of manufacturing	0.1	4	4	3	3	2	2	1	1	1
Weight	0.05	2	2	4	4	3	3	4	2	3
User experience	0.1	1	1	4	4	1	1	4	4	3
High resolution (data)	0.1	3	3	5	4	1	3	4	3	3
Total	1	2.75	2.625	4	3.5	1.875	2.5	2.875	2.75	2.75
Weighted Total		2.6	2.3	4.25	3.25	2.3	2.8	3.05	2.8	2.95

Appendix C

MATLAB/Arduino software

https://github.com/ketaro-m/FootSens