Foot Posture Sensor Insole

ECE 445 Design Document

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Group 29

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1 Introduction

1.1 Objective

Some patients with injuries develop a bad foot posture while walking, which can lead to knee issues and muscle mass loss. For growing children, if bad foot posture is not corrected, it can lead to significant muscle loss and even uneven growth in height of legs. Patients with mild cases of cerebral palsy also suffer from this and the only solution currently is physiotherapy and slings.

We propose to design shoes with pressure sensors embedded into the sole which will be prescribed by physiotherapists for patients. The sensors will detect bad foot configurations as determined by a physiotherapist and we will provide haptic feedback (vibrations) to alert the patient and to help them change their habits.

The device will be programmed by the physiotherapist using software we will provide. The device itself will have a start/stop recording button. The software will display a picture of the foot with all the pressure sensor positions shown on it. The physiotherapist will press start and ask the patient to walk and then press stop. After transferring the data over a micro-USB the software will display the different readings from the sensors as they had occured in real-time. This will let the physiotherapist know what he or she is dealing with. Next, he or she will have to choose when the vibrations go off based upon the relative difference in the readings from the sensors. He or she will then upload this data into the PCB through the micro-USB.

If someone has bad posture, they continuously keep their feet in the same wrong orientation while walking (confirmed by a physiotherapist). Therefore, once programmed, the insole will not need to be continuously updated, though occasional check-ups and reconfigurations may be necessary.
On the ankle band we will have a button that can be pressed which will shut off the vibration in cases where the user doesn't want vibration like sitting or other situations. The ankle band will be an extra piece to wear, but is a much better alternative to bulky slings.

1.2 Background

This posture correcting insole will be especially designed and catered for the use of posture correction by physiotherapists. Currently, people with long term injuries or mild cases of cerebral palsy undergo therapy sessions to bring back muscle mass/strength by performing repetitive exercises and wearing bulky slings. The patients suffer from muscle strength loss because they get used to orienting their foot a certain way due to long term injuries.
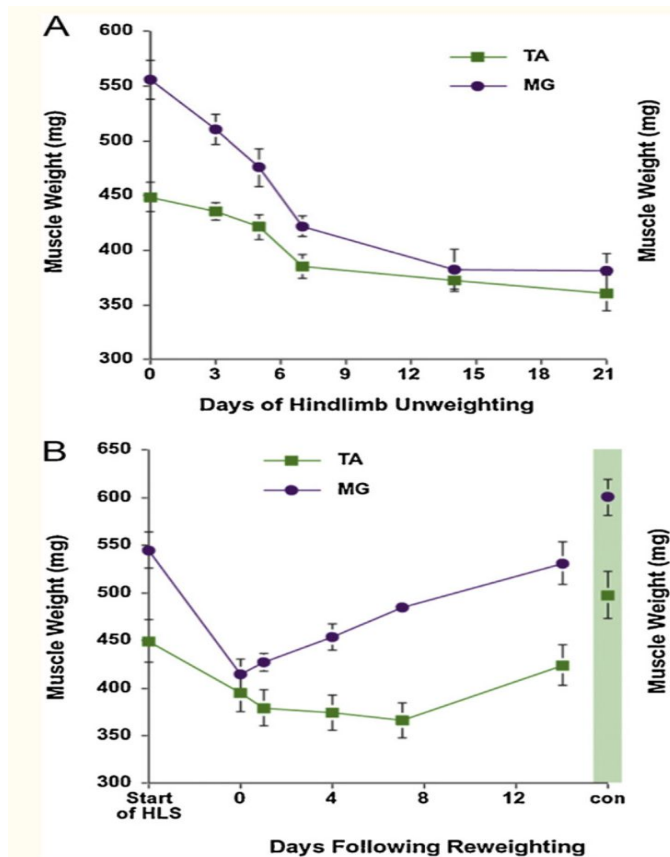
Figure 1. Bodine, S. (2020). Disuse-induced muscle wasting. Shows how quickly muscle strength decays with improper use.[3]

The above graphs generated from a study represents how quickly the muscle weight can decay with disuse. When a patient walks with a wrong foot posture; for example, if the patient puts too much weight on the outer side of the foot the toe muscles are not utilized which decay over time. This will affect the soleus muscles located in the inner calf and eventually with continued improper walking posture the size of the leg and muscle strength will decrease. Long term, this may lead to limping due to weak muscles in the leg with improper walking posture. All these issues can be avoided if the patient can be continuously reminded to maintain proper walking posture during recovery period.

Currently, there are devices to map and record weight distribution (such as Tekscan Force Sensitive Insole [1] and the SPI Foot Insole Sensor System [2]), but they do not give real time feedback to help adjust posture right away. Our implementation is specialized for patients with long term injuries who develop bad walking foot posture to give them real time feedback.

1.3 High-Level Requirements

1. The pressure sensor insole can accurately transmit weight distribution data to microcontroller to distinguish between good and bad foot orientation.
2. If the user has an incorrect foot posture, the device should set off a vibrational reminder to correct foot posture. The device should not overcorrect/bother the patient nor should it miss incorrect steps (< 5 false positives for every 100 steps).
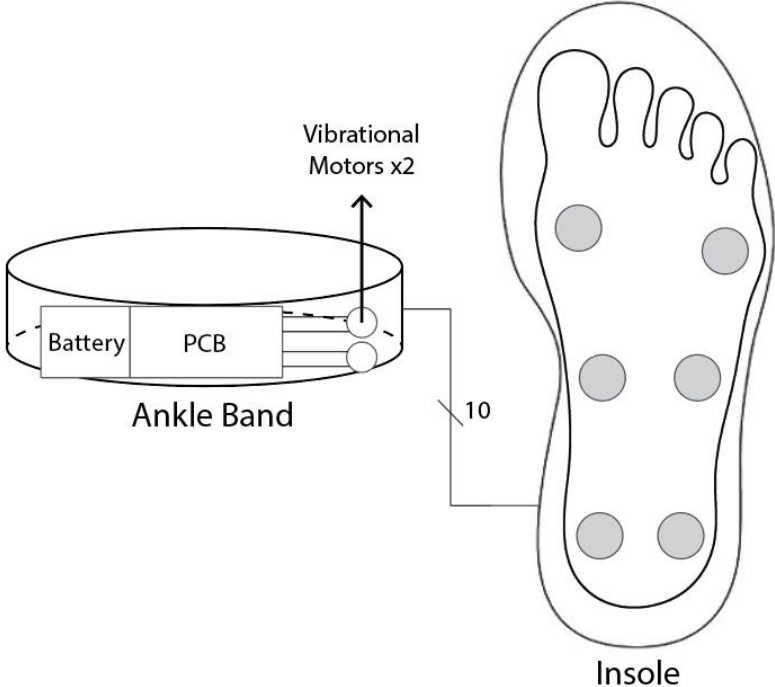3. Device can be controlled and data can be visualized through a software application.

Figure 2. Physical design sketch. This is a representation of the physical layout of the shoe sensor insole that can be inserted into any shoe. The sensor insole containing 5 sensors will be connected to the ankle band via 10 wires. The ankle band will contain the Battery pack, PCB board which will be enclosed in a black box only displaying the status LEDs, and the vibrational motors (x2) will be connected on either side of the ankle band.

2 Design

The design will have 2 main components to it: the pressure insole and the ankle band. The pressure insole will have 5 pressure sensors. The pressure sensors will be connected to a microcontroller on a PCB that we will design. The PCB, battery, buttons, vibration motors will be located on the ankle band.
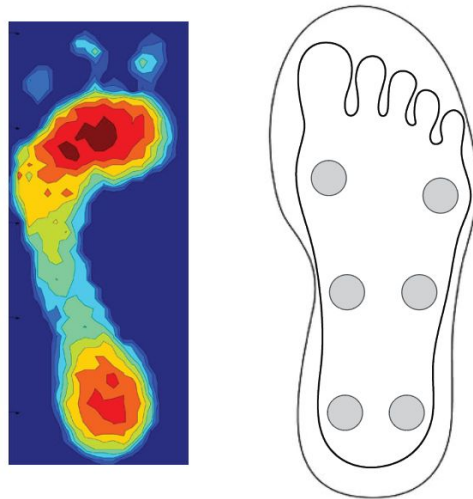

Figure 3A. High pressure zones of a foot (left)
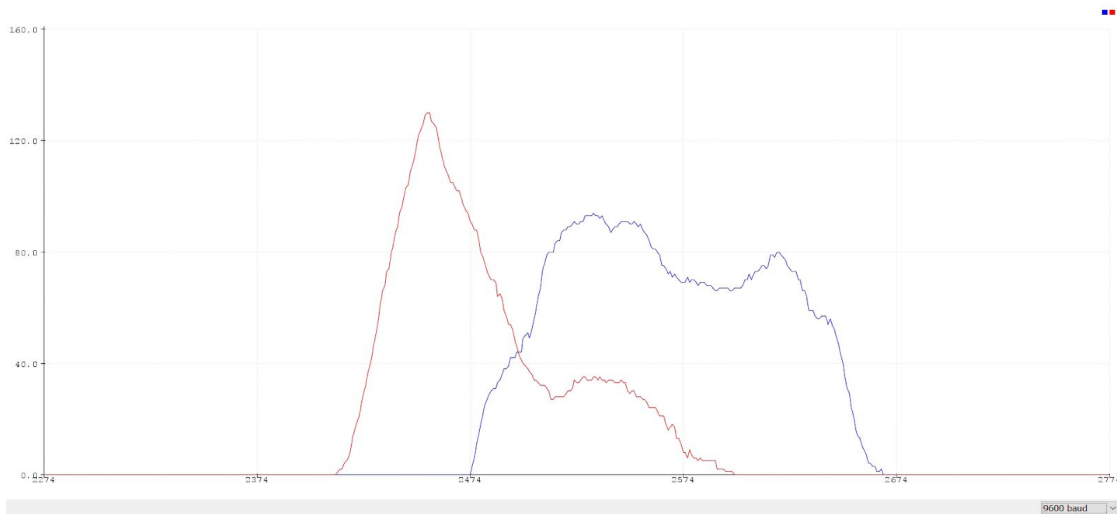Pressure sensor insole showing the sensor configuration(right)

Figure 3B. Shows a normal response to a step: the red graph shows the heel sensor response and the blue graphs represents the front left sensor on the right foot.
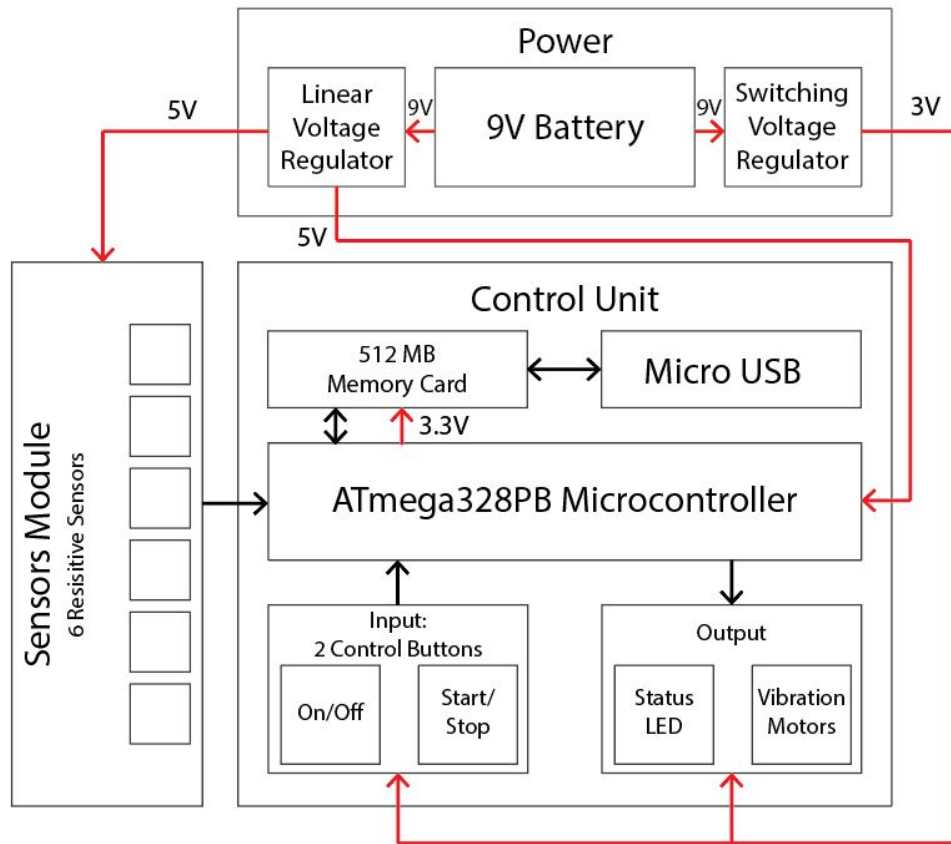
Figure 4. Block Diagram. Power is red and data is black. The main blocks as shown in the block diagram are Power, Control Unit and the Sensors Module embedded into the insole.

2.1 Power

The power block is responsible for providing power to the PCB control unit. A 9V battery pack will be attached to 2 voltage regulators, 3V and 5V, to maintain the voltage level for the sub-components. The battery and voltage regulators will be attached onto the ankle band along with the control unit, in order to minimize bulkiness within the shoe. For most components, we will be using a switching regulator, since it is more efficient. For the sensors, since we want to minimize error as much as physically possible we will be using linear regulators.

2.1.1 Battery

The 9V battery will be responsible for providing power to the whole circuit via 2 voltage regulators, 3V and 5V, which will feed into the sensors and the control unit. The battery power supply needs to be long lasting (approximately 8 hours of use). The battery and voltage regulator will be placed on the ankle band, so it cannot overheat nor be over 100g of weight.

Requirements	Verification
1. Stores and reliably provide +/- 10% of 9V. 2. Maintains thermal stability below 48°C in order to not physically harm patients [11].	1. Discharge to make sure that it lasts at least 8 hours a day (ideally should last much longer). 2. Monitor temperature for prolonged use (approximately 6 hours). Make sure that it does not cause any harm or damage.

2.1.2 Voltage Regulator

There will be 2 voltage regulators: 3V feeding the output/input block in the control unit and 5V which will feed the microcontroller and the sensor module. The voltage regulators need to work reliably all the time; any changes in the base voltage being supplied to the pressure sensors might directly affect their base readings.

Requirements	Verification
1. Linear regulator provides 5V +/- 4% from a 9V source. 2. Maintains thermal stability below 48°C in order to not physically harm patients [11].	1. Charge then discharge. Measure the output voltage using an oscilloscope, to ensure that the output voltage stays within 5% of 5V. 2. Monitor temperature for prolonged use (approximately 6 hours). Make sure that it does not cause any harm or damage.

2.2 Sensor Module

This includes the 6 pressure sensors which will be embedded into the insole. They will be wired to the ankle band containing the Control unit PCB and power. These sensors will be responsible for continuously collecting data points and feeding the data into the microcontroller.

Requirements	Verification

1. Elite running ground contact time is approximately 200 ms [7], which is very fast. The average walking stride span is 28.2 cm and the average walking stride speed is 140 cm/s, so we know a single foot-ground contact time will take approximately 500 ms [6]. Therefore, these sensors will need to respond to	1.Use an arduino to graph sensor feedback when putting a 5kg weight on it. The sensor should reach a stable resistance in under 150 ms (at least 6.66 Hz).
	2.
	   A. Short term Repeatability test: Put 1kg on sensor. Record reading. Repeat 10 times. Readings should vary by less than 5%.
	   B. Medium term Repeatability test: Test

pressure changes about 3 times [1]*per 500ms, which is 100 - 150ms (6.66 - 10Hz).* 2. *Sensors need to have a single part repeatability of +/-5%*	*responses to a variety of weights i.e.1kg, 5kg. Leave insole in shoe for 24 hours. Responses should change by less than 5%.* C. *Long Repeatability test: Repeat C, but for a week instead of 24 hours.*

2.3 Control Unit

The control unit will be responsible for coordinating the bad foot posture with haptic feedback. It will have the microcontroller which will be responsible to analyze the data points being fed to it by the pressure sensors and provide the user with vibration to remind them to correct their foot posture. It has an input block (control buttons), output block(status LEDs and vibration motors) and data management block (SD card and micro-USB).

2.3.1 Microcontroller

The microcontroller will always look for a match b/w the physiotherapist fed data points (the values of the sensor pressures when the wrong foot posture is achieved) and the data points collected. The data points being collected will be converted into an array and processed. Whenever a match is found the the microcontroller will send a signal to the vibration motors to send haptic feedback to the user to remind them to correct their posture.

Requirement	Verifications
1. *Can receive data from the sensor module at 20Hz. Should be able to transmit signal to the vibrational motor within 1-2 seconds and the signal should go low after 0.5-1 seconds.* 2. *Must be able to run simple programs involving its ADC pins.*	1. A. *Put a weight of 5 kg on the sensor and then measure the time it takes from the putting the weight on the sensor to receiving vibrations, should be under 150ms.* B. *Run alongside an Arduino to check that they produce similar sensor reading graph peaks like those generated with a +/- 10% error during preliminary tests in which we were able to identify different stages in a step.* 2. *Upload and run a known program and see if the results match the expected results.*

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[1] Measure 3 times per step because each step has 3 stages: pressure on the heel, even distribution and pressure on the ball of the foot (It will be determined by further testing if the sample rate needs to be increased).

2.3.2 Input Block

The input has 2 control buttons -- on/off and start/stop. The on/off button enables the user to turn off the haptic feedback feature. There are many situations where the user may not want to get vibrations such as when the user is sitting. The start/stop button is for the physiotherapist to record the wrong foot posture and save those data points so that the microcontroller can look for a match. The data being recorded during the start/stop by the physiotherapist will be sent to the SD card where it will be stored.

Requirements	Verifications
1. *Must be easy to press.*	1. *Pushing the button doesn't cause strain.*

2.3.3 Output Block

The output block has the status LED and the vibration motors. The status LED will be a multi-colored LED. It will let the user know if the vibration has been turned off (red) or on (green). The vibration motors are for the user haptic feedback. These vibration motors on the ankle band will be connected to the power and the microcontroller. The microcontroller will send a turn on/off signal to the vibration motors for the haptic feedback.

Requirements	Verifications
1. *Vibration must be felt even when moving.* 2. *Multi-colored LEDs must be visible from 1 meter away.*	1. *Have someone walk around and check that they can still clearly feel feedback from the motors.* 2. *Verify that you can clearly see whether the device is on or off while seated or standing.*

2.3.4 SD Card

The SD Card is responsible for storing the bad foot posture data points when the physiotherapist records them. This will be sent to the SD card where it will be saved. Anyone can access this data through a micro-USB that connects to the SD card. The microcontroller will be processing at a rate less than 1MHz. The physiotherapist can also redownload new data points back to the SD card for new evaluations.

Requirements	Verifications
1. *Should be able to store 1MB of data (the data will be less than 1MB, we are only collecting 6 data points at a rate of 20Hz. Also, this collection should not be*	1. *Fill the SD Card with 1MB of known data then read it back and verify the read data matches original data* 2. *Operate the SD Card at 1Mhz and run a known program, confirm that*

happening all the time, but only in the doctor's office during set-up). 2. *Operate reliably at 1Mhz.*	*the program works as expected.*

2.3.5 Micro-USB

The micro-USB enables the physiotherapist to download and visualize the data using software that we will provide. The physiotherapist will be able to see the data points, edit them and reload them to the SD card. There will also be a picture displaying the high pressure zones/ low pressure zones similar to (1a.). This will give the physiotherapist more control over the haptic feedback that the patient will receive.

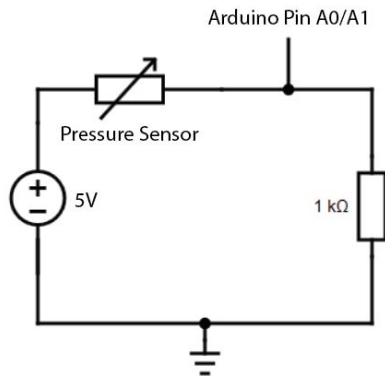| Requirements	Verifications
1. *Needs to operate reliably at 1MHz and be able to read/write data from the microcontroller/SD Card data bus.*	1. *Send 1MB of known data and then read it back and verify the read data matches original data.*

2.6 Schematics and Graphs

Figure 5. Internal schematic of the sensor insole connected with an Arduino.
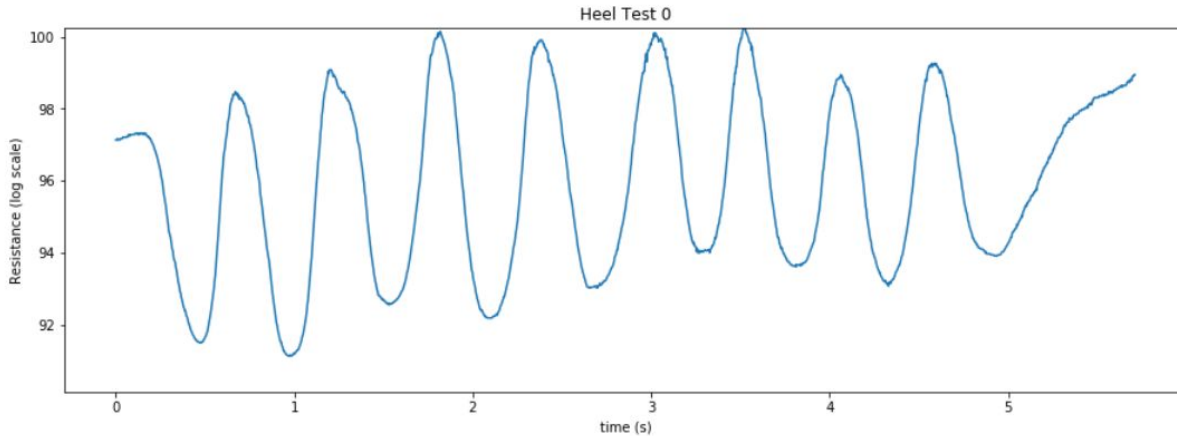
Figure 6. Initial data collection from tapping the heel. This was done by using force resistive resistors taped on the bottom of a foot and then inserted into a shoe (followed schematic in figure 5.) Initial readings were in milliVolts, but were then converted to the resistance of the pressure sensor using the following formula: $R = 1$ if $V = 0$ and $R = (5000 - V)/(V) * 1000$ otherwise where R was the resistance of the pressor sensor and V was the reading on the Arduino pin.

We performed preliminary tests, using an arduino to simulate collecting data from the pressure sensors and tried to analyze and differentiate the kind of response we will receive from the pressure sensors to get a better idea of how to process this data to provide haptic feedback to the patient. The data collected from these pressure sensors have been shown below using graphs created in python.

We tried to walk 3 steps slowly and repeated the walk multiple times to collect more data. This data only represents the front left sensor and the heel sensor. The graphs below show the readings obtained separately for each sensor (as they have been labelled). Another thing to note is that the pressure sensor reading decreases with increase in pressure (but this has been flipped in the graphs for ease of understanding). When there is no weight/pressure being applied to the sensor the pressure sensor overloads. Keeping this in mind for ease of representation in the graphs below - overload of the sensor is denoted by zero resistance.

Now to understand this graph, a spike in the graph shows that the most pressure is being applied to that sensor. One step has 3 stages : so for test 1, we can see that at first there is a spike in the pressure sensor reading for the heel sensor while the front left sensor is overloaded during that time($R = 0$). The second stage of walking is when there is flat distribution so there is a relatively equal signal and then in the last stage the weight is on the ball of the foot so there is a spike in the resistance of the front left sensor. Then this is repeated around 3 times.
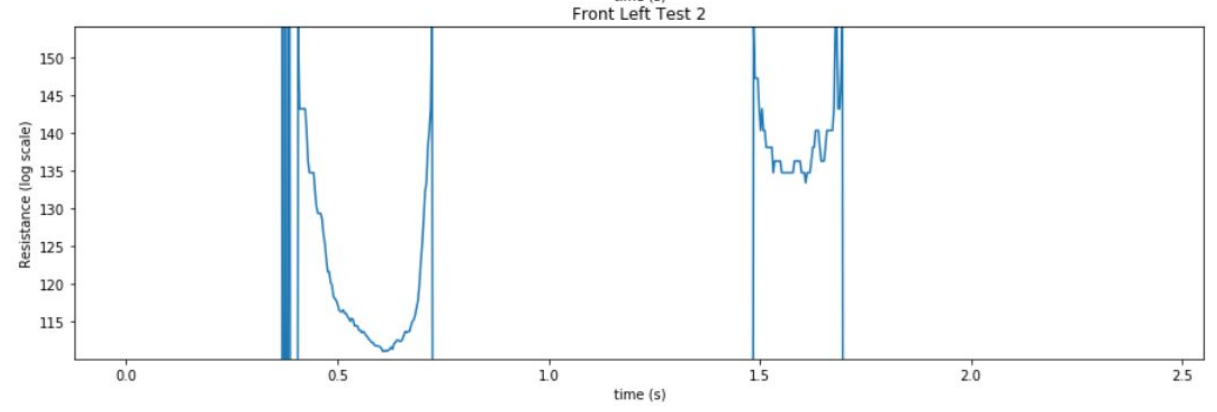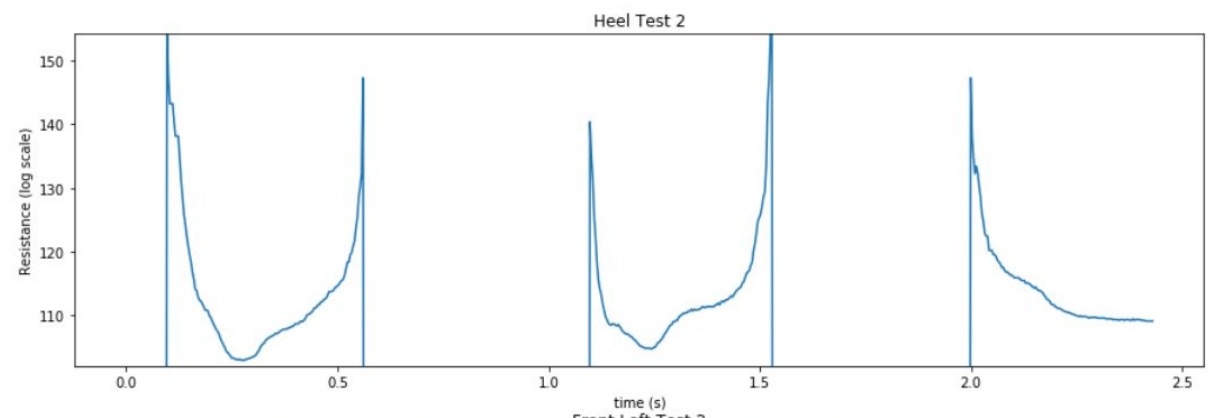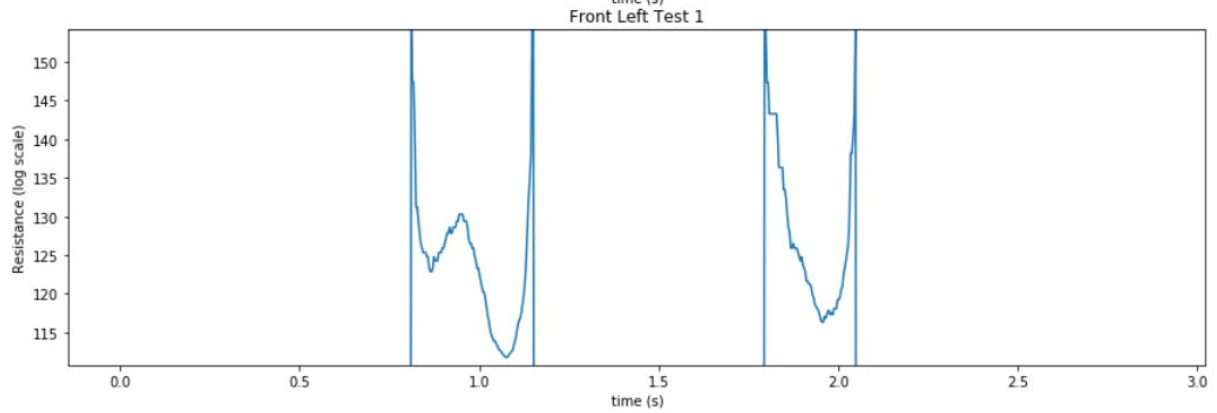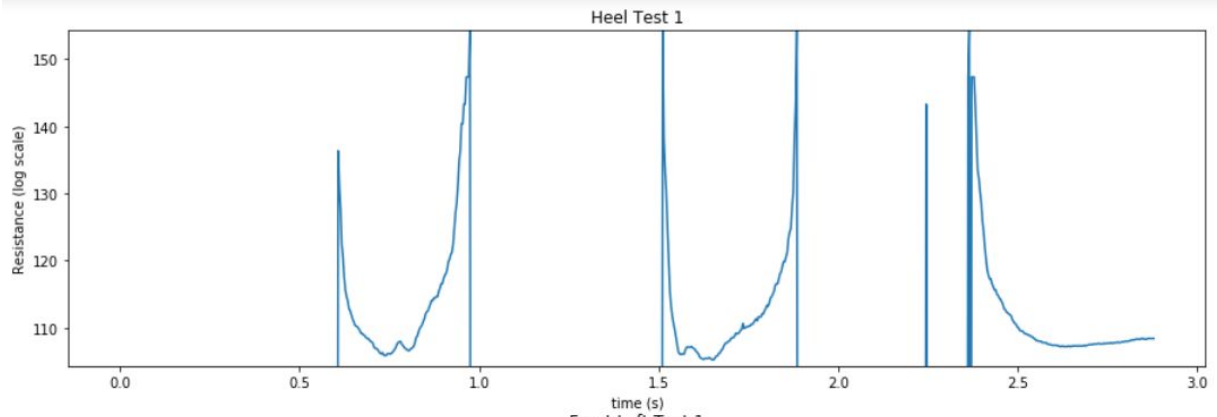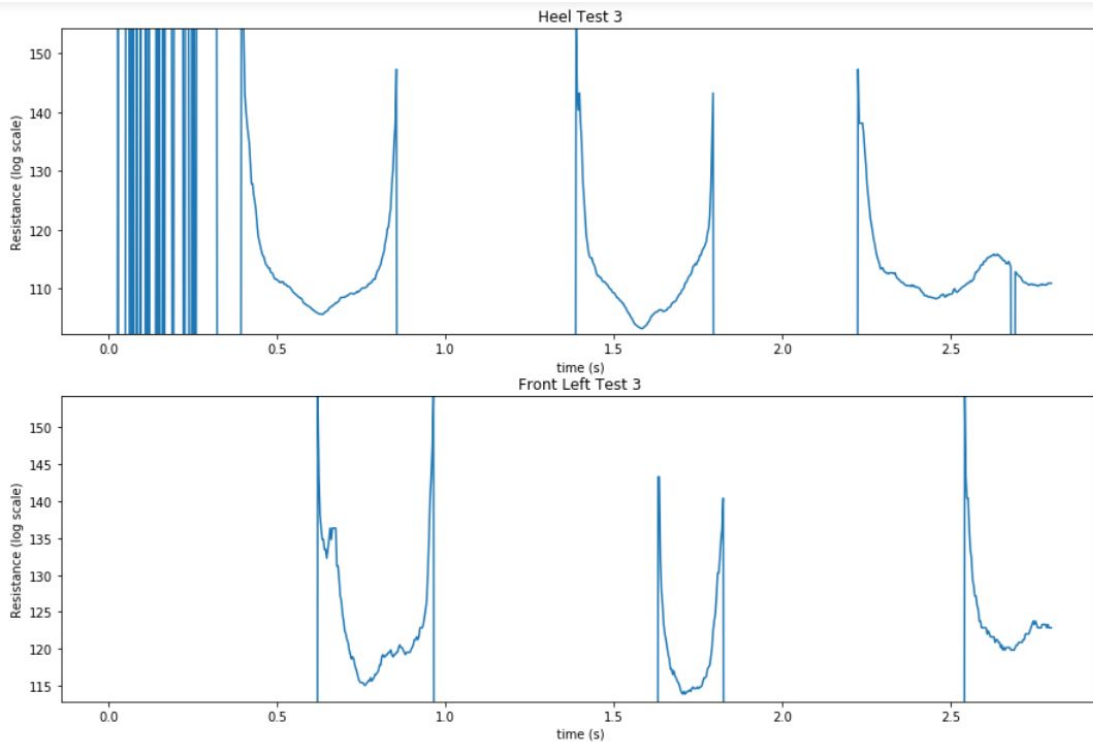
Figures 7-12. Subsequent tests performed while taking steps. In each test, the top graph is from the sensor on the heel and the bottom graph is from a sensor on the front left of the right foot. A zero value denotes overload (0V measured on arduino pin).

2.7 Software

The software is an interface for physiotherapists, which will be used to visualize the data and present the data values for each sensor. So, using the graphics presented the physiotherapist will be able to see the high pressure points and will be able to modify those data points. (software described in much more detail in the next section). After finalizing the data points the physiotherapist will be able to download this data into the microcontroller to perform more testing and make sure that the patient is getting good enough haptic feedback.
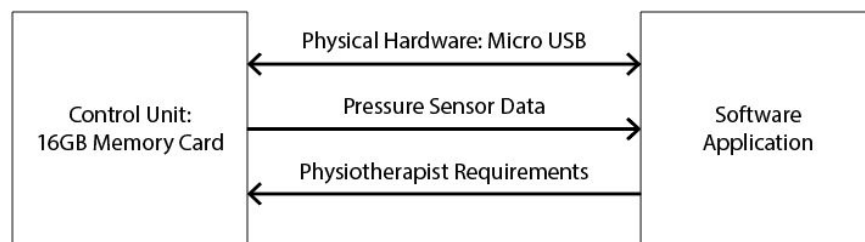

Figure 13. Device Microcontroller/Computer Application communication

2.7.1 Software Control Flow

The software will enable the physiotherapist to personalize the device to cater to each patient based on their needs. The physiotherapist will ask the patient to wear the device and walk to record the bad foot posture. The patient will hit the start button located on the ankle band which will start the recording of data. The patient will walk 3-4 steps to record the bad foot posture pressure sensor configuration points. The patient will then press the stop recording button. The physiotherapist will then load this data to the software using the micro-USB. The software application will be responsible to do the underlying calculations required to display user-friendly data to the physiotherapist.

The software window will display (see Figure 15) the maximum pressure sensor values, average pressure sensor values and a table displaying all the sensor values recorded separately for each sensor. A color coded image will also be displayed with color ranging from green to red - showing max pressure areas, to make data easy to understand.

Also, the software will provide the physiotherapist with an input table asking for a min and max range for each pressure sensor. The physiotherapist will be able to enter the pressure sensor range based on all the data displayed. A second color-coded pressure sensor image will be displayed to represent the information based on the values of the input table. Once the physiotherapist is done inputting the values they will upload it back to the SD card using the micro-USB.
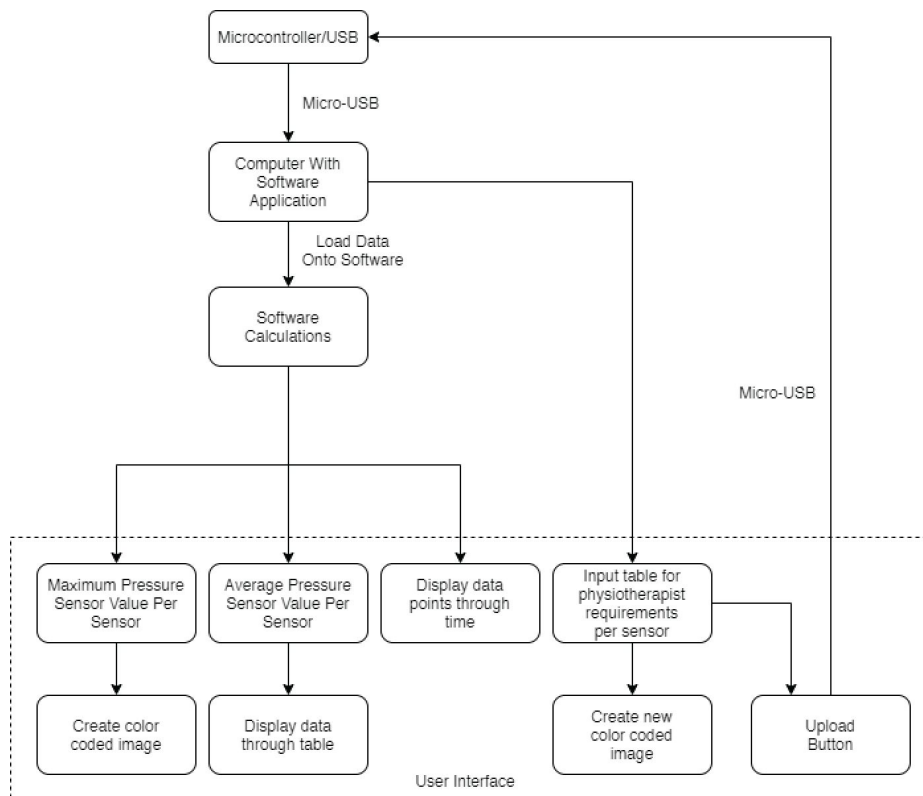
Figure 14. Software control flow

Patient: John/Jane Doe

Maximum Pressure Values					
1	2	3	4	5	6

Average Pressure Values					
1	2	3	4	5	6
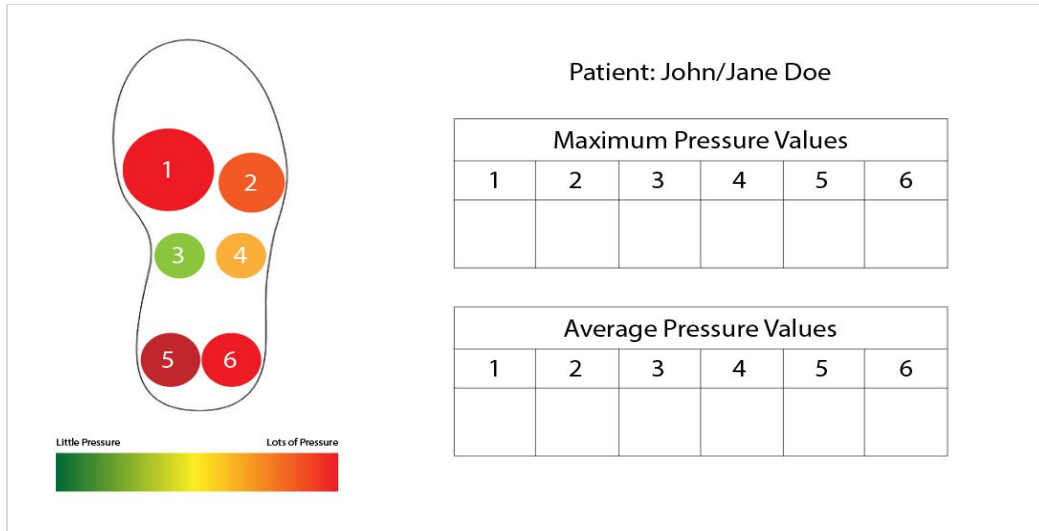
	Daily Maximum Pressure Values						Daily Average Pressure Values					
	1	2	3	4	5	6	1	2	3	4	5	6
Time #1												
Time #2												
Time #3												
Time #4												
Time #5												

Minimum Requirement					
1	2	3	4	5	6

Maximum Requirement					
1	2	3	4	5	6

Update Diagram   Upload to Insole

Figure 15. Display window UI in the software showing different pressure sensor readings and color coded image.

Table 1[2]:

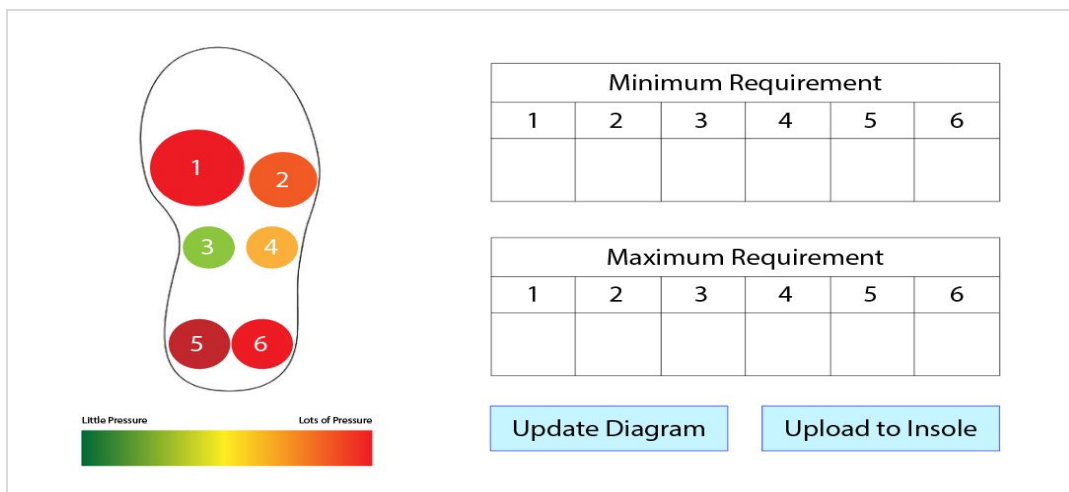| Parameters	Neutral	Pronated	Supinated	P-value
Total contact area (cm^2)	13.50	13.50	13.30	0.971
Contact area				
Forefoot	7.50	7.50	7.90	0.555
Midfoot	1.50	1.50	1.50	0.124
Rearfoot	3.00	3.00	1.50	0.189
(N/cm^2)				
Toe 1	2.20	0.90	1.40	0.875
Toe 2–5	2.00	2.20	2.75	0.465
Metatarsal 1	10.30	7.90	13.30	0.460
Metatarsal 2	16.10	7.70	12.75	0.177
Metatarsal 3	18.30	9.70	15.10	0.071
Metatarsal 4	12.50	4.20	11.90	0.026
Metatarsal 5	9.50	2.20	6.70	0.006
Medial heel	20.00	18.90	15.75	0.187
Lateral heel	13.90	10.30	13.05	0.387

2.8 Tolerance Analysis

In order for our project to work it needs to map a particular foot configuration to a range of values on each sensor that can then be made accessible to the physiotherapist. This mapping also needs to be persistent for at least a week.. The key to this lies in getting from the physical foot configuration to the processor. Pressure readings and foot configuration have been found to be highly correlated [10] [13]. For example in table 1 (above), you can see that the median max pressure in the Metatarsal 5 area is 6.70N/cm^2[10] for a patient with a supinated foot posture. Whereas for neutral pressure that area is associated with

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[2] Data from "Plantar Pressure Distribution among Older Persons with Different Types of Foot and Its Correlation with Functional Reach Distance". Median values listed. [10]

9.50N/cm²[10] for a patient with a neutral posture which is roughly a 30% difference. To give ourselves a buffer we choose the requirement of being able to a 15% difference in pressure in the range 1N/cm² - 20 N/cm². The sensor module, our voltage regulator, and the analog to digital conversion are the biggest sources of error in this process.

We first examine our sensors' range. Our sensors have an active area of 2.63cm² [12] and a minimum force sensing capacity of 20g [12] which translates into 0.1961N. So, 0.1961/2.63 = 0.0746N/cm² well under our lower bound. Additionally, they have a maximum force sensing capacity of 6kg which, after switching units and dividing by area again, translates to $9.81 * 6/2.63$ = 22N/cm². This is above our upper bound. Thus our range criteria is satisfied.

Next, we examine our sensors' repeatability. First, we note that part-to-part repeatability does not matter for our design. The reason for this is that we are giving a physiotherapist the straight sensor readings rather than attempting to convert those readings to a specific pressure. So long as the readings are repeatable and resolvable for inputs with a 15% difference, we do not care if one sensor reads 75 and another 100 for the same pressure. So, we examine their single part repeatability. The datasheet gives under 5% drift for a 24 hour period with a constant load of 2.5kg [12]. For the purpose of this analysis, we will assume that this is a worse case and therefore specify the single part repeatability at 5%.

Sensors' response: $R = 153.18 f^{-0.699}$ where f is force [12].

The voltage regulator has an error of +/- 4% [14]. We used a linear regulator here to minimize the error as much as physically possible.

For the processor, we have a 10-bit resolution over 5V which translates to a least significant bit (LSB) of 5V/1024 = 0.00488V. There is a max error of 2 LSB at the pin [15]. So, 2*0.00488 = 0.00977V.

Integrating all of this into the circuit shown in Figure 16 yields the following:

$$VPP = 5.00 +/- e_v V$$
$$R_v = e_{rv} * 153.18 f^{-0.699} k\Omega$$
$$R_p = 17k\Omega$$
$$V_o = VPP * \frac{R_p}{R_v+R_p} + e_{vo} \text{ V}$$
$$R_v^{-1} = \frac{(VPP-V_o) * V_o}{R_p}$$
$$f^{-1} = (\frac{R_v^{-1}}{153.18})^{\frac{1}{-0.699}}$$
$$0.02< e_v < 0.02$$
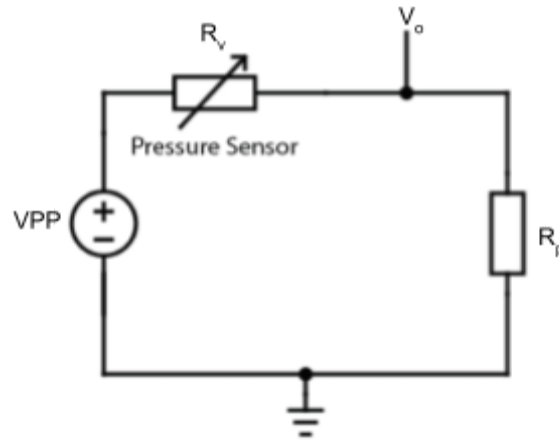$$0.95 < e_{rv} < 1.05$$
$$-0.0097 < e_{vo} < 0.0097$$

Figure 16: Circuit including 1 pressure sensor.
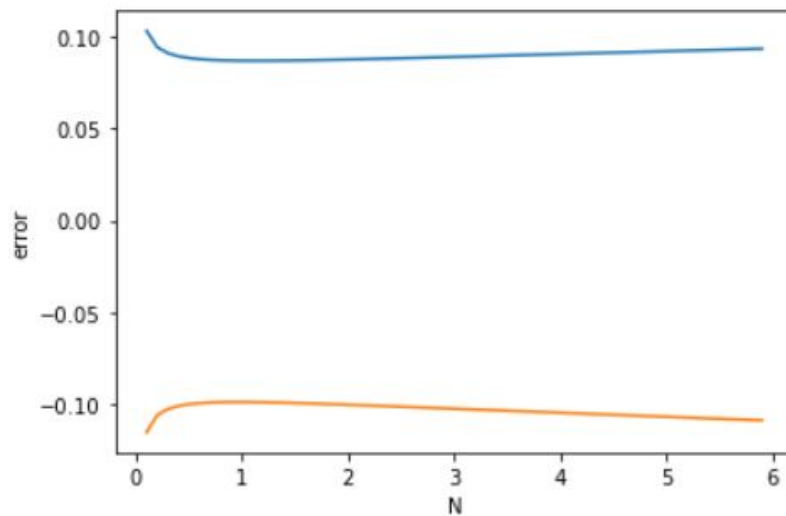
Figure 17: Results from running model with:
$e_v = -0.02$, $e_{vo} = -0.0097$, $e_{rv} = 1.05$ (blue line)
$e_v = 0.02$, $e_{vo} = 0.0097$, $e_{rv} = 0.95$ (orange line)

These meet our requirements. Additionally, these are the parameters for which the error was maximized.

This device is also a HID, so according to the average pace as mentioned in the requirements section, the average human pace data collection needs to be done at 20 Hz. This requirement is way below the minimum 1 Mhz microcontroller operating frequency we have chosen. So, this also standardizes the operating frequency of the microcontroller for every patient.

3 Cost

People	Hourly wage	Total Hours	Total
Tyler Schuldt	$40/hour	200	$8000
Isha Sharma	$40/hour	200	$8000
Umaiyal Sridas	$40/hour	200	$8000
Total x 2.5			$60000

Part	Manufacturer	Part Number	Cost Per Unit	Total Cost
Pressure Sensors x6	DFRobot	SEN0294	$5.05	$30.30
Vibrational Motors x2	Jinlong Machinery & Electronics, Inc.	C1030B028F	$2.88	$5.76
9V Battery	Duracell	4967493	$3.61	$3.61
Switching Voltage Regulator	Texas Instruments	TPS562201DDCR	$0.24	$0.24
Linear Voltage Regulator	Texas Instruments	UA78L05AC	$0.41	$0.41
Microcontroller	Microchip Technology	ATMEGA328PB-MUR	$1.33	$1.33
LEDs x2	Lite-On Inc.	LTL1BEKVJNN	$0.39	$0.78
Buttons x2	C & K	D6R10 F1 LFS	$1.20	$2.40
SD Card	ATP Electronics, Inc.	AF512SDI-OEM	$13.59	$13.59
Assorted Resistors, etc.	Various	Various	~$10.00	~$10.00
Total				$110.25

4 Schedule

Week	Tyler Schuldt	Isha Sharma	Umaiyal Sridas
3/2	PCB Layout	PCB Schematic design	Verify layout and schematic and buy sensors and test them
3/9	Submit PCB for audit get everything verified / assemble insole	Continue to test sensors with the arduino, collect data	Software Debugging and UI/UX,
3/16	Speed and Haptic Feedback Test, order finalized parts	Speed and Haptic Feedback Test with arduino based on processing data method.	Software Debugging and Speed and Haptic Feedback Test
3/23	Accuracy Testing, match up results from arduino testing	Accuracy Testing, durability testing, assemble ankle band	Accuracy Testing and Software Testing
3/30	Soldering and Physical Configuration	Soldering and Physical Configuration	Sensor Insole Final Product Design
4/6	Environment Testing and Debugging	Environment Testing and Debugging	Environment Testing and Debugging
4/13	Prepare final presentation and final report.	Prepare final presentation and final report.	Prepare final presentation and final report.

5 Safety and Ethics

5.1 Over-Corrections

One concern about our eventual product is that it might cause over-correction. For instance, there are probably certain configurations of one's foot that make sense if done occasionally but would be bad if done repeatedly over a long range of time. We don't want to cause the patient to avoid using the configuration in the instances where it makes sense.

As part of our design process we plan to do some testing on the sensors (finding the best place to put them, making sure our pressure range is adequate, etc…) we can have part of that testing be walking normally and checking the readings to forecast how many false positives we think we will have for instantaneous readings. If we decide that we are having too many, then we can change our approach to instead look at a range of readings over time and if we are spending a lot of time in a bad configuration, then activate feedback. (We should make sure sensors in combination are reading improper foot posture, instead of singular sensors setting off the vibrational motor. We could also implement an algorithm that would need a series of incorrect footsteps to activate the feedback, rather than one incorrect footstep, which could have been accidental.)

5.2 Distractions

Frequent responses from the vibrational module could become inhibiting and distracting. To counter this, we can apply similar techniques to the over-correcting problem. By making criteria for the vibrational feedback be a series of mistakes rather than a singular incorrect footstep, we can reduce the chances of unnecessary vibrations.

As with all medical devices, this insole should be used with care. This project design allows the user to turn off the vibrations to minimize distractions in dangerous situations or situations where the vibrations can distract the user. Wearing this device while doing activities like driving may be very distracting and lead to distracted driving/accidents.

The freedom over device control also gives the patient the luxury to switch off the device whenever they want to and reduce its effectiveness if they don't ensure its proper use. It is very important that the patient is self-driven to wear this device and ensure that it is worn as much as possible while walking.

Our beliefs align with the IEEE Code of Ethics, #3: "to be honest and realistic in stating claims or estimates based on available data" [2]. We wish to achieve our results reliably by using data we collect and helping the patients. Our device can be misused by the patient if they do not wear it the number of recommended hours per day but the current solution are slings which have the same issue. We will try to ensure that our device provides real time feedback reliably.

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