Smart-shoes for Physiotherapy Diagnostics

EE344: Electronic Design Lab
Final Work Report

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Group number D08

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Abstract:

Humans generate unique pressure distributions under their feet while standing and walking. These foot pressure distributions are very vital information to analyze balance and walking in humans. Evaluating plantar pressure through the use of an in-shoe system helps provide a better understanding of foot function, offers a more complete gait analysis and can help optimize orthotics used to treat pathologies like flat foot diagnosis, assessment of the diabetic foot, diagnosis of lower limb problems, footwear design, sport biomechanics, injury prevention and other applications [7]. This project involved development of a measurement system for measuring foot pressures using the *Tangio Printed Electronics'*[1] Standard Force Sensor ™, characterization of the system and conducting some experiments to evaluate the system and introduce some statistical measures to characterize the pressure maps. The interface electronics were designed and the data visualisation system was built using a Python based graphical interface. The system has to be powered by a 5V source. The in-shoe system has been made real-time, wireless, and thus portable using a Bluetooth module to send data to the host computer system.

Keywords: Pressure map, plantar pressure, wireless system, Force sensitive resistance

[1]TPE-501 is an FSR (Force Sensitive Resistance) used widely in biomedical and other applications. The datasheet can be found `here`.

Contents

1 Introduction

A huge component of the forces acting on the body are due to the contact of the foot with the ground during the support phases of the gait. The contact pressures and forces under the sole of the foot are important external features that affect the bipedal locomotion. The important components of the pressure maps are:

- Magnitude of the pressures
- Spatial distribution patterns of the pressures
- Dynamic variations in magnitude and distribution patterns

The pressure distributions are caused by the contact of the foot with the surface below the foot. The factors that affect the pressure distributions are:

- Structure of the foot
- Structure of the surface under the foot
- Posture of the foot while standing and walking dynamically
- Kinetics of the placement of the foot

Considering all the above factors and dependencies, our project focuses on developing a real-time, portable, low-cost, low-power and easy-to-use device to map plantar pressure for analysis by physiotherapists in diagnosis of several diseases listed in [7].

1.1 Motivation

Modern biomedical research has shown ([2] and [5]) several foot and palm disorders affecting people with intellectual disabilities and have an impact on their ability to mobilise in the community. This is prevalent in the case of differently-abled kids. The basic and initial diagnosis of such disabilities involves the foot-palm pressure-map analysis by doctors and medical technicians. Continuous analysis of the palm pressure areas helps doctors drive important and direct conclusions. Present day technology used for this diagnostics and analysis is the commercially available pressure-mat[2]. Such pressure mats cost upto $1700 to $2000, and come with constrained portability. Also, the data from such a pressure mat can be examined on a screen but with limited distant wireless connectivity. The above two considerations form the major part of the motivation of our project. The need of a real-time, portable and wireless, low-cost, low-power and easy-to-use device to map plantar pressure for convenient diagnosis by doctors inspired us to take up this project.

[2] MatScan- Low-profile pressure sensing mat

1.2 Project Objectives

Our projects aims to build a robust device, embedded in the shoe, capable of sensing pressure values from the sole of the shoe and send them over air to the host computer to generate a plantar pressure map from sensor values. The plantar pressure map can be analysed on the host computer. The objectives of our project can be summarized in the following manner:

- Design a sensor-embedded shoe sole with sensor placement in accordance with the anatomical analysis [9] of foot as shown in figure 1
- Design a Signal Conditioning block as an interface between the sensors and micro controller for stability in transient and steady state response of sensors
- Devise an algorithm to send wirelessly the conditioned sensor data to the host system using Tiva C microcontroller (EK-TM4C123GXL) and Bluetooth module HC-05
- Implement a real-time portable system to send pressure data to the host computer and represent it in a visually useful form, so that patient-monitoring can be done more efficiently in real time
- Most importantly, the device should be low cost and easy to interface enabling ordinary people to afford and to use in daily life.

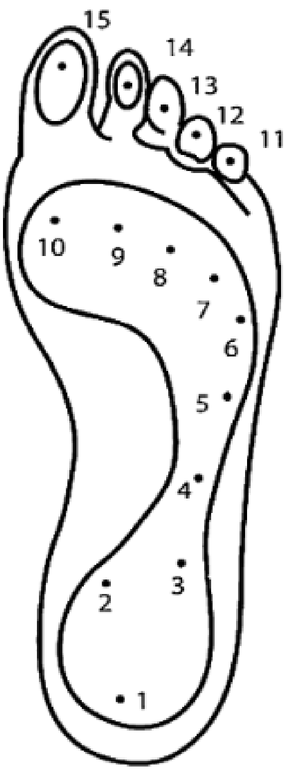


Figure 1: Foot anatomical areas

1.3 Block Diagram

The block diagram of the overall system is showed in figure 2.

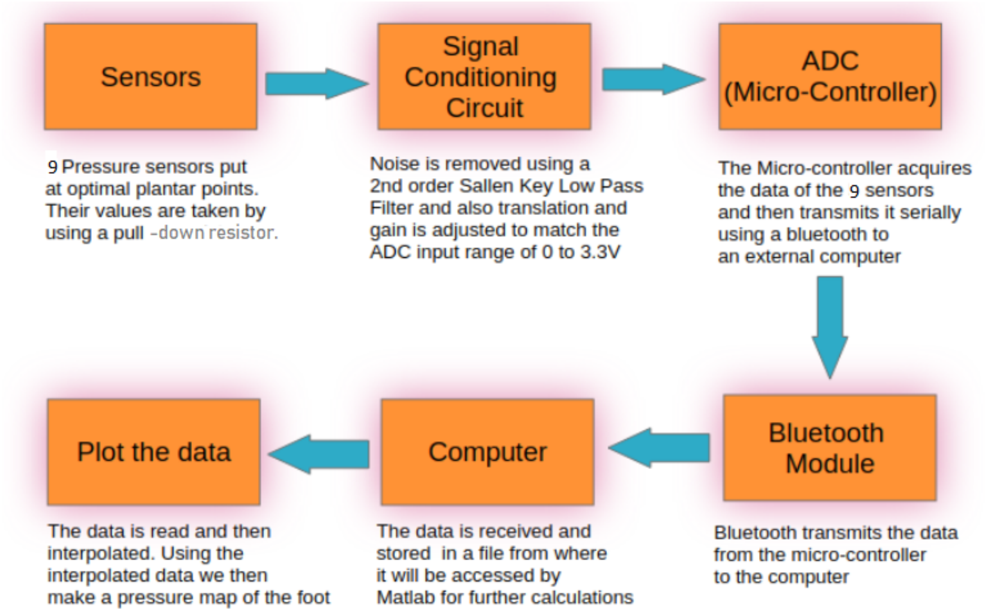


Figure 2: System Block Diagram

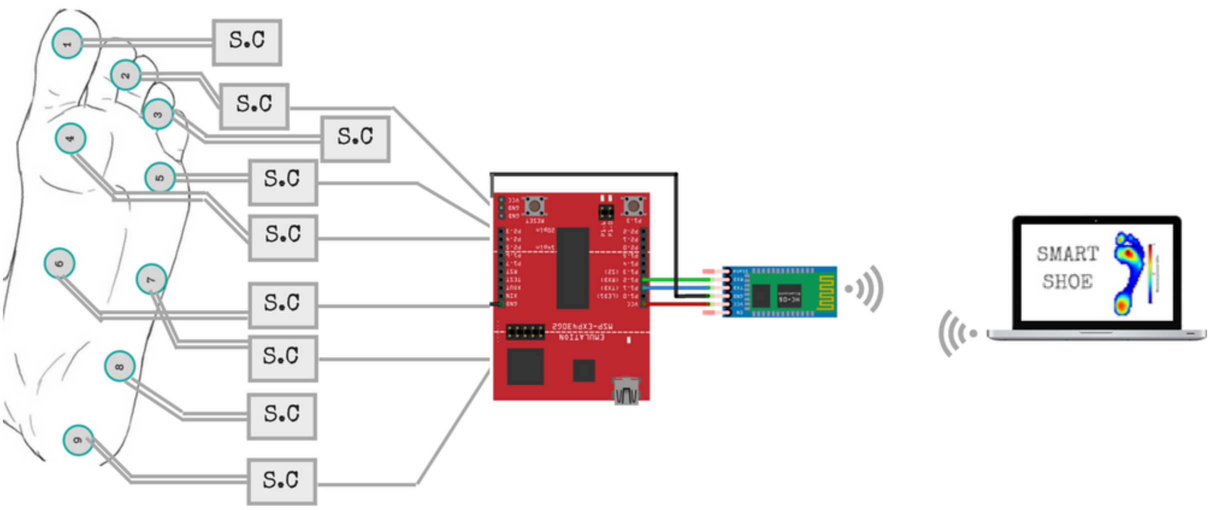


Figure 3: Schematic overview of the system

2 Project Design

2.1 System Design Overview

One of the most crucial parts of the project was to finalize on the subsystems to be designed and implemented independently. The system is broadly divided into 4 subsystems, namely, **Sensors, Signal Conditioning block, Transmission block, Pressure map generation system.**

2.2 Choice of Subsystems

2.2.1 Sensors

Real-time measurement of plantar pressure requires that sensors should be mobile, untethered, can be placed in the shoe sole, and can sample effectively in the target environment. The main requirements of such sensors are as follows:

1. **Physical parameters:** A sensor should be mobile, and for that it must be light and of small overall size.
2. **Limited Cabling:** A foot plantar system should have limited wiring.
3. **Sensor Placement:** To be located in the shoe sole, the sensor must be thin, flexible and light. The placement of sensors play a crucial role in foot pressure mapping as the areas shown in figure 1 support most of the body weight and are adjusted by the body's balance. Accordingly we have designed the placement of the sensors on the sole to generate accurate pressure map. Refer figure 4.

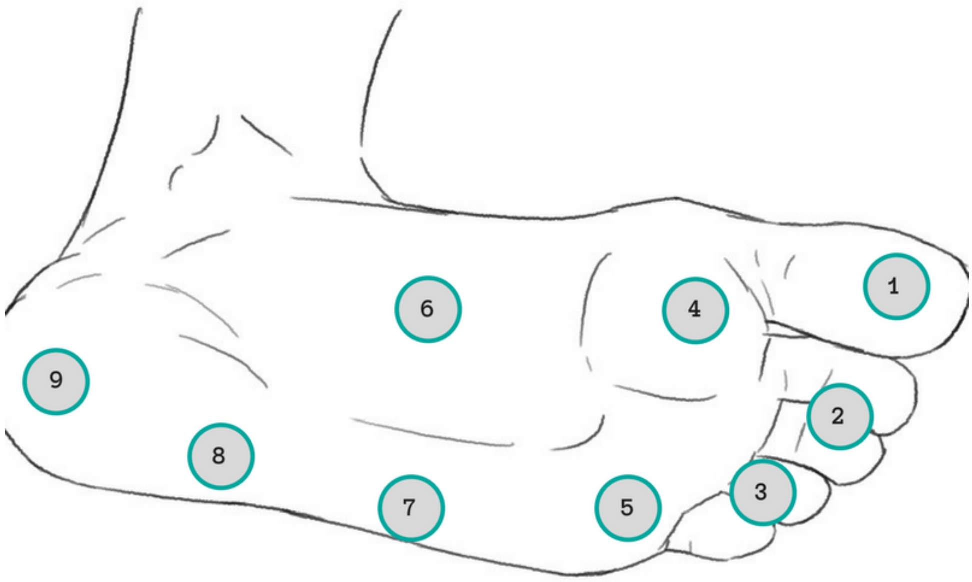


Figure 4: Sensor placement on the shoe sole

2.2.2 Signal Conditioning block

The entire system has to be embedded in a shoe and sensors are to be placed on the sole, so naturally the Signal conditioning block, which is the most crucial susbsystem, has to be **small and compact** in size. The signal conditioning involves three major parts, namely, Bandwidth Limiting, Linearization, Analog to Digital conversion and Translation. To minimize the hardware, we have implemented the Linearization in software after receipt of serial data. Analog to digital conversion is performed on the Tiva C series microcontroller.

2.3 Design Strategy & Steps

2.3.1 Signal Conditioning block design

The following table summarises the typical signal conditioning functions [8],

Signal Conditioning Category	Example Function
Excitation	dc source for sensor ac source for sensor
Input matching	High-impedance amplifier for high-impedance sensors Matched-impedance inputs for complex-impedance sensors
Signal translation	Amplification for low-level signals Offset or ac-coupling for signals with dc offset
Signal detection	Synchronous detection for signals modulating a carrier
Linearization	Curve fitting for nonlinear signals Piecewise gain fitting
Noise rejection	Filtering (low-pass, high-pass, band-pass)
Protection	Transient suppression networks

The circuit design for interfacing the resistive sensor to the ADC will influence the dynamic range of the sensor. Usage of op-amps would introduce spurious effects of offset especially when we are using the ADC with lower reference voltage. Also, op-amps amplify high frequency noise creating problems for further signal conditioning. So, the other way for resistance to voltage conversion is BJT based circuit, which is a design with just a voltage divider followed by an emitter-follower, using an NPN transistor as shown in figure 5.

The issue with usage of the BJT based circuit was the high temperature (internal as well as external) dependence of the circuit. This was affecting the dynamic range of the output voltage quite significantly. The ranges of the output voltage varied from $[0.8, 2.6]V\ to\ [1.4, 1.9]V$ with differences in temperatures. This made difficulties in designing the signal conditioning circuit to cater to this change in dynamic range of output voltage.

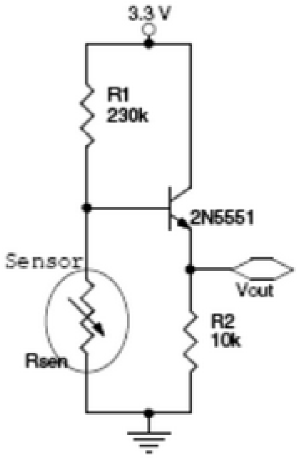


Figure 5: Interface circuit for the sensor using BJT

The other choices for the interface circuit were the Wheatstone bridge circuit as described in [6], figure 6 and a simple pull-down resistor circuit.

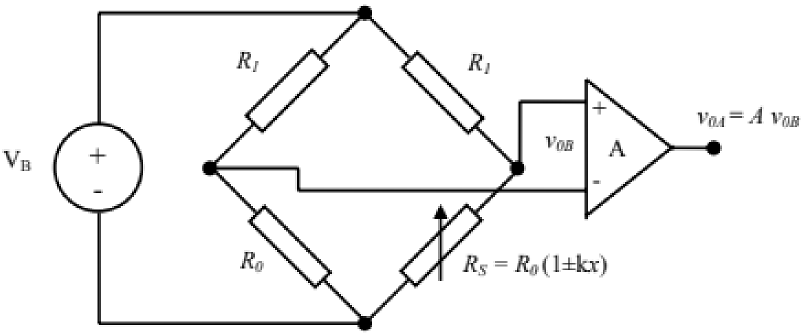


Figure 6: Wheatstone Bridge for a single active Resistive Sensor

For the wheatstone bridge based circuit, one of the bridges is the sensor, while the others have to be constant resistance values equal to that of the steady state values of the sensor with zero input force. However it is practically difficult to get a resistance of the constant value equal to the steady state zero input resistance of sensors, which restricted us from using the wheatstone based circuit for resistance to voltage conversion.
The simple pull-down resistor circuit has been proved to be quite stable for resistance to voltage conversion for the sensors we are using.

Sallen Key Low Pass Filter:
The standard frequency domain equation for a second order low-pass filter is: Where fc is

$$H_{LP} = \frac{K}{-\left(\frac{f}{fc}\right)^2 + \frac{jf}{Qfc} + 1}$$

the corner frequency and Q is the quality factor. When f¡¡fc, Equation reduces to K and the circuit passes signals multiplied by a gain factor K. When f=fc, Equation reduces to –jKQ, and signals are enhanced by the factor Q. When f¿¿fc, Equation reduces to K(fc/f)2 , and signals are attenuated by the square of the frequency ratio. With attenuation at higher frequencies increasing by a power of 2, the formula describes a second order low-pass filter.

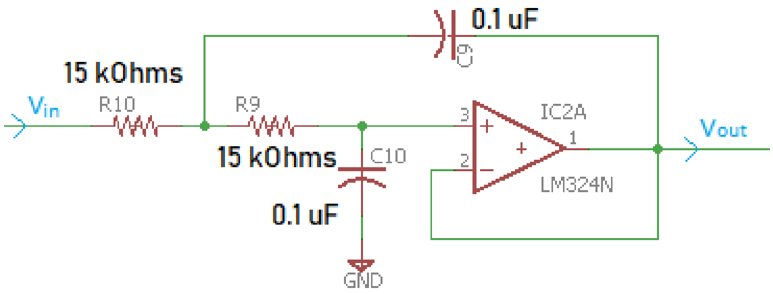


Figure 7: Sallen Key Low Pass Filter

Next comes the translational block,for which TIVAC 123M board was the alone contender with 12 Analog to Digital conversion channels.

2.3.2 Transmitter block

We had two options to go with for the transmitter block viz bluetooth module and Sim 808 module. Sim 808 module had a provision of long distance transmission but on the same point was to much bulky to be incorporated below a shoe sole. We therefore opted for HC 05 bluetooth module to transmit the digital datapoints generated by the microcontroller.

3 Project Implementation

3.1 Hardware Involved

Image on next page.

3.2 Assembling subsystems & Fabrication

The translational block which convert sensor's resistance datapoints into voltage, produces an analog output which is then fed to the analog input pin of TIVA C board. Throught the ADC channel the analog voltage is encoded in 1024 voltage levels. The voltage level datapoints are then transmitted via the Bluetooth module. Any Bluetooth enabled receiver device in the range of 10 m can receive the data on its python interface.

We have build a rigid structure using wooden planks on which a person can climb and use the device. For protecting the PCB and other modules all the circuitry have been sandwiched inside the rigid body. On the top of wooden plank a sole is placed through which the sensors peek out. The process is shown in figure 9.

3.3 Inter Academic departmental work

The project has practically made us the realise the fact that any engineering problem at it's core isn't something which can be confined by the boundaries of Academic departments. All system designs need inter-departmental collaborations in various stages of the design and implementation. Particularly for our project, the most essential part was the Force Sensitive Resistance we are using to measure the pressure map of foot. The characterization of these sensors forms one of the crucial parts of our project. This process involved quite a lot of inter-departmental working right from sensor calibration techniques, to sensor stress analysis (MEMS, Civil engineering departments) upto the selection of a minimum damping disc (Mechanical engineering department, TATA Centre for Reserach and Development) as a precursor to the calibration and a protective case while calibration.

The foam sensors referred from [1] were initially used for pressure measurement. The calibration of these sensors was done using laboratory weights and analysing the change in resistance.

3.3.1 Plastic Electronics and Energy Laboratory, IIT Bombay

The PEEL Lab in MEMS department, IIT Bombay has a sophisticated sensor calibration facility with real-time data logging facility. We calibrated the FSR sensors in this lab to characterize the sensors and design the pressure map generation strategy based on the known force to resistance values. However, the resolution of the machine for calibration was large and thus we could not get transient analysis of the sensors.

We also visited the *TATA Centre for Reserach and Development* and *Mechanical Workshop* to fabricate a metal or acrylic ring of the size of the sensor to ensure equal distribution of force onto the sensor.

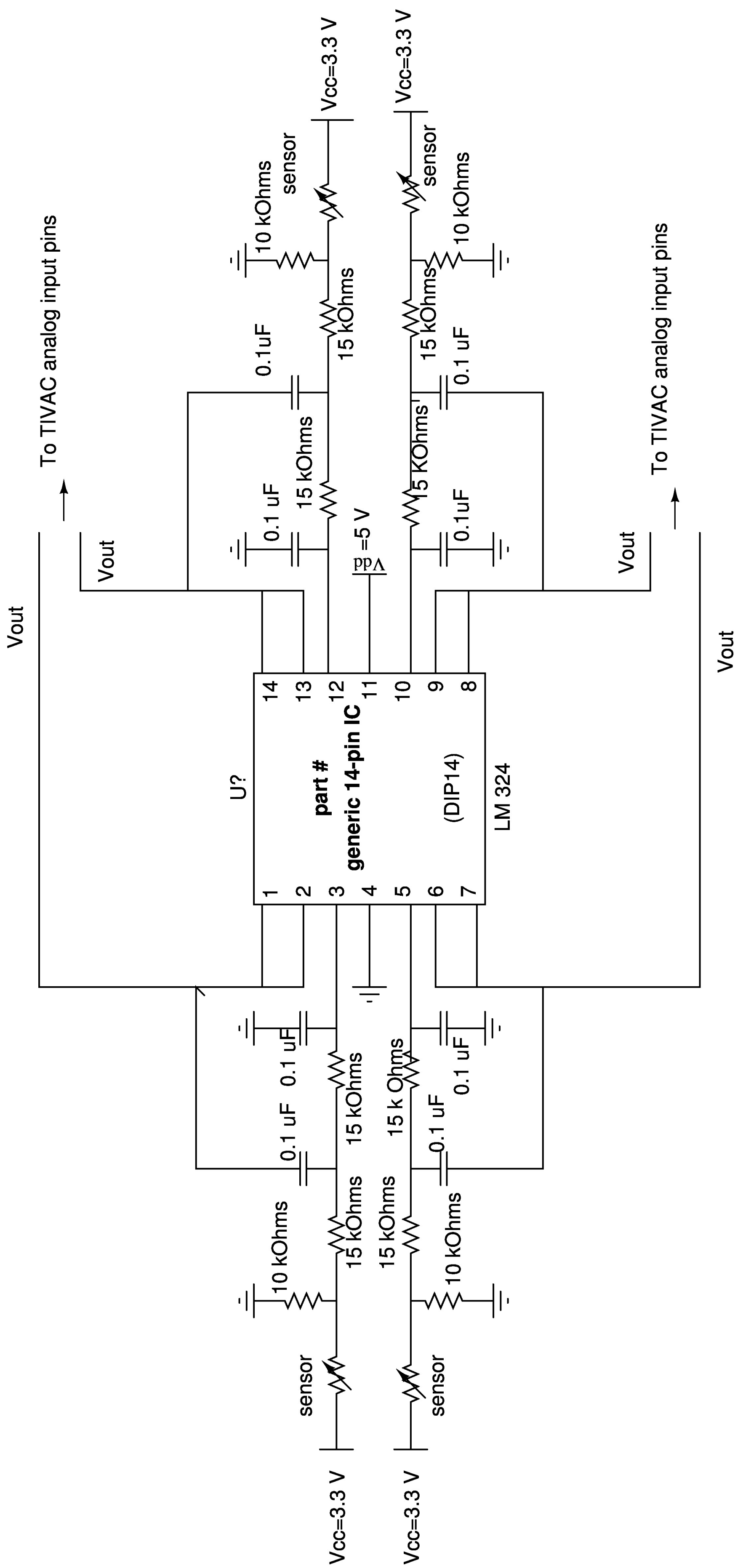


Figure 8: Hardware

Figure 9: Fabrication process

3.3.2 Advanced Geotechnology Lab, IIT Bombay

Since the calibration data from the PEEL Lab wasn't enough to extract sensor information for prediction while generating pressure maps, we found another technique for calibration from the paper [3]. We used dead weights for calibrating the sensor in steps of $\tilde{4}50$ grams, from 0 to $\tilde{8}$ kgs, followed by unloading. The pictures of the setup are shown in figure 15.15

4 Performance Evaluation

4.1 Prototype details

4.1.1 Costings

Sensors	₹ 4500
Tiva C board	₹ 1130
HC-05 Bluetooth module	₹ 450
ICs and other circuit elements	₹ 200
Total (including some stationary)	**~₹ 6500**

Figure 10: Costing in Fabrication of device

4.2 Test Results

4.2.1 Characterization of Tangio Force resistive sensors

We have used commercially available Tangio TPE-510 force resistive sensors for measuring the pressure. As the name suggests these sensors have variable resistance with varying pressure. These FSRs are used in shunt in the circuit. Each sensor has an independant signal conditioning block. The FSRs datasheet claims to have linear log(resistance)-log(applied pressure) relationship. We used the calibration setup as in figure15 and obtained a approximately quadratic relationship between log(resistance)-log(applied pressure), as visible in the plots below.1314

Figure 11: TP 501 FSR

Characteristic	Value
Active area	Φ 25.42mm
Actuation force	10g
Observed Hysteresis	23%
Observed log/log characteristics	Parabolic (y = -0.3494x2 + 2.5184x - 0.2713)

Figure 12: Characteristics of a FSR

4.2.2 Plots:

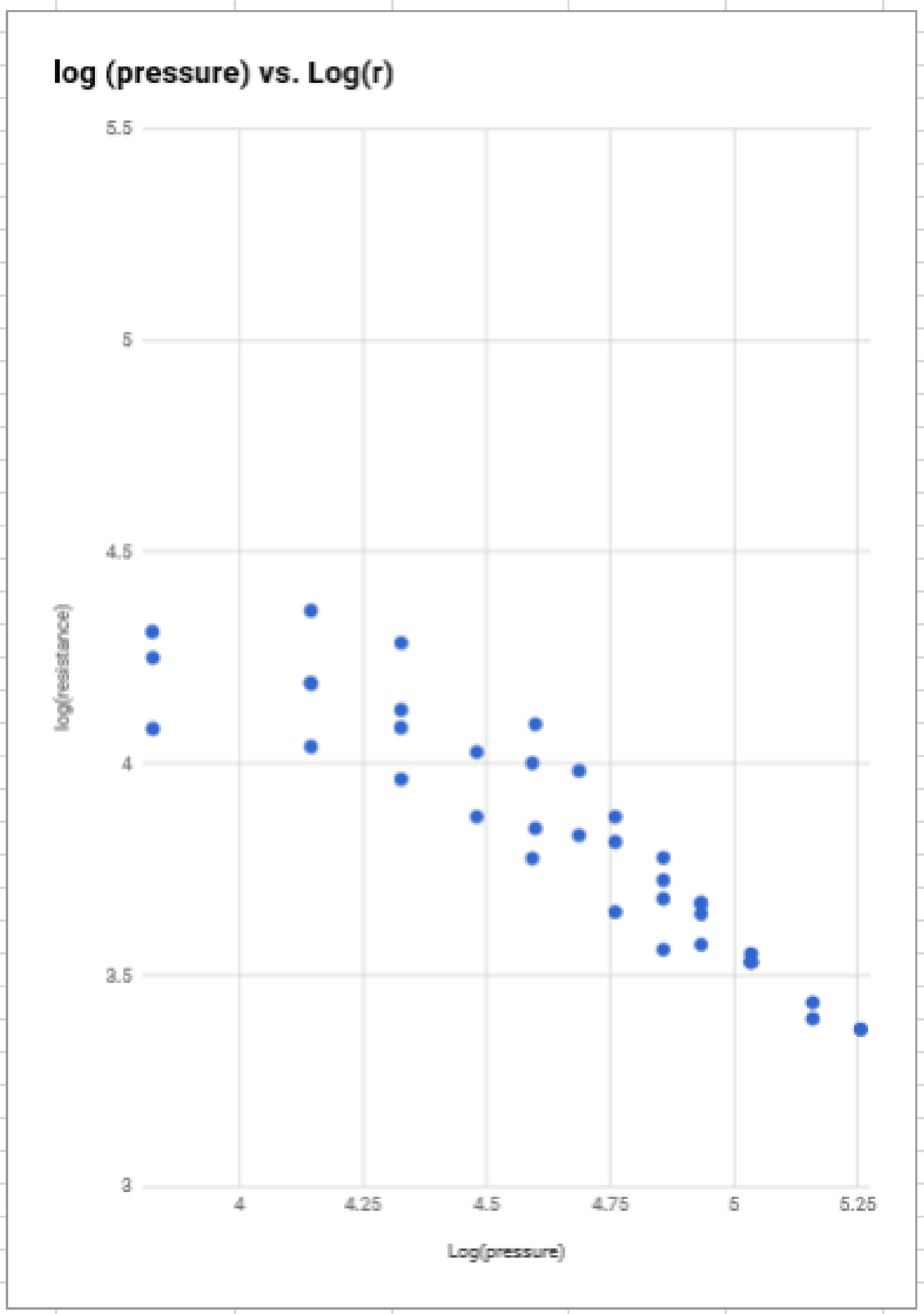


Figure 13: Log(resistance) vs Log(pressure) -clubbed data of 2 loading-unloading cycles

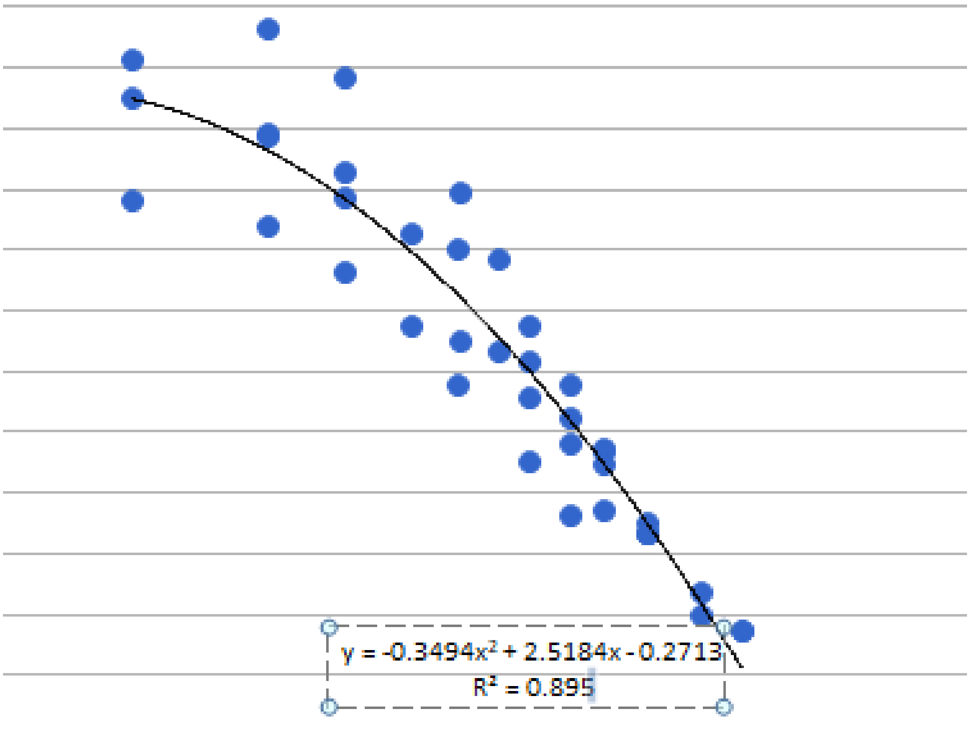


Figure 14: Approximated curve

(a) Calibration setup (b) Pressure is applied using Dead weights

Figure 15: Calibration of FSR using the facility in Advanced Geotechnolgy Laboratory, reference in [3]

4.3 Problems & Challenges faced

4.3.1 Characterization of PU Foam sensor:

These PU foam based sensors are novel in terms of their dynamic range of operation, their size and their cost. However, the following were the major issues we noted after analysing their characteristics:

1. **High settling time:**
Although the rise time was close to 30-40 ms (which is very good as compared to the commercially available FSRs, [4]), after the withdrawal of the input force, the sensor takes quite a large time to return to it's initial state. Also, this settling time varies every time the sensor is tested by weights or otherwise.

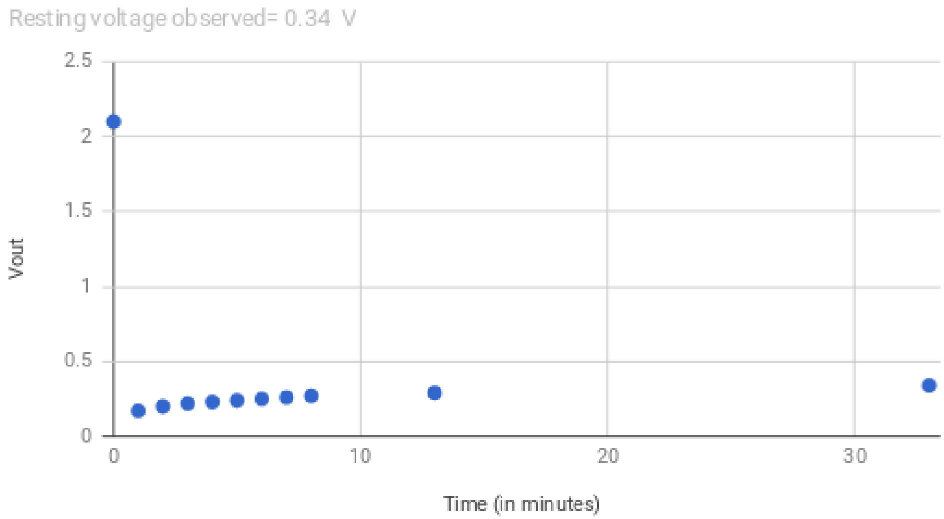
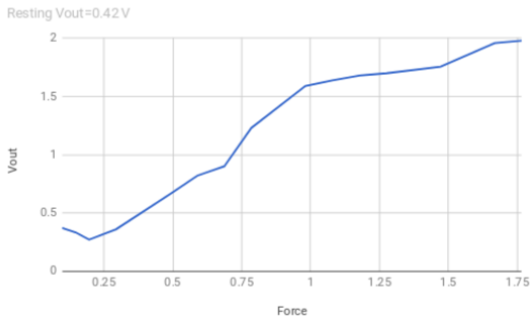


Figure 16: Time taken by the foam sensor to reach a steady state after sudden release of pressure

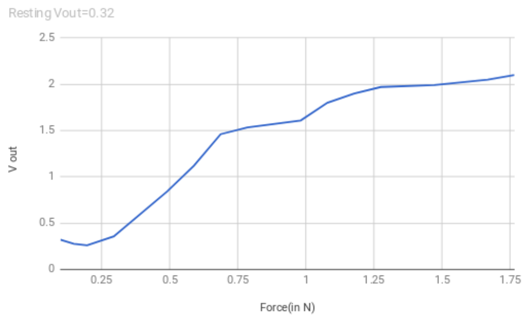
2. **Steady state error:**
In the context of the sensor testing, steady state error is defined as the difference between the desired value of resistance to be attained by the sensor and the actual resistance it offers for a particular input function. The steady state error is significantly different for different sets of experiments in time with same input functions and for the same sensor. This makes it difficult to predict the steady state value for a given input at any time instant. The prediction of values is important for this project because the ultimate requirement is the relative pressure map of the foot for several diagnostics, which is possible only when we have a 'look-up' table of input force-resistance.

3. **Fluctuations in resistance for constant input:**
The PU foam sensors failed to show stable values for constant input even after sufficiently large time as compared to rise time. The values weren't stable and a constant but gradual decrease/increase was seen in the resistance. This again hindered in designing the look-up table.

4. **Repeatability:**
The PU foam sensor gave different zero-input resistance values when tested in different time scales. The difference was quite significant as evident from the figure 17.



(a) $V_{out,max} = 0.42V$



(b) $V_{out,max} = 0.32V$

Figure 17: At zero pressure, the steady state voltage measurements at different time instances for the same sensor

4.3.2 Reading serial data into host computer

The conditioned sensor data is transmitted from the system using Bluetooth module HC-05. This data has to be read into host computer and plot pressure maps accordingly. However, we faced the following problems while doing so:

1. **MATLAB Serial module:**
   The serial module in MATLAB is used to directly read serial data into MATLAB and thus allow direct operations on serial data in real time. However, the serial ports weren't able to synchronize with MATLAB's serial module commands. This restricted the use of any serial port `/dev/ttySi`, $i = 1, 2, 3, \ldots$. A similar problem was faced with Octave.

2. **Pressure Map generation in Python:**
   We have used the `Numpy` module in Python for all matrix computations involved in smoothening the pressure map from finite data points. The `flops` (floating point operations) in every inetration of pressure map generation are:

   $$flops \;\; = 9 * [482 * 242] \;\; = 9 * 116644 \approx 10, 50, 000$$

   The average time of computations of these *flops* is 3 seconds. So, every update of the pressure map has a lag of about $2 - 3$ seconds. This has restricted the working of the system in real time and we are trying to optimize the computations to reduce the updation lag.

5 Conclusion & Future work

In the report we tried to demonstrate how did we go on to fabricate a low cost, low power and easy to use smart shoe, which in real time produces a pressure heat map of the foot of the person standing on it. We were fairly able to complete all the goals which we set in our project proposal as well as those mentioned in evaluation 1 report. Using 9 wirelessly transmitted datapoints generated from 9 FSR sensors we were able to generate a pressure heat map using Gaussian curve to extrapolate the data. We aim to work more on our prototype and build on the future scopes.

5.1 Future Scope

- Inclusion of just TM4C123GH6PM microcontroller in final PCB instead of development board for modular design
- Design and print a *Flex* PCB for compact design and come up with a commercially sound prototype
- Long term goal is to use cutting-edge technology in Internet of Things (**IoT**) to analyse the data and usage from all the nodes of the IoT chain to get real-time feedback of the device and also implement new features into the all devices then used using direct server to node communication.

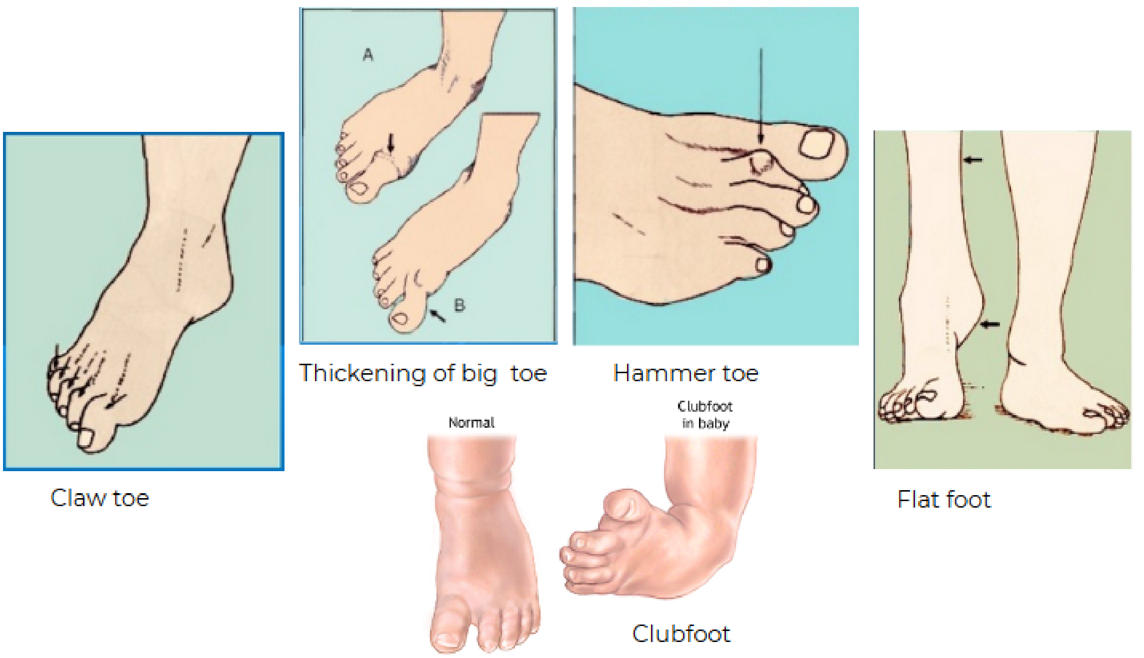


Figure 18: Commonly found foot deformities

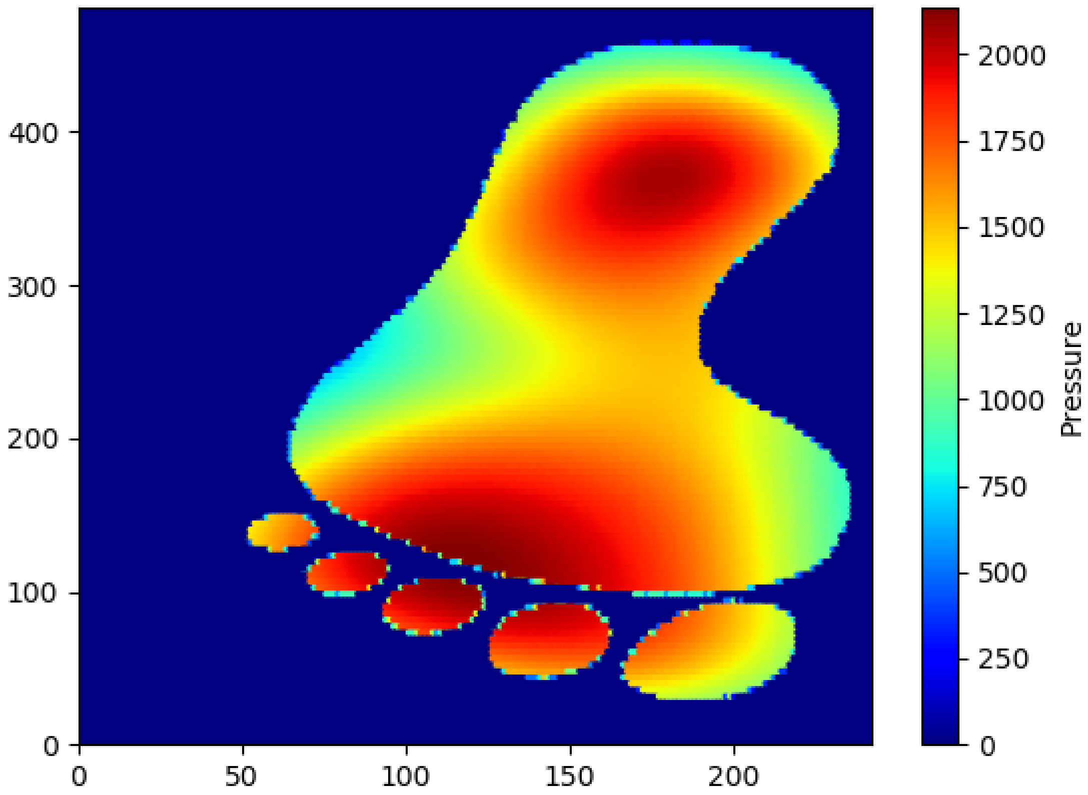


Figure 19: Pressure heat map of a normal foot

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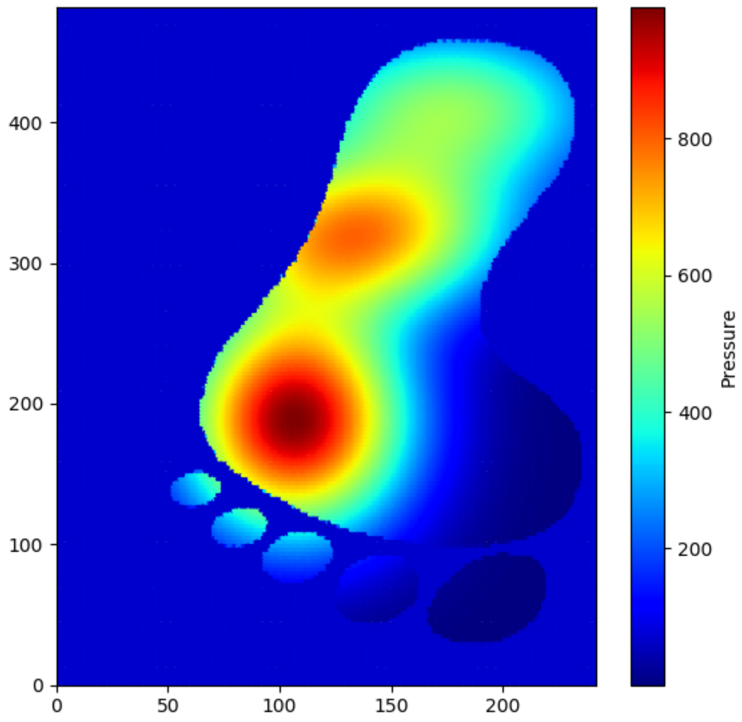

Figure 20: Pressure heat map when pressure is applied only on left metatarsal bone side--**Clubfoot**

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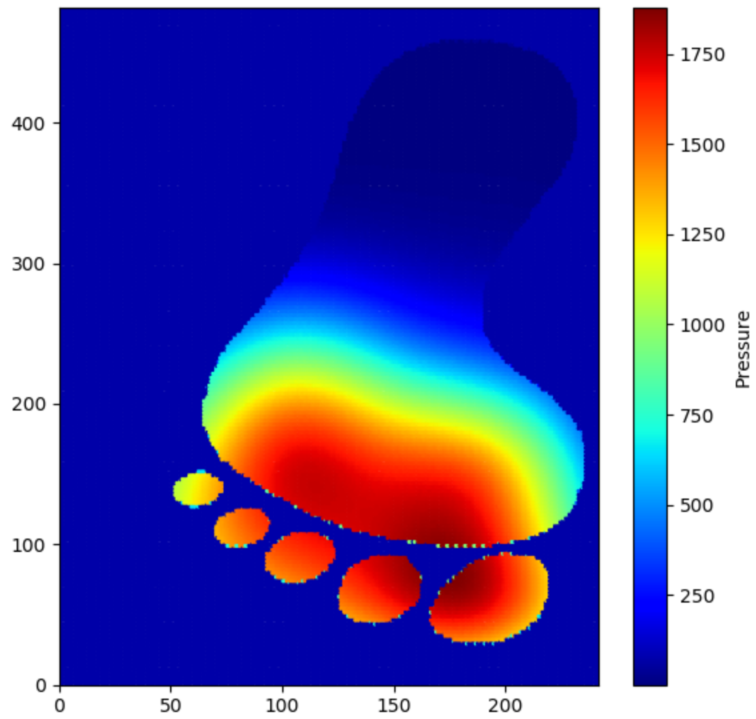

Figure 21: Pressure heat map when pressure is applied only on phalanx bone(front side)-**Clubfoot**

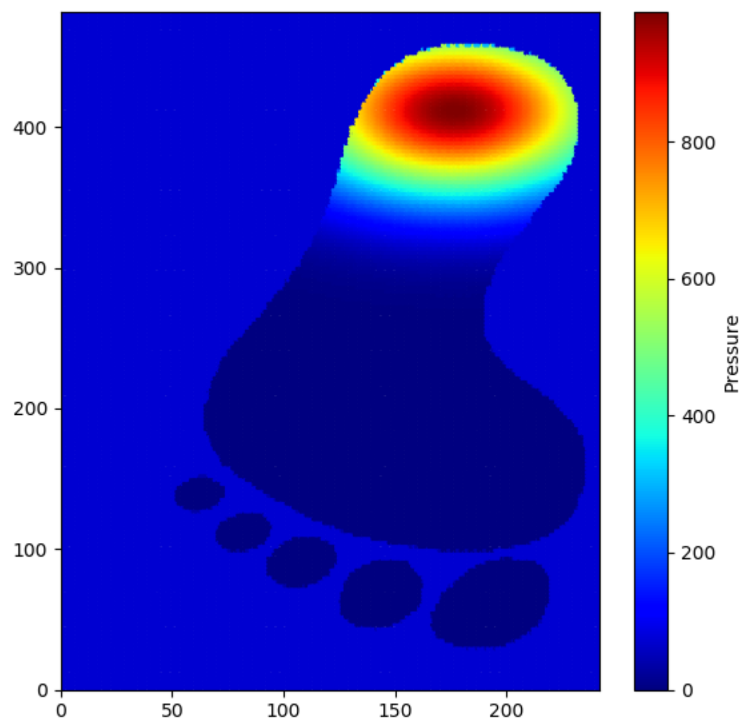

Figure 22: Pressure heat map when pressure is applied only on heel-**Clubfoot**