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ABHISHEK MANISH LELE * , DNYANESHWAR WAGHOLE , PANKAJ DHATRAK

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Article

Development of a Mock-Up of a Smart Insole Using FSR and ADXL345

Abhishek Lele *, D. R. Waghole and Pankaj Dhatrak

Department of Mechanical Engineering, Dr. Vishwanath Karad MIT World Peace University, Pune 411038, MS, India
* Correspondence: 1032210464@mitwpu.edu.in

Abstract: This research article describes the creation of a mock-up for a Smart Insole prototype that employs Force Sensitive Resistors (FSRs) and an ADXL345 accelerometer. The mock-up is an early step towards realising the concept and functionality of the planned Smart Insole system. The key factors in the mock-up's design, integration, and testing are highlighted, with a focus on the iterative refining and optimisation process. The mock-up, which was carefully planned and implemented, highlights the practicality and possible applications of Smart Insole technology in healthcare, sports performance measurement, and rehabilitation. The paper outlines the development process and implementation of a "Smart Insole" utilizing Force Sensitive Resistors (FSR) and the ADXL345 accelerometer. The project aims to create an innovative wearable technology solution for monitoring foot biomechanics and enhancing human performance. The Smart Insole prototype integrates FSRs strategically placed on the insole to capture pressure distribution across the foot, along with an ADXL345 accelerometer to track foot orientation and movement. Through a combination of hardware integration, firmware development using Arduino IDE, and visualization using Processing application, the Smart Insole offers real-time monitoring and analysis of gait dynamics, pressure distribution, and foot movement.

Keywords: force sensitive resistor; accelerometer; gait analysis; pressure mapping; orientation tracking

1. Introduction

This research paper describes the creation of a mock-up for a Smart Insole prototype that employs Force Sensitive Resistors (FSRs) and an ADXL345 accelerometer. The mock-up is an early step towards realizing the concept and functionality of the planned Smart Insole system. The key factors in the mock-up's design, integration, and testing are highlighted, with a focus on the iterative refining and optimization process. The mock-up, which was carefully planned and implemented, highlights the practicality and possible applications of Smart Insole technology in healthcare, sports performance measurement, and rehabilitation.

1.1. Problem Statement

Assessing foot health is crucial for preventing injuries, improving mobility, and maintaining overall well-being, as the feet are fundamental for daily activities and physical function.

This project aims to develop a smart insole prototype utilizing FSR and IMU sensors to provide real-time feedback on foot pressure distribution, movement, and orientation. By addressing these limitations, we seek to empower individuals with actionable insights into their foot health, enabling timely intervention and improved quality of life.

1.2. Objective And Scope

The primary objective of this project is to develop a smart insole prototype integrating FSR and IMU sensors to provide real-time feedback on foot pressure distribution, movement, and orientation, aiming to empower individuals with actionable insights into their foot health for proactive management and prevention of potential complications.

Existing methods for assessing foot health lack accessibility and real-time monitoring capabilities, leading to challenges in proactive management of foot-related conditions.

The scope of this project encompasses the design, development, and testing of a smart insole prototype integrating FSR and IMU sensors for real-time monitoring of foot health.

Additionally, the project aims to contribute to the advancement of wearable technology by addressing challenges related to foot health monitoring and promoting proactive management of foot-related conditions.

By embedding these sensors discreetly into an insole, we envision a wearable device that can:

1. revolutionize the way we understand and monitor foot dynamics
2. offer insights into gait analysis
3. balance
4. foot health

1.3. Background

The background of the project centers on the growing interest in wearable technology solutions for monitoring and optimizing human performance, particularly in the context of foot biomechanics and gait analysis.

Traditional methods of assessing gait dynamics often rely on expensive laboratory equipment and specialized settings, limiting accessibility and scalability. In response to this challenge, there has been a surge in research and development efforts aimed at creating portable, non-invasive solutions capable of providing real-time insights into foot pressure distribution and movement patterns.

Leveraging advancements in sensor technology, the integration of Force Sensitive Resistors (FSRs) and the ADXL345 accelerometer within a Smart Insole prototype offers a promising avenue for addressing these needs. By combining sensor data acquisition with data processing and visualization techniques, the Smart Insole has the potential to revolutionize gait analysis, sports performance assessment, and rehabilitation practices, fostering a new era of personalized and accessible healthcare solutions.

2. Literature Survey

The literature review for this project encompasses a broad spectrum of research and developments in wearable technology, foot health monitoring, and sensor technologies.

- Studies emphasize the importance of proactive foot health monitoring in various populations, including athletes, individuals with diabetes, and the elderly, highlighting the significance of early detection and prevention of foot-related complications.
- Research on Force-Sensitive Resistor (FSR) sensors and Inertial Measurement Unit (IMU) sensors provides insights into their capabilities in measuring foot pressure distribution and capturing foot movement, orientation, and gait patterns.
- Additionally, investigations into wearable technology in healthcare underscore the potential for integrating wearable sensors into rehabilitation, diagnostics, and chronic disease management.

The literature review also delves into algorithm development for sensor data analysis, user interface design principles, applications in sports rehabilitation and diagnostics, and consumer acceptance of wearable health monitoring devices.

Authors	Title	Findings	Publication Details	Link
Juan Tao et. al.	Real-time pressure mapping smart insole system based on a controllable vertical pore dielectric layer	Capacitive pressure sensors were used	Microsystems & Nanoengineering 6, Article	Real-time pressure mapping smart insole system based on a controllable vertical pore dielectric layer | Microsystems & Nanoengineering (nature.com)

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			no.62 (2020)	
Mi Zhou et. al.	Design and manufacture of intelligent fabric-based insoles for disease prevention by monitoring plantar pressure	Disease detection was demonstrated by pressure mapping	Materialstoday Communication Vol. 37 (2023)	Design and manufacture of intelligent fabric-based insoles for disease prevention by monitoring plantar pressure - ScienceDirect
Marshall Kendall et. al.	Predicting vertical and shear ground reaction forces during walking and jogging using wearable plantar pressure insoles	Gait/motion analysis was done using pressure insoles	Gait and Posture Vol. 104 (2023)	Predicting vertical and shear ground reaction forces during walking and jogging using wearable plantar pressure insoles - ScienceDirect
Yin He et. al.	Textile-film sensors for a comfortable intelligent pressure-sensing insole	Performance monitoring in sports	Maesurement Vol. 184 (2021)	Textile-film sensors for a comfortable intelligent pressure-sensing insole - ScienceDirect
Katie E Chatwin et. al.	An intelligent insole system with personalised digital feedback reduces foot pressures during daily life: An 18-month randomised controlled trial	18 month study was conducted	Diabetes Research and Clinical Practice Vol. 181 (2021)	An intelligent insole system with personalised digital feedback reduces foot pressures during daily life: An 18-month randomised controlled trial (sciencedirectassets.com)
Soumya Manna et. al.	Optimal locations and computational frameworks of FSR and IMU sensors for measuring gait abnormalities	Review article based on usage of IMU and FSR	Heliyon Vol. 9 Issue 4 (2023)	Optimal locations and computational frameworks of FSR and IMU sensors for measuring gait abnormalities (sciencedirectassets.com)
Q Zhang et. al.	A low-cost and highly integrated sensing insole for plantar pressure measurement	Low cost and easily accessible sensors were used	Sensing and Bio-Sensing Research Vol. 26 (2019)	A low-cost and highly integrated sensing insole for plantar pressure measurement (sciencedirectassets.com)
Rui Hua et. al.	Smart insoles review (2008-2021): Applications, potentials, and future	Overview on smart insole tech	Smart Health Vol. 25 (2022)	Smart insoles review (2008-2021): Applications, potentials, and future - ScienceDirect
Carlúcia Ithamar Fernandes Franco et. al.	The Use of Smart Insoles for Gait Analysis: A Systematic Review	Integration of software with pressure and inertial sensors	Innovations in Mechanical Engineering (2021)	The Use of Smart Insoles for Gait Analysis: A Systematic Review | SpringerLink

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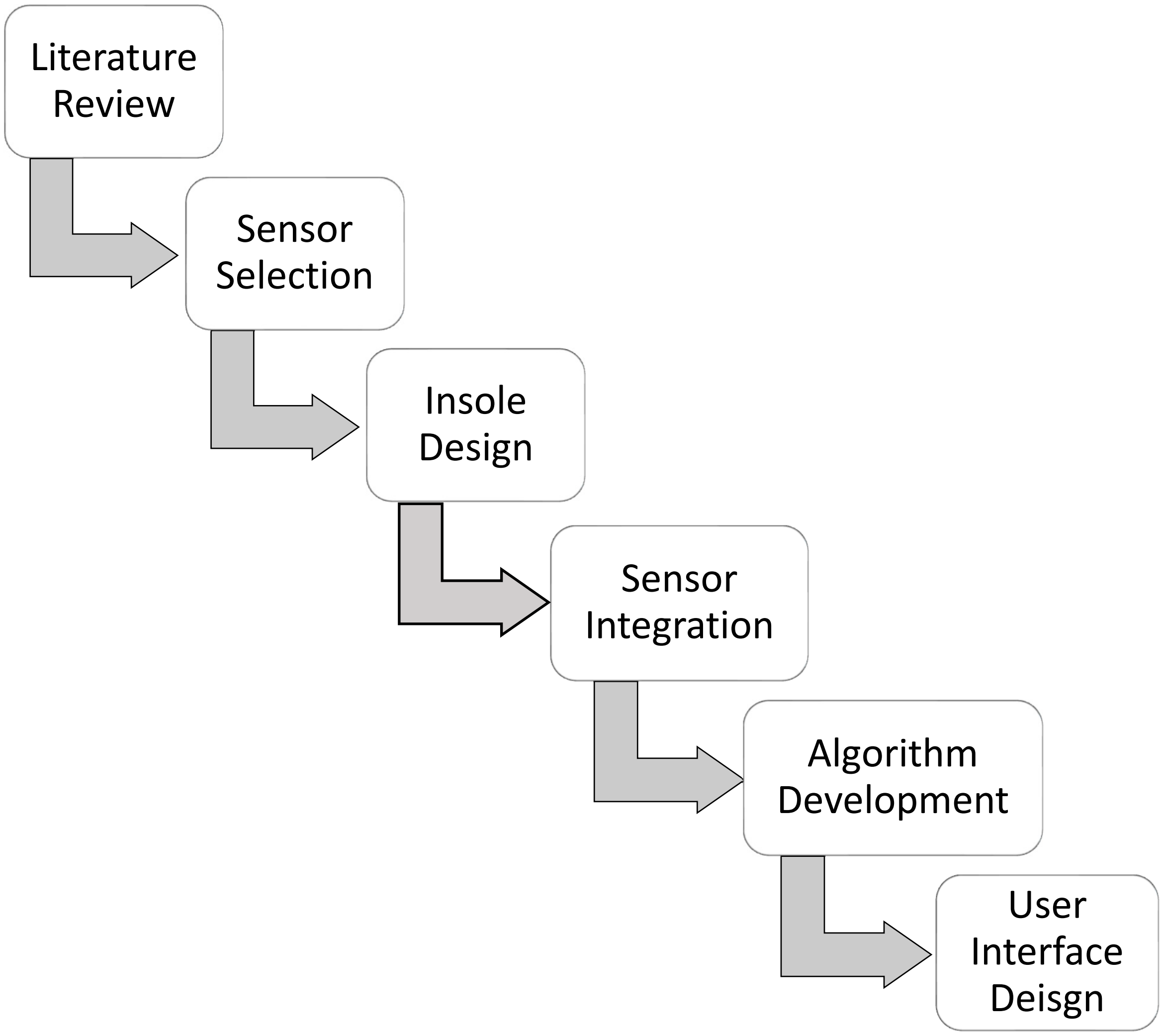
3. Methodology



3.1. Literature Review

The literature review for this project encompasses a broad spectrum of research and developments in wearable technology, foot health monitoring, and sensor technologies. The literature review delves into algorithm development for sensor data analysis, user interface design principles, applications in sports rehabilitation and diagnostics, and consumer acceptance of wearable health monitoring devices.

3.2. Sensor Selection

Thoroughly evaluating various Force-Sensitive Resistor (FSR) and Inertial Measurement Unit (IMU) sensors based on technical specifications, accuracy, and suitability for foot health monitoring, ensuring optimal sensor performance.

Force Sensitive Resistors (FSRs) are sensors that detect changes in resistance in response to applied force or pressure. They consist of a conductive polymer material whose resistance decreases as force is applied to its surface. Initially, the conductive particles within the polymer are separated, resulting in high resistance. However, when pressure is exerted on the FSR, the particles come into closer contact, creating more conductive pathways, and causing a decrease in resistance. This change in resistance is proportional to the magnitude of the applied force, allowing FSRs to provide continuous feedback on pressure levels. This working principle enables FSRs to be used in various applications such as touch sensing, force measurement, and pressure mapping, including their integration into the Smart Insole prototype for monitoring foot biomechanics and gait analysis.

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An Inertial Measurement Unit (IMU) functions as a sensor system capable of measuring and reporting accelerations, angular velocities, and sometimes magnetic fields, typically using a combination of accelerometers, gyroscopes, and magnetometers. Accelerometers detect changes in linear acceleration along multiple axes, gyroscopes measure rotational speed around those axes, and magnetometers track changes in magnetic field strength. These sensors work together to provide comprehensive motion sensing capabilities, enabling IMUs to track orientation, velocity, and gravitational forces in three-dimensional space. IMUs are widely used in various applications, including navigation systems, robotics, virtual reality, and motion tracking. In the Smart Insole project, the ADXL345 accelerometer, an integral component of the IMU, is employed to monitor foot orientation and movement dynamics, contributing to the analysis of gait patterns and foot biomechanics.

Figure 1. Force Sensitive Resistor (FSR).

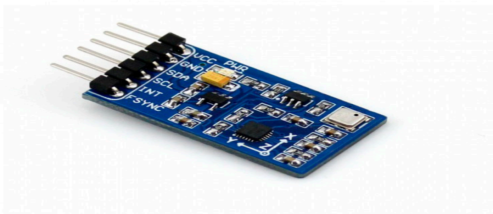

Figure 2. Inertial Measurement Unit (IMU).

3.3. Insole Design

Meticulously crafting the design of the smart insole, considering factors such as material selection, sensor placement, and ergonomic considerations to ensure both comfort and functionality for the user.

3.4. Sensor Integration

Embedding FSR and IMU sensors into the insole, ensuring precise wiring and connections to guarantee reliable data transmission and accurate capture of foot dynamics.

3.5. Algorithm Development

Developing sophisticated algorithms for processing and analyzing sensor data, employing advanced techniques for noise reduction, signal filtering, and feature extraction to derive meaningful insights into foot health metrics.

3.6. User Interface Design

Designing an intuitive and user-friendly interface for real-time monitoring of foot health data, prioritizing simplicity, usability, and clear visualization of sensor data to enhance user engagement and understanding.

4. Development and Execution

The design and planning phase of the Smart Insole mock-up development involved comprehensive consideration of key factors to ensure the effectiveness and functionality of the prototype. The process began with a thorough assessment of the intended application scenarios, user requirements, and technical specifications.

Initial discussions and brainstorming sessions were conducted to define the objectives and scope of the project. This included identifying the target user demographic such as:

- Athletes
- Patients undergoing rehabilitation
- Individuals seeking to improve gait dynamics

Understanding user needs and expectations played a crucial role in informing design decisions and feature prioritization.

The physical design of the Smart Insole mock-up involved conceptualizing the layout, form factor, and integration of components. Considerations were made regarding the placement of Force Sensitive Resistors (FSRs), the ADXL345 accelerometer, and the Arduino Uno R3 within the insole base to optimize sensor coverage and data accuracy.

4.1. Analyzing the Gait Cycle

The gait cycle, also known as the walking or locomotion cycle, encompasses the sequence of movements involved in human walking. It consists of two main phases: the stance phase and the swing phase. During the stance phase, the foot makes contact with the ground, beginning with the heel-strike as the initial point of contact, followed by the midstance where the foot bears the body's weight, and concluding with the toe-off as the foot pushes off from the ground to initiate the swing phase. The swing phase involves the leg swinging forward to advance the body's position, characterized by the swing-through motion of the foot until the next heel-strike occurs.

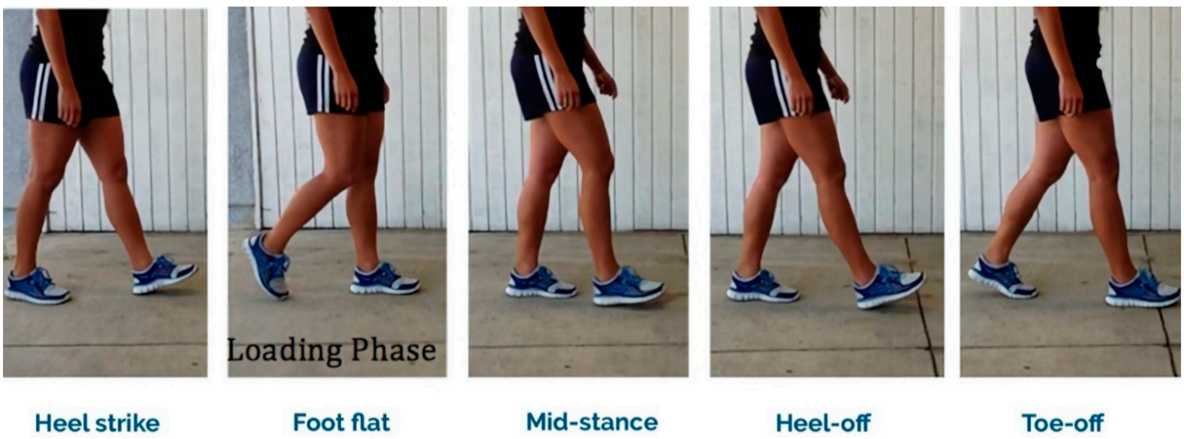

Figure 3. Gait Cycle.

4.2. Integration of FSRs:

The integration of Force Sensitive Resistors (FSRs) within the Smart Insole prototype is strategically designed to capture pressure distribution across key areas of the foot during various phases of the gait cycle. With one FSR positioned at the heel, one at the midfoot, and one at the forefoot (toes), the system aims to provide comprehensive insight into foot biomechanics and pressure dynamics.

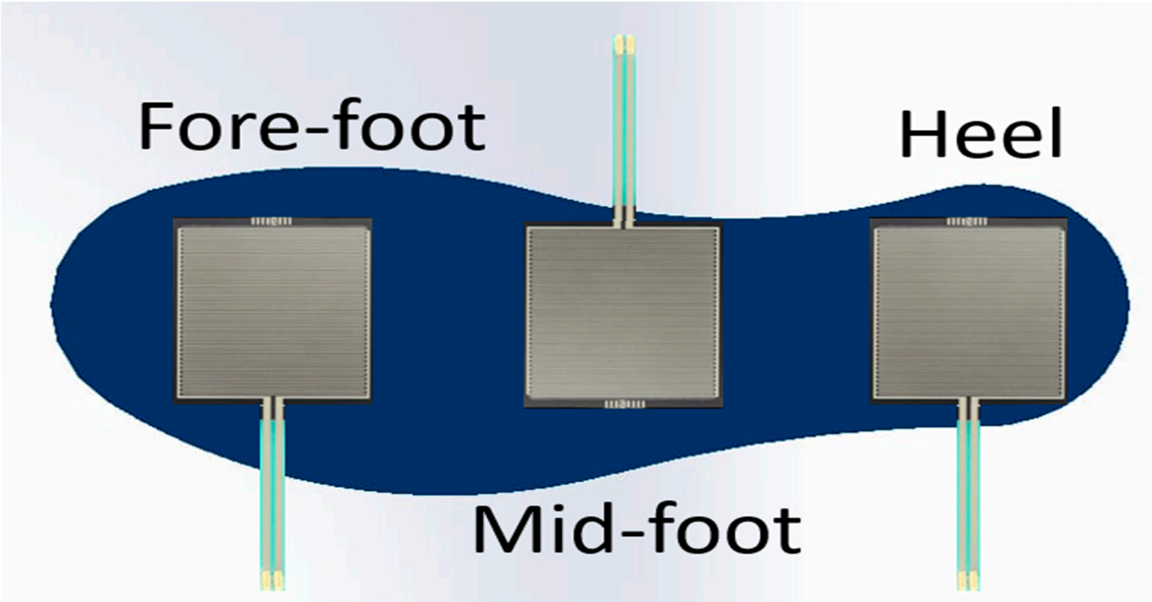

Figure 4. Integration of FSRs.

Placing an FSR at the heel allows for the detection of initial ground contact during the heel-strike phase of the gait cycle. This sensor captures the distribution of pressure as weight is transferred from the heel to the midfoot and forefoot during the subsequent phases of stance and propulsion. The FSR at the midfoot provides additional data on pressure distribution as the foot rolls forward and redistributes weight from the heel to the forefoot. Finally, positioning an FSR at the forefoot, near the toes, enables the measurement of pressure exerted during toe-off, the final phase of the gait cycle where the foot pushes off from the ground.

By integrating FSRs at these strategic locations, the Smart Insole prototype can effectively monitor pressure variations across the entire foot, offering valuable insights into gait dynamics, foot loading patterns, and potential areas of imbalance or discomfort. This comprehensive pressure mapping capability enhances the utility of the Smart Insole for applications in healthcare, sports performance analysis, and rehabilitation, enabling personalized monitoring and optimization of foot biomechanics.

4.3. Circuit Development:

The development of the circuit for integrating three Force Sensitive Resistors (FSRs), three 10k ohm resistors, and an Arduino Uno R3 microcontroller unit (MCU) is a pivotal step in creating the Smart Insole prototype for monitoring foot biomechanics. The circuit design aims to accurately measure pressure distribution across the foot and facilitate data acquisition for subsequent analysis.

The circuit configuration employs a voltage divider setup for each FSR, comprising the FSR and a 10k ohm resistor connected in series between the supply voltage (VCC) and ground. The voltage output from the junction between the FSR and resistor is proportional to the resistance of the FSR, which varies with applied pressure. This varying voltage is then fed into the analog input pins of the Arduino Uno R3 for analog-to-digital conversion.

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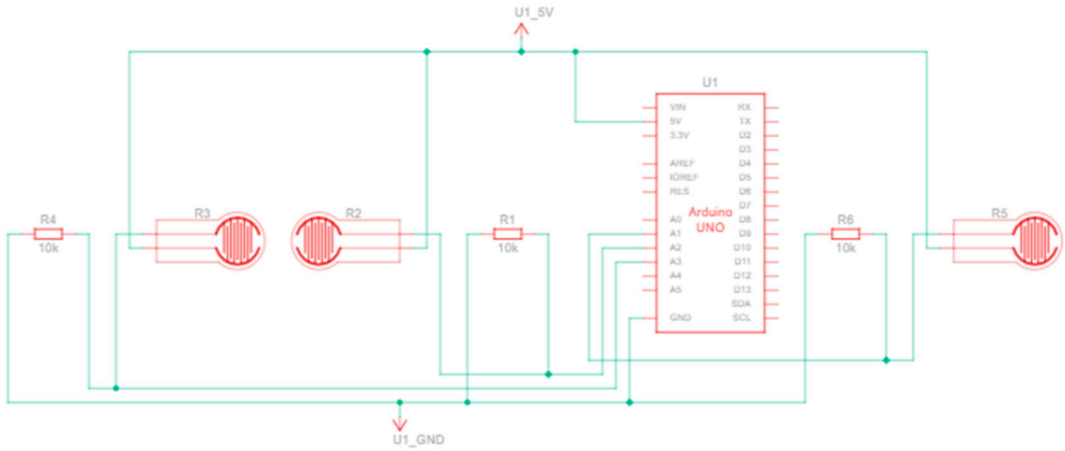

Figure 5. Schematic View of Circuit.

Through this arrangement, each FSR's pressure-dependent resistance is converted into a corresponding analog voltage signal, which the Arduino Uno R3 reads and processes. The MCU interprets these voltage signals and translates them into meaningful pressure readings, allowing for real-time monitoring of foot pressure distribution.

5. Integration with Arduino Ide

The Arduino IDE serves as the development platform for programming the Arduino Uno R3 microcontroller unit (MCU) embedded within the Smart Insole prototype. Custom firmware is developed using the Arduino programming language, facilitating the configuration of sensor interfaces, data processing algorithms, and communication protocols.

5.1. Establishing FSR Connectivity Using Arduino IDE

Integrating Force Sensitive Resistors (FSRs) with Arduino IDE is a crucial step in the development of the Smart Insole prototype, facilitating real-time monitoring of foot pressure distribution. The process begins with configuring the Arduino Uno R3 microcontroller unit (MCU) to interface with the FSRs and acquire analog sensor data.

In the Arduino IDE, a dedicated sketch is developed to initialize analog input pins corresponding to the FSR connections. Each FSR is connected to a specific analog input pin, along with a 10k ohm resistor forming a voltage divider circuit. This configuration ensures accurate measurement of voltage variations across the FSRs in response to applied pressure.

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```
const int FSR_Pins[] = {A3, A2, A1}; // Analog pins for FSRs
int FSR_Values[3]; // Array to store FSR readings

void setup() {
  Serial.begin(9600); // Start serial communication
}

void loop() {
  // Read analog values from each FSR
  for (int i = 0; i < 3; i++) {
    FSR_Values[i] = analogRead(FSR_Pins[i]);
    Serial.print(FSR_Values[i]);
    Serial.print(",");
  }
  Serial.println(); // Print a new line to indicate the end of the data for one iteration
  delay(100); // Delay for stability
}
```

Figure 6. IDE Code for FSR Connectivity.

These calibrated pressure readings are then processed and transmitted for visualization and analysis, laying the foundation for comprehensive monitoring of foot biomechanics using the Smart Insole prototype.

5.2. Linking ADXL345 Via Arduino IDE

In the Arduino IDE, a dedicated sketch is developed to initialize the communication interface and configure the necessary registers within the ADXL345 sensor module. This includes setting up parameters such as data rate, measurement range, and power modes to optimize sensor performance for the specific application requirements.

The Arduino IDE sketch further includes routines for reading accelerometer data from the ADXL345 sensor module, parsing the raw sensor readings, and converting them into meaningful units such as acceleration along three axes (x, y, z). These calibrated acceleration values are then processed and utilized for monitoring foot orientation, detecting movement patterns, and analyzing gait dynamics within the Smart Insole prototype.

```
#include <Wire.h>  // Wire library - used for I2C communication

int ADXL345 = 0x53; // The ADXL345 sensor I2C address

float X_out, Y_out, Z_out;  // Outputs
float roll,pitch,rollF,pitchF=0;

void setup() {
  Serial.begin(9600); // Initiate serial communication for printing the results on the Serial monitor

  Wire.begin(); // Initiate the Wire library
  // Set ADXL345 in measuring mode
  Wire.beginTransmission(ADXL345); // Start communicating with the device
  Wire.write(0x2D); // Access/ talk to POWER_CTL Register - 0x2D
  // Enable measurement
  Wire.write(8); // Bit D3 High for measuring enable (8dec -> 0000 1000 binary)
  Wire.endTransmission();
  delay(10);

  //Off-set Calibration
  //X-axis
  Wire.beginTransmission(ADXL345);
  Wire.write(0x1E);
  Wire.write(1);
```

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```
  // === Read accelerometer data === //
  Wire.beginTransmission(ADXL345);
  Wire.write(0x32); // Start with register 0x32 (ACCEL_XOUT_H)
  Wire.endTransmission(false);
  Wire.requestFrom(ADXL345, 6, true); // Read 6 registers total, each axis value is stored in 2 registers
  X_out = ( Wire.read() | Wire.read() << 8); // X-axis value
  X_out = X_out / 256; //For a range of +-2g, we need to divide the raw values by 256, according to the datasheet
  Y_out = ( Wire.read() | Wire.read() << 8); // Y-axis value
  Y_out = Y_out / 256;
  Z_out = ( Wire.read() | Wire.read() << 8); // Z-axis value
  Z_out = Z_out / 256;

  // Calculate Roll and Pitch (rotation around X-axis, rotation around Y-axis)
  roll = atan(Y_out / sqrt(pow(X_out, 2) + pow(Z_out, 2))) * 180 / PI;
  pitch = atan(-1 * X_out / sqrt(pow(Y_out, 2) + pow(Z_out, 2))) * 180 / PI;

  // Low-pass filter
  rollF = 0.94 * rollF + 0.06 * roll;
  pitchF = 0.94 * pitchF + 0.06 * pitch;

  Serial.print(rollF);
  Serial.print("/");
  Serial.println(pitchF);
}
```

Figure 7. IDE Code for ADXL345 Connectivity.

Through the seamless integration of ADXL345 connectivity within the Arduino IDE environment, the Smart Insole prototype becomes a powerful tool for assessing foot biomechanics, enhancing sports performance analysis, and facilitating rehabilitation practices. This linkage between the ADXL345 accelerometer and Arduino IDE forms the backbone of the Smart Insole's sensor system, enabling comprehensive monitoring and analysis of human movement.

6. Results

The integration of Force Sensitive Resistors (FSRs) and the ADXL345 accelerometer with the Arduino Uno R3 microcontroller unit (MCU) yielded real-time data output on the Arduino Serial Monitor. The FSRs provided continuous pressure readings, reflecting changes in foot pressure distribution during different phases of the gait cycle. Concurrently, the ADXL345 accelerometer delivered acceleration values along three axes, offering insights into foot orientation and movement dynamics. This real-time feedback on foot biomechanics enables users to monitor gait patterns, detect abnormalities, and optimize performance.

The seamless integration of FSR and ADXL345 connectivity with the Arduino IDE environment demonstrates the feasibility and effectiveness of the Smart Insole prototype for comprehensive monitoring and analysis of foot biomechanics.

6.1. Results on Arduino Serial Monitor for FSRs

Upon integration with the Arduino Uno R3 microcontroller unit (MCU) and configuration within the Arduino IDE, the Force Sensitive Resistors (FSRs) provide real-time data output on the Arduino Serial Monitor. As pressure is applied to the FSRs embedded within the Smart Insole prototype, corresponding analog voltage values are captured and transmitted via the analog input pins of the Arduino Uno R3. These voltage values are converted into digital readings using the built-in analog-to-digital converter (ADC) of the MCU.

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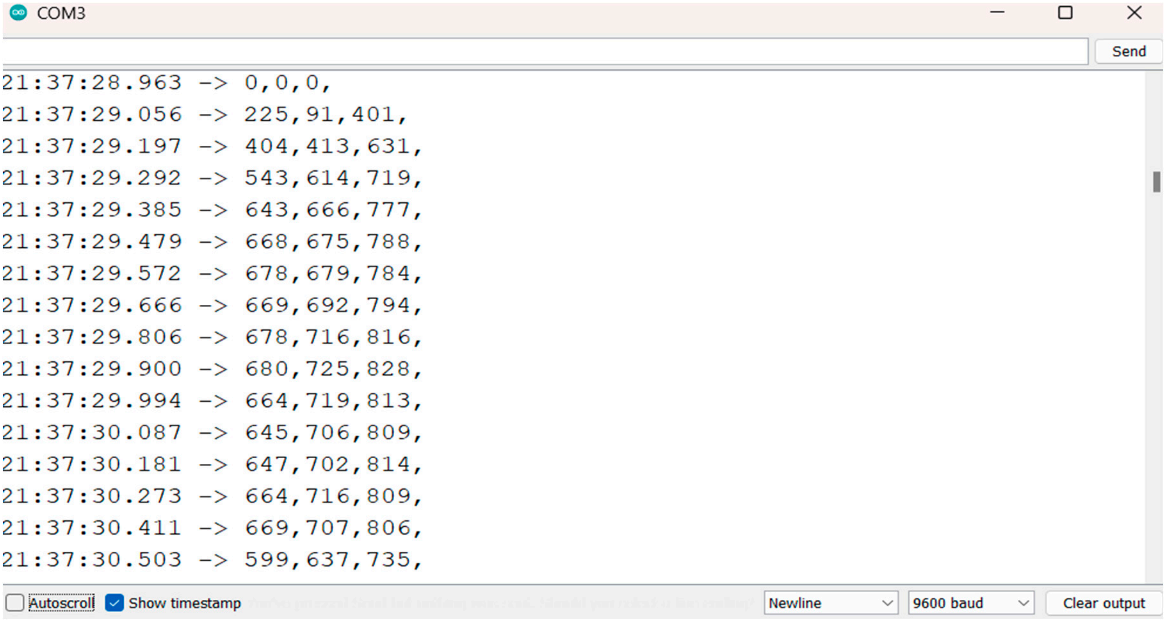

Figure 8. Serial Monitor Readings of FSRs.

On the Arduino Serial Monitor, users can observe the continuous stream of pressure readings from each FSR, providing insights into foot pressure distribution during various phases of the gait cycle. Through this visualization, users can monitor changes in pressure patterns, detect anomalies, and assess foot biomechanics in real time, enhancing the utility of the Smart Insole for gait analysis and performance optimization.

6.2. Results on Arduino Serial Monitor for ADXL345:

The integration of the ADXL345 accelerometer with the Arduino Uno R3 MCU enables real-time data output on the Arduino Serial Monitor. The accelerometer continuously measures acceleration along three axes (x, y, z) and transmits raw sensor readings to the MCU via the I2C or SPI communication protocol. On the Arduino Serial Monitor, users can observe the real-time acceleration values corresponding to each axis, providing insights into foot orientation and movement dynamics. Changes in acceleration readings reflect variations in foot position, velocity, and acceleration during the gait cycle. By visualizing these data on the Arduino Serial Monitor, users can monitor foot movement patterns, detect deviations from normal gait, and assess balance and stability in real time.

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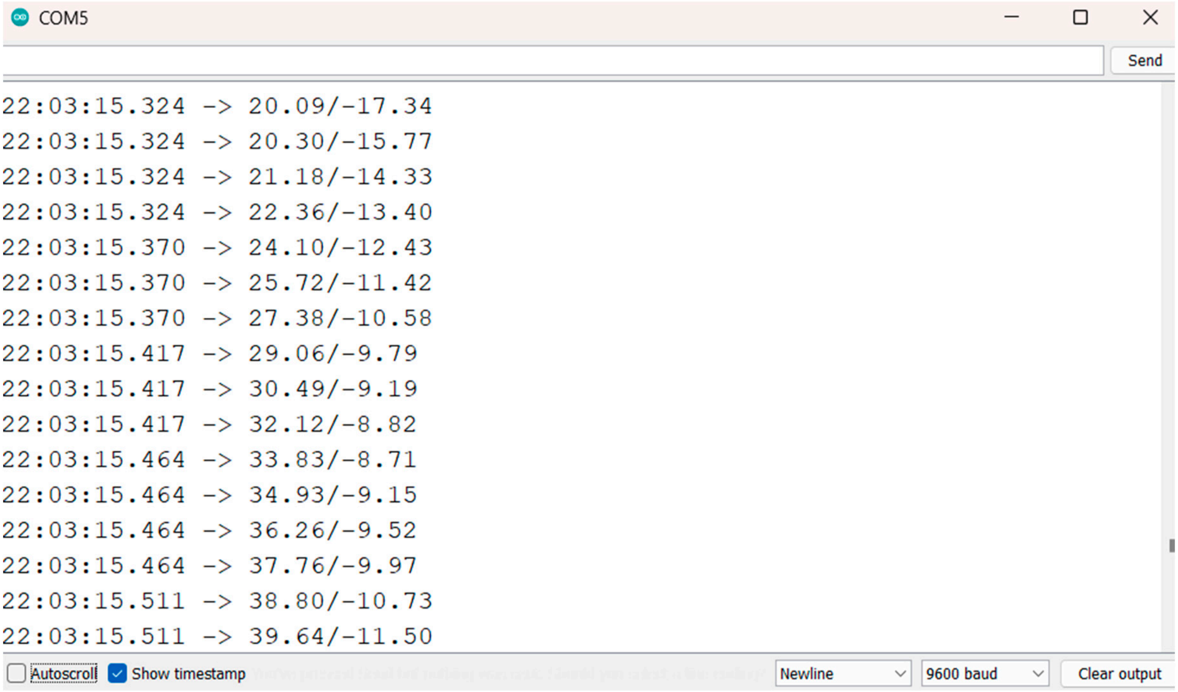

Figure 9. Serial Monitor Readings of AXDL345.

Through the seamless integration of ADXL345 connectivity within the Arduino IDE environment, the Smart Insole prototype becomes a powerful tool for assessing foot biomechanics, enhancing sports performance analysis, and facilitating rehabilitation practices. This linkage between the ADXL345 accelerometer and Arduino IDE forms the backbone of the Smart Insole's sensor system, enabling comprehensive monitoring and analysis of human movement.

7. Result Visualization Using Processing Application

The integration of the Smart Insole prototype with Processing application facilitated real-time visualization of sensor data, enhancing the interpretability and usability of the system. The Processing application received sensor data streams from the Arduino Uno R3 microcontroller unit (MCU) via serial communication, allowing for dynamic visualization of foot pressure distribution and movement dynamics.

7.1. Visualizing FSR Readings Via Processing

For Force Sensitive Resistors (FSRs), the Processing application generated visual pressure profiles, providing intuitive representations of pressure distribution across the foot. Areas of high pressure, such as the heel or forefoot, were depicted with distinct colors or intensity gradients, enabling users to identify pressure hotspots and assess foot loading patterns during various phases of the gait cycle. The visualization was obtained for different gait patterns such as:

1. No pressure moment
2. Heel strike
3. Toe off
4. Stance phase
5. Flat feet

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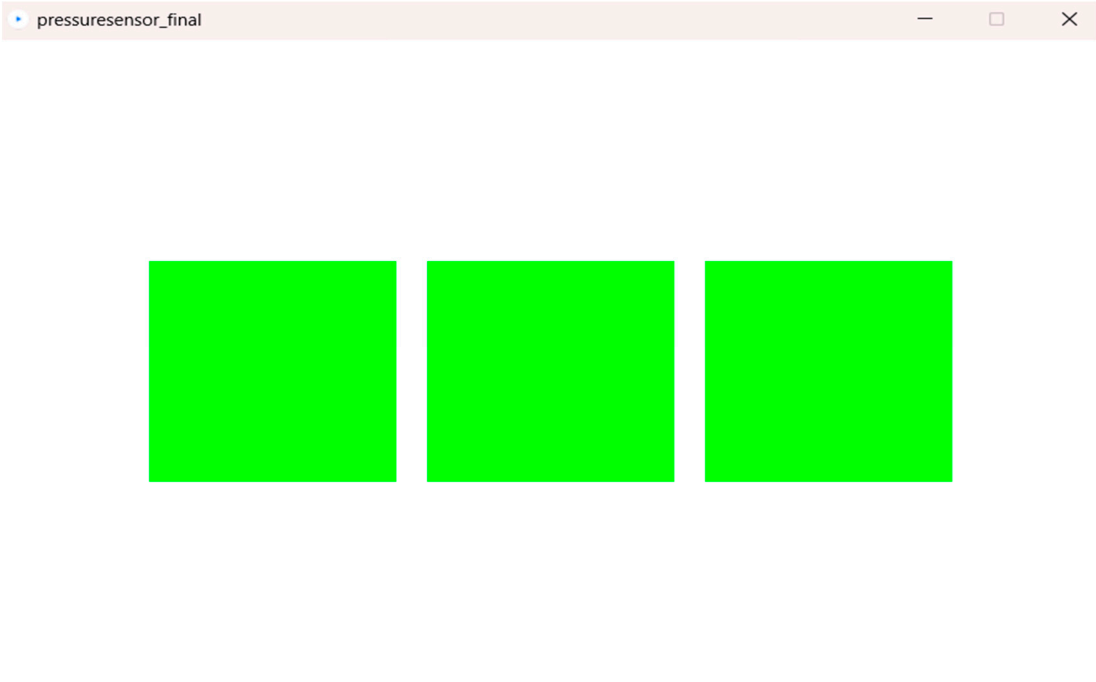

Figure 10. No Pressure Moment.

Figure 11. Heel Strike.

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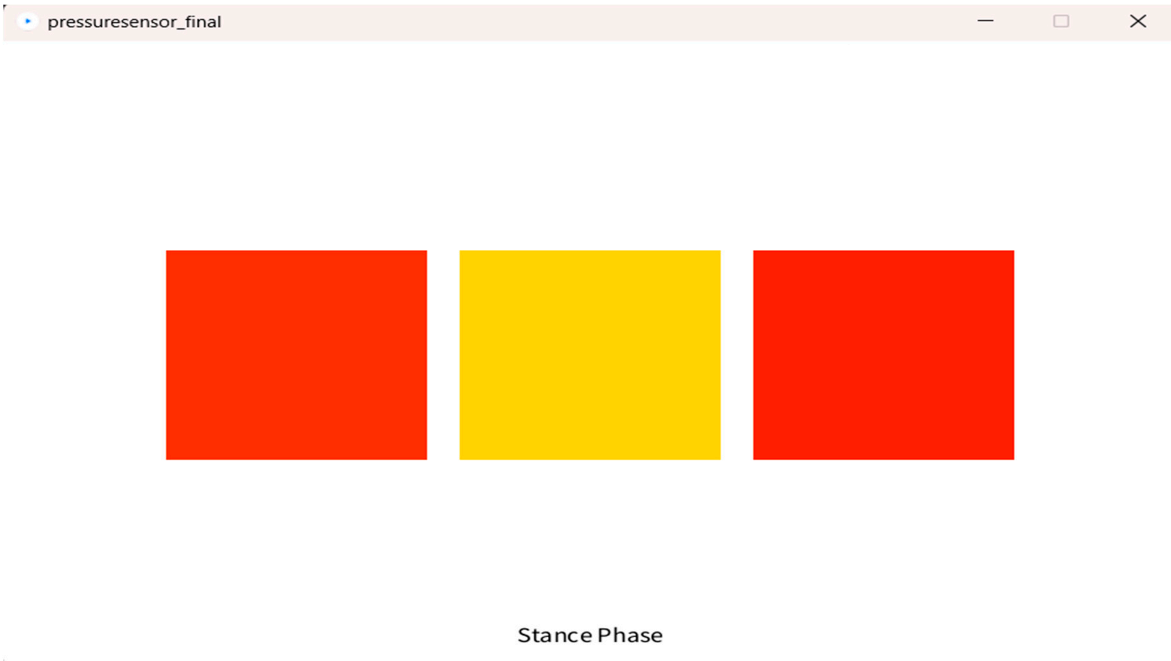

Figure 12. Stance Phase.

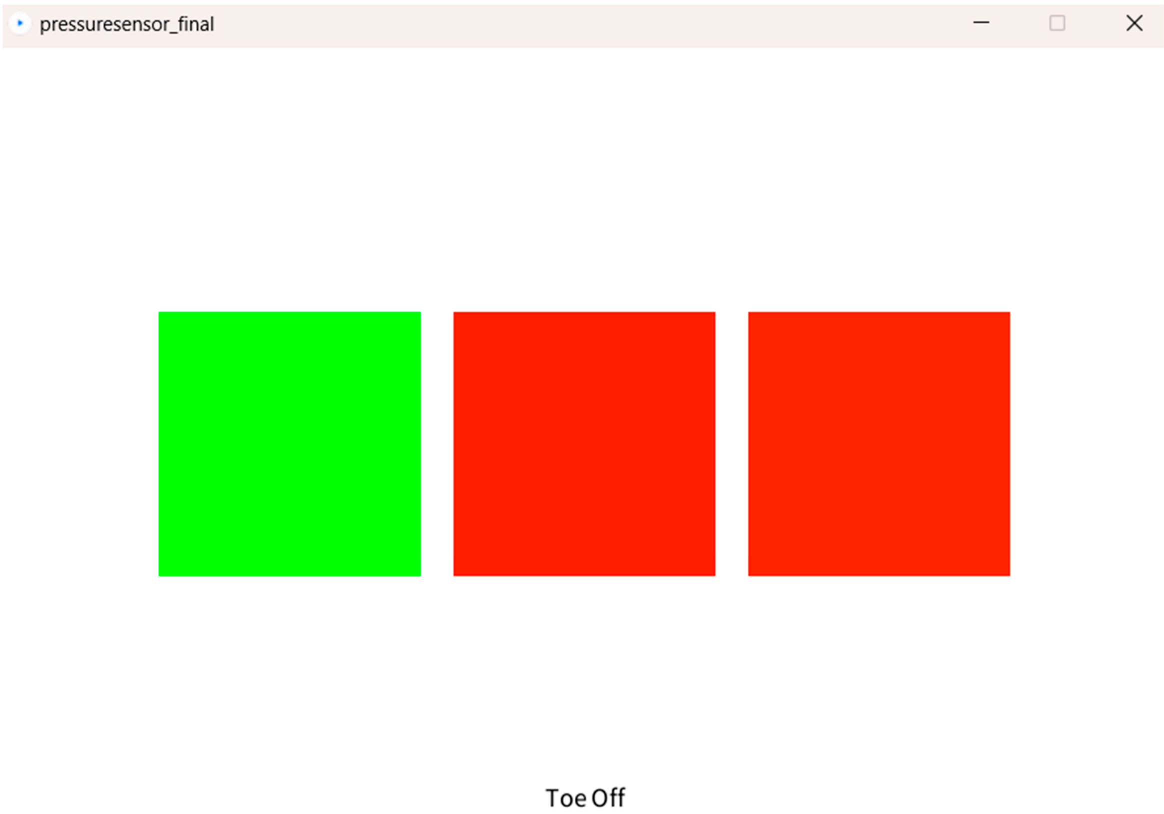

Figure 13. Toe Off.

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Figure 14. Flat Foot Detected.

7.2. Visualizing FSR Readings Via Processing

For the ADXL345 accelerometer, the Processing application visualized foot orientation and movement dynamics using graphical representations such as line plots or 3D animations. Changes in acceleration along different axes were depicted in real time, allowing users to monitor foot movement patterns, detect deviations from normal gait, and assess balance and stability.

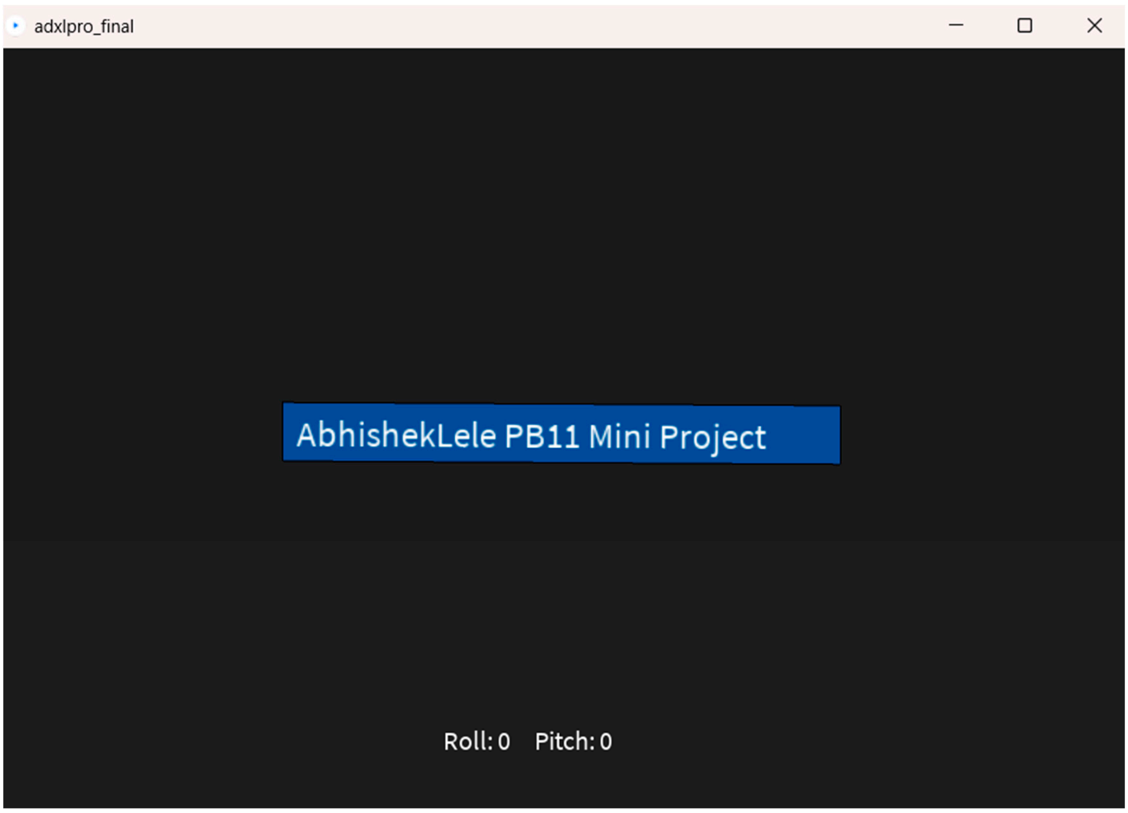

Figure 15. ADXL345 at idle condition.

Figure 16. ADXL345 at operating condition.

8. Annexure

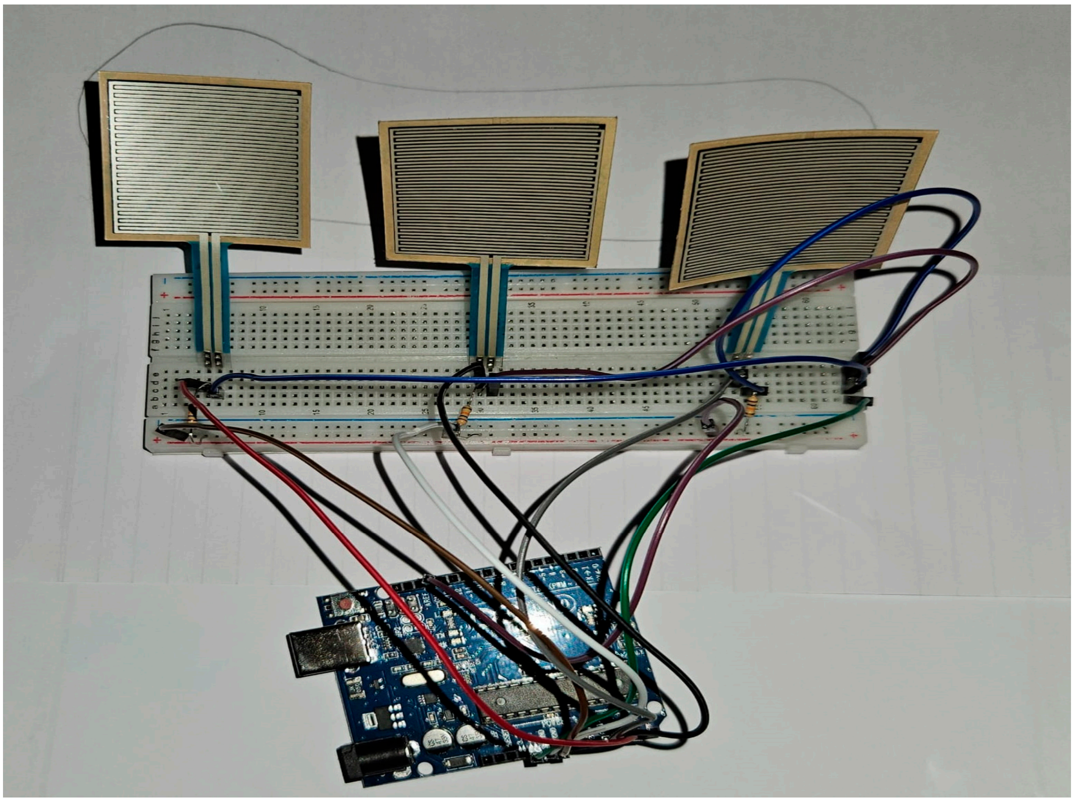

Figure 17. Actual Mock-up of Smart Insole Using FSR and ADXL345.

9. Conclusion and Future Scope

The development of the Smart Insole mock-up represents a significant milestone in the journey towards realizing wearable technology solutions for monitoring foot biomechanics and enhancing human performance. Despite its status as a prototype, the mock-up demonstrates promising functionality and potential applications in healthcare, sports performance analysis, and rehabilitation.

Through meticulous design, integration, and testing, the Smart Insole mock-up successfully showcases the feasibility of incorporating Force Sensitive Resistors (FSRs), an ADXL345 accelerometer, and an Arduino Uno R3 microcontroller unit (MCU) into a wearable form factor. While accurate testing was not feasible at this stage, preliminary assessments confirmed the proper functioning of the system components at a small scale, laying the groundwork for further development and refinement.

The integration with the Arduino IDE and Processing application enables real-time data acquisition, processing, and visualization, enhancing the usability and interpretability of the Smart Insole prototype. By seamlessly integrating sensor data with graphical representations, the prototype offers valuable insights into foot pressure distribution, orientation dynamics, and gait patterns.

Moving forward, comprehensive testing and evaluation of the Smart Insole prototype will be pursued to validate its performance, accuracy, and reliability under diverse conditions. This will involve collaboration with domain experts, healthcare professionals, and end-users to ensure that the prototype meets the needs and expectations of its intended users.

References

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