# Portable Gait Analysis Device

M. Sai Srinivas Tatwik, M. Vishnu Bhargav, N. Danis R.P. Sriram, and S. Sabareesh Karthick

*Abstract*— **Design and development of a portable device to detect abnormal walking parameters and collect data that doctors can analyze and come up with treatments to correct the patient's abnormal gait pattern**

*Clinical Relevance*— **The traditional methods for gait analysis and the existing devices used in the process are too expensive, involve complex machinery, and are huge, making it inaccessible to the general population. The portable device being built is aimed at resolving these limitations without compromising data accuracy, making it a better alternative.**

## I. INTRODUCTION

Team SoulTech is dedicated to applying engineering knowledge to develop innovative and practical solutions that benefit the healthcare industry. One of their latest endeavors involves creating a portable embedded system for gait analysis that provides real-time therapy feedback to doctors and patients at the Barrow Institute. Gait analysis is essential to diagnosing walking abnormalities and devising treatment plans for patients. However, traditional gait analysis methods can be costly and time-consuming, limiting accessibility for many individuals. The invention of gait analysis socks or shoes offers a more cost-effective and accessible solution for stakeholders and clients seeking to analyze their gait. By utilizing specialized sensors to capture real-time data on an individual's walking patterns, these devices provide valuable insights into gait mechanics that can help improve overall walking patterns and balance. In this way, the development of gait analysis socks or soles has the potential to revolutionize the field of gait analysis and improve the lives of many individuals.

## II. BACKGROUND

### A. Normal Gait

Gait is the continuous movement pattern that constitutes a person's walking or running motions. The process of walking makes use of different structures of the central and peripheral nervous systems, which can be summarized into 8 phases [1] of a cycle, i.e.,

1. **Initial Contact** is when the leading foot touches the ground and both feet are on the ground. Ideal gait shows 20 degrees of hip flexion and neutral alignment in the knee and ankle.

2. **Loading Response:** This is the transition phase from double-leg to single-leg weight bearing and shock absorption. For ideal gait, hip, and knee flexion should be 20 degrees, and there should be 5 degrees of plantar flexion in the ankle.

3. **Midstance:** Begins when the non-stance foot lifts and ends when the non-stance shin is vertical and both hips and knees are extended (20 degrees to neutral). The ankle starts at 5 degrees of plantar flexion and ends at 5 degrees of dorsiflexion.

4. In **Terminal Stance**, hip extension at 20 degrees, neutral knee, and 5-10 degrees ankle dorsiflexion occurs as the stance foot lifts and the non-stance foot touches the ground.

5. **Pre-swing**: Begins with non-stance foot contact, and ends with stance leg toe-off. The hip starts at 20° extension and moves back to neutral. The knee moves from neutral to ~40° flexion. The ankle moves from 10° dorsiflexion to 20° plantar flexion.

6. **Initial Swing**: Begins with swing foot lift, and ends when the foot is parallel to the other leg. The hip moves from neutral to 10° flexion, the knee bends to 40-60° flexion, ankle decreases from 20° plantar flexion to 5°.

7. **Mid Swing** starts with swing foot passing stance leg, ending with shin vertical. 20-degree hip flexion, 30-degree knee flexion, and neutral ankle occur.

8. In **Late Swing**, the hip flexes at 20 degrees and the knee moves to the neutral position as the swing leg is brought forward for the next gait cycle. The neutral ankle is maintained until the next cycle. Neurological or musculoskeletal factors can affect gait and balance.

### B. Demographics Of Affected

Disorders of gait are frequent in older adults, and their occurrence increases with age. About 30 percent of 60-year-old and older community-based adults have gait disorders. Among adults aged 80 years and older, the rate is 60 to 80 percent [2]. Gait disorders are associated with reduced mobility. Neurological gait disorders in particular are associated with repeated falls, poor cognitive function, and poor quality of life [3].

### C. Abnormal Gait and its types

A wide range of conditions like injuries to the legs or feet, arthritis, infections in the soft tissue of the legs, broken bones in feet and legs, birth defects, infections in the inner ear, cerebral palsy, stroke, tendonitis, conversion disorder, or other psychological disorders that may lead to gait deviations [4]. Some of the major deviations include:

**Antalgic**: A gait dysfunction where an injured leg is bearing all the weight caused by arthritis or a traumatic injury leading to slow and short steps or limping.

**Ataxic**: This results in erratic and inconsistent foot placement, often seen in people with Multiple sclerosis, stroke victims, and drug or alcohol intoxication.

**Parkinsonian**: Affects people with Parkinson's disease making them take short, shuffled steps with difficulty to start or stop walking.

**Steppage**: This is a type where the affected person cannot lift their foot from the ankle. They need to lift the affected leg higher, so the toe clears the ground when walking. It is seen in people with Lumbar radiculopathy, Neuropathy, and muscle weakness related to stroke.

[1]*Research and development is supported by Arizona State University and Barrow Neurological Institute.

**Vestibular unsteadiness:** This leads to people walking unsteadily, often falling to one side caused by Vertigo, Meniere's disease, and Labyrinthitis.

**Waddling**: Individuals with this type of impairment walk on their toes and wobble from side to side, usually because of conditions such as Muscular Dystrophy, muscle disease, and weakness in the muscles of the hips and thighs.

*D. Treatment Processes*

Treatment of gait disturbances initially involves diagnosing the underlying cause, and based on its severity, different plans like gait training, medications, assistive devices, deep brain stimulation, or multimodal rehabilitation can be incorporated. The most common form of treatment involves a set of exercises that improve motion in lower extremity joints, improve strength and balance, and, as a result, correct the gait abnormality.

In gait training, the therapist first performs gait analysis. The parameters in the analysis may include anthropomorphic data like height, weight, or BMI. spatial-temporal data like step and stride length, cadence, velocity, and pressure at first contact, and other data like the angle of different joints during movement.

Gait restoration is a crucial goal in neurological rehabilitation and requires a thorough evaluation before therapy. Various therapy methods, including force exercise, spasticity reduction, and musical biofeedback, are chosen based on the patient's needs. The spectrum of already available treatments can now be expanded to include locomotor medication, treadmill training with partial body weight support, and a targeted reduction in spasticity with botulinum toxin injections [7].

*E. Measurement methods in clinical gait analysis*

The methods of conducting gait analysis can be mainly categorized into four categories:

- Vision based
- Sensor based
- Electro goniometer or Magnetic systems.
- Combination of the three [5]

The patient's manner of walking can be analyzed based on factors such as the length of each step, stride length, pace, time between steps, and joint angles. Clinical gait analysis employs various techniques, including

- "Computerized video cameras to show movement in slow motion.
- Markers placed on the skin to monitor motion on the camera.
- Sensors on a platform to measure footstep pressure and stride length.
- Electrodes placed on the skin to monitor muscle movement.
- Infrared markers to measure joint movement in three dimensions" [6].

In some situations where balance is an issue, assistive aids like canes and walkers may be useful. In other situations, physical therapy and strengthening exercises may be necessary to increase balance, strength, and flexibility. It might be necessary to use leg braces or in-shoe splints to maintain normal foot alignment. A shoe raise may be used if the legs are not the same length.

If the cause of the irregular gait is addressed, the patient may regain some of their functions. For individuals with osteoarthritis, surgery or the use of prostheses such as hip and knee replacements may be recommended [8]. As an aid, the exoskeleton is an external structural mechanism with joints and linkages that are similar to those found in the human body. These wearable robots give consistent, stiff control along joint trajectories throughout the whole gait cycle. This implies that the patient receives assistance both during crucial gait phases and during periods during which support is not required [9].

Robotic-assisted Gait Training (RAGT) systems are alternatives to powered exoskeletons. Assistive movement strategies for people with Parkinson's disease (PD) can improve walking and balance through external cues such as white lines or rhythmical beats, compensating for hypokinesia and allowing for longer and faster steps. Cognitively intact individuals with PD can take longer steps by focusing their attention [10].

*F. Challenges of the problem*

Major challenges hindering the process of gait rehabilitation are

- The accuracy of the equipment used for gait analysis.
- The ability of the person to complete the rehabilitation process and the accessibility of the equipment.
- The severity of the gait deviation is based on the underlying cause.

To estimate gait moments the most challenging problems that the team found are:

- Complexity of the human body
- Variable gait patterns among everyone
- And noise and interface of the sensors

## III. RELATED WORK

*A. Established competitors*

**Competitor (Smart Insole): Feetme**

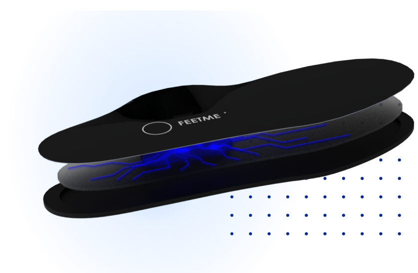



Figure 1. Feetme [11]

Description**:**

Costing around $640.00, Feetme is a fully functional professional mobility device that can be installed and used with ease. It involves integrating pressure and motion sensors into the insoles of shoes, which accurately calculate a set of gait parameters with each step. This device includes a Li-ion battery, which takes 2 hours and 30 minutes to fully charge. It has an active mode autonomy of 16 hours and utilizes Bluetooth connectivity. It also includes protective disposable over-soles for cleaning purposes. It can provide real-time spatiotemporal and pressure data and can analyze various gait parameters such as pace, rhythm, variability, asymmetry, posture, and dynamics [11].

Sensors Used:

- 6-axis motion sensors/IMU (Inertial Measurement Unit)
- 18 pressure sensors
- Gyroscope
- Acceleration sensor

Advantages and disadvantages:
The product provides real-time analysis and bio-feedback during exercise through visual, vocal, or haptic feedback. It complies with medical electrical equipment safety standards, ensuring safe and effective use for a wide range of individuals. It is highly durable, with an IP55 rating for water and dust resistance, and offers wireless connectivity and internal storage. The product is currently available in sizes ranging from 35 to 46, which may be a limiting factor for some individuals [11].

**Competitor (smart socks): Sensoria Smart Socks**

Figure 2. Sensoria Smart Socks [12]

Description:

Sensoria Fitness Socks are smart socks that measure gait and running metrics. The socks have textile pressure sensors and a detachable anklet that collects data on foot landing, stride length, and cadence. The data is sent to a smartphone app via Bluetooth. The app provides real-time feedback and coaching to help improve running form and also tracks steps taken, distance traveled, and calories burned. The socks are comfortable, made of a breathable material, and are available in different sizes [12].

3 sensors at 3 key positions:

- Plantar pressure sensor(flexible textile pressure sensors)
- Hallux (big toe) pressure sensor- for measuring the push-off phase of stride
- The detachable anklet contains an accelerometer and a gyroscope

Advantages and disadvantages:

The product provides accurate gait analysis and multi-functionality, tracking metrics such as cadence and calories burned. It features washable moisture-wicking fabric for a cool and dry exercise experience. However, it has limited battery life and may not provide pressure distribution across the entire foot. Users may experience inaccurate readings, particularly with distance tracking, and compatibility may be an issue with some devices. The product is primarily designed for running and may not be suitable for clinical use [12].

**Research (Smart Insole): A wireless flexible sensorized insole for gait analysis.**

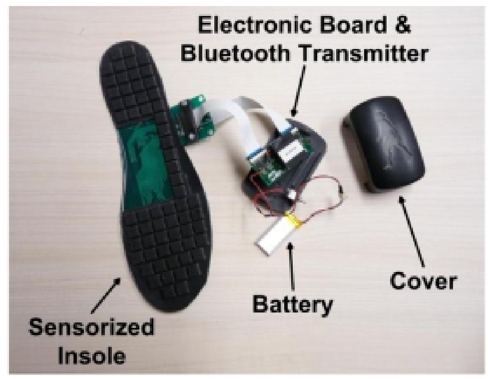



Figure 3. Wireless sensorized insole for gait analysis [13].

Description:

A pressure-sensitive flexible foot insole system for monitoring pressure distribution during walking. The system was experimented on two normal subjects and was compared with results from an instrumented force platform: The developed system had quantitative disparities when compared with the force platform but has a high qualitative correlation. A transduction unit consisting of a black-dyed silicone layer divided into 64 cells and a 0.2mm PCB housing the optoelectronic components. An electronic board consisting of four ADC, STM32F103x8 microcontrollers, power, and communication socket. Data transmission to a remote device is done through Bluetooth at a sampling rate of 100Hz [13].

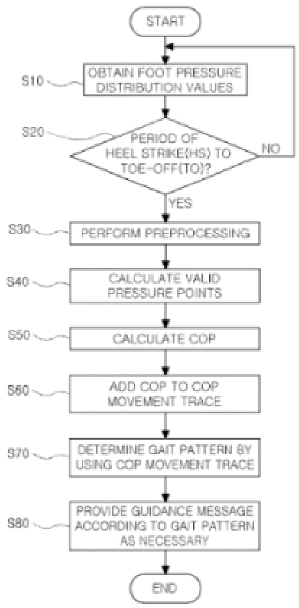
Advantages and disadvantages:

The product is a reliable tool for estimating Vertical Ground Reaction Force (vGRF) and is non-sensitive to humidity and temperature. It does not require amplifiers and is designed with a small electronic board. However, it uses a unique calibration curve for the sensors that may affect the estimation of vGRF and potentially lead to inaccuracies. The noise threshold applied to the sensors may also result in errors in the estimation of vGRF.

**Patent (Smart sole): Method and apparatus for analyzing gait pattern**

Description:

Sole-like Apparatus to measure gait pattern and provide instructions for guiding the user.Valid pressure points are calculated by the data from the sensor by eliminating the pressure lower than the threshold and calculating the center of pressure (COP). The COP movement trace from heel strike to toe-off is used to find the gait pattern. The process is shown in the figure below. Many Force Sensing Resistors (FSR) are aligned together as an array in a sole as shown in Figure 12 and it is connected to a center of pressure (COP) movement trace calculation unit, a gait pattern correction unit, a gait pattern determining unit, and an alarm unit. It is also connected to a wireless unit that sends data to a computer [14].



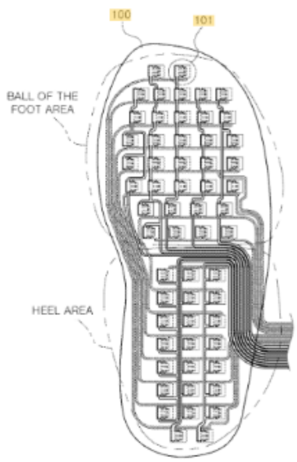




Figure 4. Process Graph [16]    Figure 5. Pressure Sensor Array [16]

Advantages and disadvantages:

The product can measure and identify every gait type and features wireless data transfer and an inbuilt alarm unit. However, it relies on assumed pressure rather than providing direct pressure data, which may affect its measurement accuracy. It does not offer biofeedback and spatial data such as stride length or foot placement is not provided, limiting its usefulness for some applications. Additionally, the product may not be easy to wash, which could be a concern for hygiene-conscious users [14].

## IV. PROPOSED APPROACH

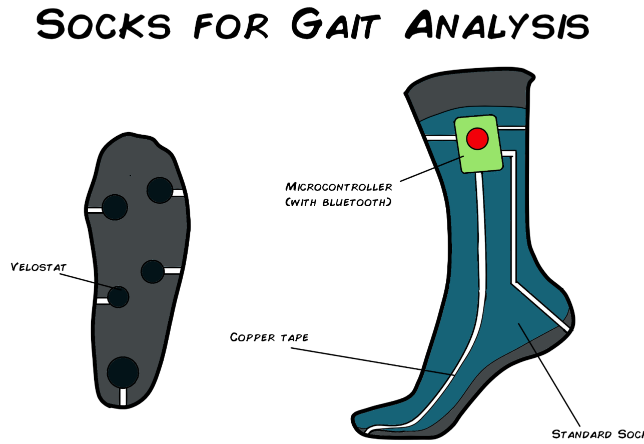



Figure 6. Concept for Sock Gait Analysis

As per the client's preference, the team has decided to go with a sock system. The ideal product includes Pressure-sensitive socks made of washable and comfortable microfibre laced with Velostat (a thin pressure-sensitive material) to relay the data required to the microcontroller through copper strips. In addition, the detachable casing that contains the microcontroller, IMU, and a linear vibration motor for feedback minimizes recurring costs. With real-time therapy feedback capabilities, the device is poised to revolutionize gait analysis for both doctors and patients. The device is designed to be highly compact and portable without compromising accuracy, is user-friendly, and ensures accessibility to all users.

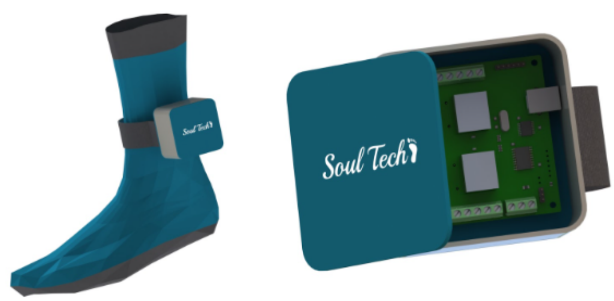



Figure 7. 3D Renders of the Sock Gait Analysis.

Components used to build the prototype include Arduino Nano 33 IoT, LSM9DS1 (Inbuilt IMU), 3.7V Rechargeable Battery, Sole Pressure Sensor, and Linear Vibration Motors. The Gait Characteristics Calculated by the integration of these components are Pressure distribution, Stance time, Point of contact, Stance, Stride, Length, Stride Width, Cadence steps per min, and Spatial Characteristics.

## V. IMPLEMENTATION

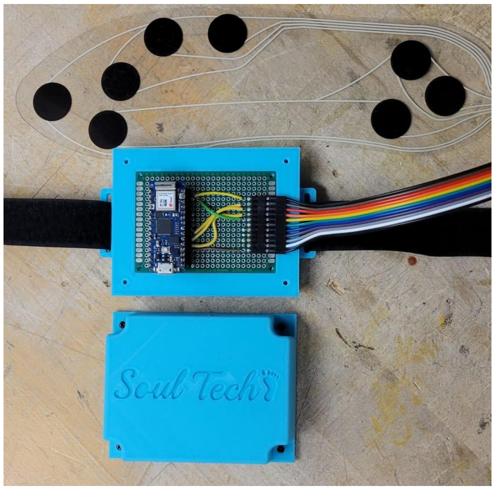



Figure 8. Casing, PCB, and Sensors

The team used Solidworks to visualize and conceptualize the product design. In this design, the team incorporated a portion of the smart sensing sole concept. The device's housing encapsulated the printed circuit board (PCB) that includes the microcontroller, sensors, and actuators. The PCB acted as the backbone of the device, facilitating integration and communication between various components. The vibrator motor served as the actuator for the bio-feedback, to provide physical cues to the user based on the pressure measurements obtained from the system. Overall, the team's design aimed to provide a robust and effective solution for a portable gait analysis device.

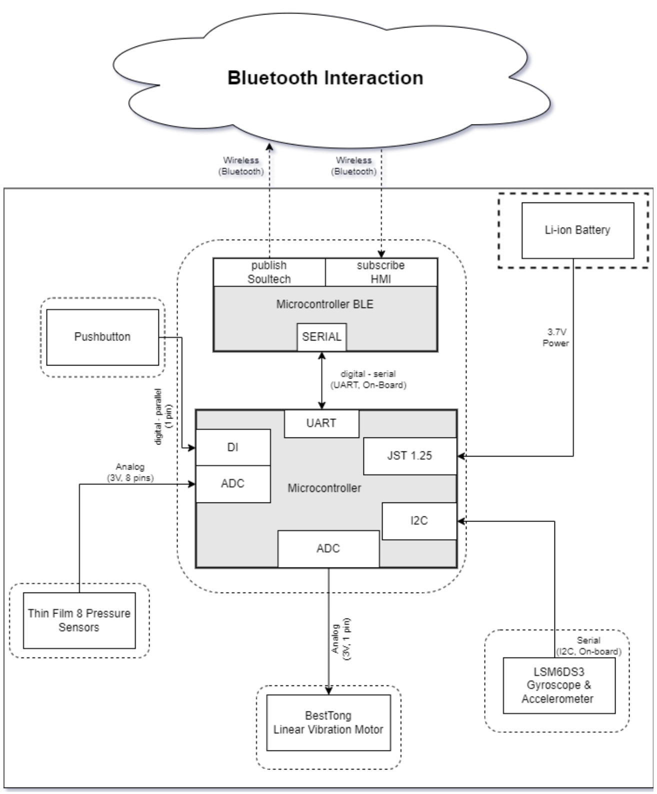



Figure 9. Electrical Block Diagram of the Sock Gait Analysis.

Presented here in Figure 8 was the proposed block diagram of the system. To facilitate the control and communication aspects of the device, the Arduino Nano 33 IoT is selected as the microcontroller. Operating primarily on a 3.3V power supply, this microcontroller was the main processing unit for the system.

8 Analog Input pins are used to obtain the pressure readings. Additionally, an analog pin was used for the haptic feedback with a linear vibrator motor. An in-built IMU was incorporated into the system which enabled the team to obtain precise measurements of the orientation and movement of the device. Furthermore, to enhance the user experience and enable a more user-friendly interface, Bluetooth connectivity was also implemented. This allowed for seamless smartphone communication, enabling the user to monitor and control the device.

The combination of the Arduino Nano 33 IoT, pressure sensor, haptic feedback vibrator motor, accelerometer, and Bluetooth connectivity enabled team SoulTech to build a highly efficient and user-friendly system for pressure measurement and gait analysis.

The figure below illustrates the software diagram.

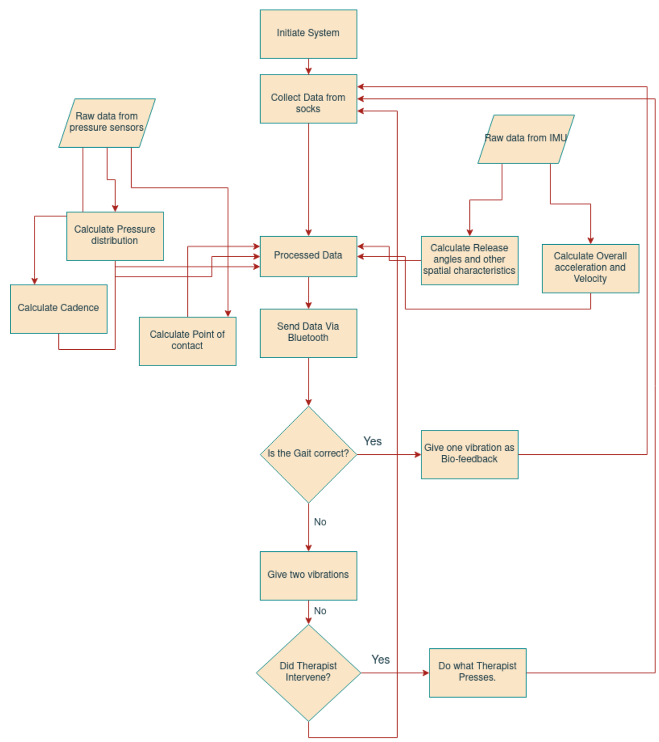



Figure 10. Software Diagram

As the patient walks using the Gait Analysis sock, the doctors can analyze the pressure applied, time information, and spatial characteristics of the feet. Utilizing pressure sensors, the system records the pressure distribution, initial point of contact, and angle of the foot. By employing a complementary filter that combines pressure distribution and accelerometer data (modified with homogeneous transformation), the angle of the foot on the ground can be calculated while the sensor is attached to the ankle. The IMU data can further aid in determining spatial characteristics and cadence.


Figure 10. Final Product

## VI. FUTURE WORK/RECOMMENDATIONS

Since this is currently a working prototype, future iterations can focus on improving data accuracy and integrating the device with a sock for potential use in clinical settings or commercial sales.

1. Using Advanced Microcontrollers

Arduino Platform is great for straightforward tasks but fails when burdened with huge data and when accurate data is expected as its computational abilities are very limited. The team could explore more microcontrollers such as Raspberry, on the other hand, offers a better platform as it can handle larger complex data, handle multiple tasks concurrently, and integrate additional functionalities, such as advanced algorithms, communication protocols, or even graphical user interfaces.

2. Implementing advanced filtering algorithms:

Sophisticated filtering algorithms can improve the accuracy of gait analysis by reducing noise in data. AI techniques like machine learning and signal processing can be used to develop these algorithms, which can adjust to various data scenarios, ensuring accurate results for different patients and settings.

3. Detecting patterns and predicting future gait changes:

Applying machine learning algorithms to gait data can identify recurring patterns, anomalies, and changes over time, which can help detect potential problems, monitor treatment success, and develop customized rehabilitation programs. Predicting and modeling future gait changes can also be accomplished using AI techniques like time-series analysis and recurrent neural networks. These prediction programs can anticipate issues before they arise by analyzing past gait data, allowing healthcare practitioners to intervene proactively, modify treatment plans, or offer advice to patients. This has the potential to enhance patients' long-term health and mobility.

4. Integration with other wearables and IoT devices:

A more thorough view of a patient's general health and activity levels can be obtained by expanding the system to incorporate data from additional wearable devices, such as smartwatches or fitness trackers. By integrating IoT devices, healthcare professionals, patients, and researchers can share data and monitor patients remotely. Better decisions, more individualized care, and greater health outcomes can all be facilitated by this connected environment.

## APPENDIX

For a more detailed understanding of the algorithm and implementation of the device, please refer to the following link: https://github.com/Tatwik19/SoulTech-Portable-Gait-Analysis-Device.

## ACKNOWLEDGMENT

The authors would like to express their sincere appreciation to Professor Troy McDaniel, the team's mentor, and EGR 555 Mechatronic Systems class professor. His invaluable guidance, expertise, and support throughout the project were greatly appreciated. The authors would also like to extend their gratitude to Joelly Lobato De Faria and Kyle Sandoval, health practitioners at Barrow Institute, for serving as clients and main customers. Their insights, feedback, and direction provided invaluable support for the project's success.

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