

ECE 445  
SENIOR DESIGN LABORATORY  
PROJECT PROPOSAL

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**StepWise: A Smart Insole System for  
Offline Gait Analysis and Muscle  
Rehabilitation**

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# 1 Introduction

StepWise addresses a persistent challenge in rehabilitation and preventive care: clinicians and users often lack continuous, objective gait data outside controlled lab settings. Existing gait assessments are periodic, expensive, and difficult to access, while many wearable products provide limited biomechanical insight and weak linkage to actionable muscle-training feedback.

## 1.1 Problem

Despite walking being the most fundamental human movement, the majority of the population suffers from undiagnosed gait abnormalities. These include structural issues such as Pes Planus (Flat Feet), functional misalignments like foot valgus or varus, over-pronation, and irregular strike patterns—often manifested as in-toeing or out-toeing. When coupled with muscular imbalances like Tibialis Anterior weakness, these conditions lead to a ‘kinetic chain’ of health failures.

When a person suffers from improper heel-to-toe transition, the misalignment doesn’t stay in the foot. It forces the ankles to roll unnaturally and places compensatory stress higher up the chain, resulting in knee hyperextension, genu varum, or genu valgum. These issues force the knees to rotate unnaturally and the pelvis to tilt, creating a primary driver for chronic lower back pain, hip bursitis, and premature osteoarthritis. Because these issues develop slowly over years, most individuals do not realize their walking posture is the root cause until permanent joint damage has occurred.

## 1.2 Solution

StepWise is a 3D-printed smart insole designed to serve as a portable, test-based gait screening and rehabilitation-support ecosystem. The hardware integrates a 5-point pressure sensor array and a tri-axial (XYZ) inclinometer to log high-fidelity biomechanical data during specific walking trials. Unlike continuous monitors, this system focuses on capturing precise data snapshots of plantar pressure distribution and spatial foot orientation. During a test session, the biomechanical data is streamed via Bluetooth to a mobile application for logging. Following the session, offline algorithms on the app analyze the gait cycle to identify pathologies such as Pes Planus, foot valgus/varus, and Tibialis Anterior muscle weakness, providing an offline screening report and targeted exercise recommendations.

## 1.3 Benefits

By moving structured gait screening and rehabilitation support out of the lab and into a portable insole, StepWise empowers clients with a deep understanding of their unique biomechanical profile through a simple, non-invasive test. For individuals dealing with Pes Planus (Flat Feet), foot valgus, or Tibialis Anterior weakness, the system provides an objective “gait signature” that visual observation alone cannot capture. By identifying

these subtle misalignments—such as in-toeing or knee hyperextension—StepWise acts as an early warning system, allowing users to intervene before the “kinetic chain” reaction causes permanent damage to the knees, hips, and lower back. Ultimately, clients benefit from a clear, data-driven roadmap to recovery: a personalized screening report paired with targeted exercises that transform their walking posture from a source of chronic pain into a foundation of long-term musculoskeletal health.

## 1.4 Features

StepWise disrupts the gait analysis landscape by bridging the gap between high-cost clinical labs and passive orthotics through a portable, 3D-printed screening and rehabilitation-support ecosystem. While traditional systems like Vicon or GAITRite are cost-prohibitive and confined to specialized facilities, StepWise utilizes a strategic sensor fusion of a 5-point pressure array and an XYZ inclinometer to capture high-quality biomechanical data during a simple, short-duration test. Unlike standard orthotic inserts that act as a passive “crutch”—supporting the arch while potentially weakening the surrounding musculature—StepWise facilitates active rehabilitation. By identifying specific pathologies such as Pes Planus and Tibialis Anterior weakness, the system provides users with a data-driven roadmap of personalized exercises designed to actively strengthen the foot and correct the kinetic chain, rather than merely masking the symptoms.

## 1.5 High-level Requirements List

1. The first requirement is end-to-end data integrity during standardized walking trials. The insole and app pipeline shall capture complete, time-aligned sensor streams from all pressure channels and the XYZ inclinometer, with no more than 5% packet loss per session and no channel-level dropout longer than 1 second. This requirement focuses on data availability and transmission stability.
2. Hardware baseline validation shall be performed using accessible bench-top references rather than expensive motion-capture labs. Pressure sensors shall be tested with standard weights under static and repeated-loading conditions, and the inclinometer shall be tested with a protractor or fixed-angle jig under static and slow-tilt conditions. The system shall report RMSE and repeatability for each channel, with target performance of pressure error  $\leq 5\%$  (static), pressure error  $\leq 8\%$  (dynamic), angular error  $\leq 2^\circ$  (static), and angular error  $\leq 3^\circ$  (dynamic).
3. Software-side validation shall focus on whether the mobile app can reliably receive and correctly classify offline test data. The team shall use labeled simulated gait datasets (including normal gait, flat-foot-like pressure patterns, and valgus/varus-like loading asymmetry) to verify the full data pipeline. Target performance shall be  $\geq 95\%$  successful packet/session parsing and  $\geq 90\%$  classification accuracy on the labeled validation set.

## 2 Design

The design translates project requirements into a wearable sensing system that is physically robust, computationally efficient, and easy to evaluate. This section presents the two primary diagrams used for system communication and verification.

### 2.1 Physical Diagram

Figure 1 shows the physical architecture and hardware placement of the StepWise system.

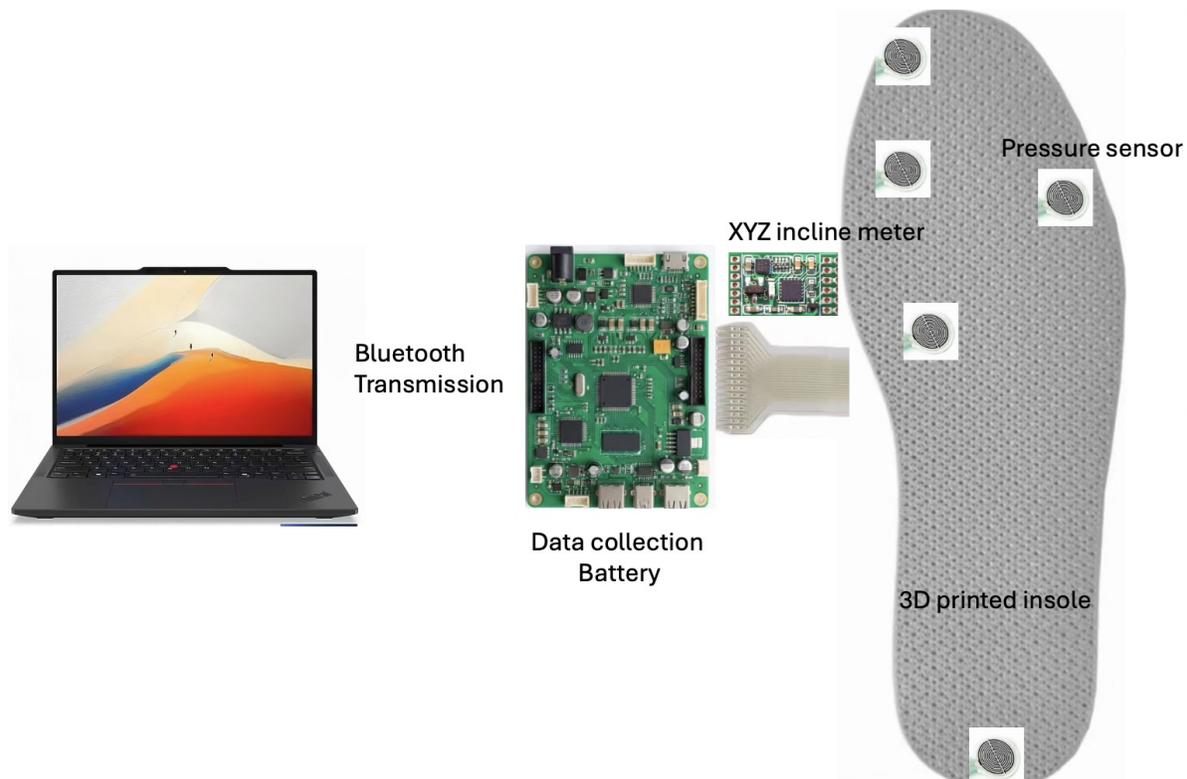


Figure 1: StepWise physical diagram.

### 2.2 Block Diagram

Figure 2 shows the functional signal flow from sensors to processing and output.

### 2.3 Descriptions & Requirements of Diagrams

The diagrams are used as engineering baselines and must satisfy the following requirements.

1. The physical diagram shall identify all major hardware modules and interconnections.

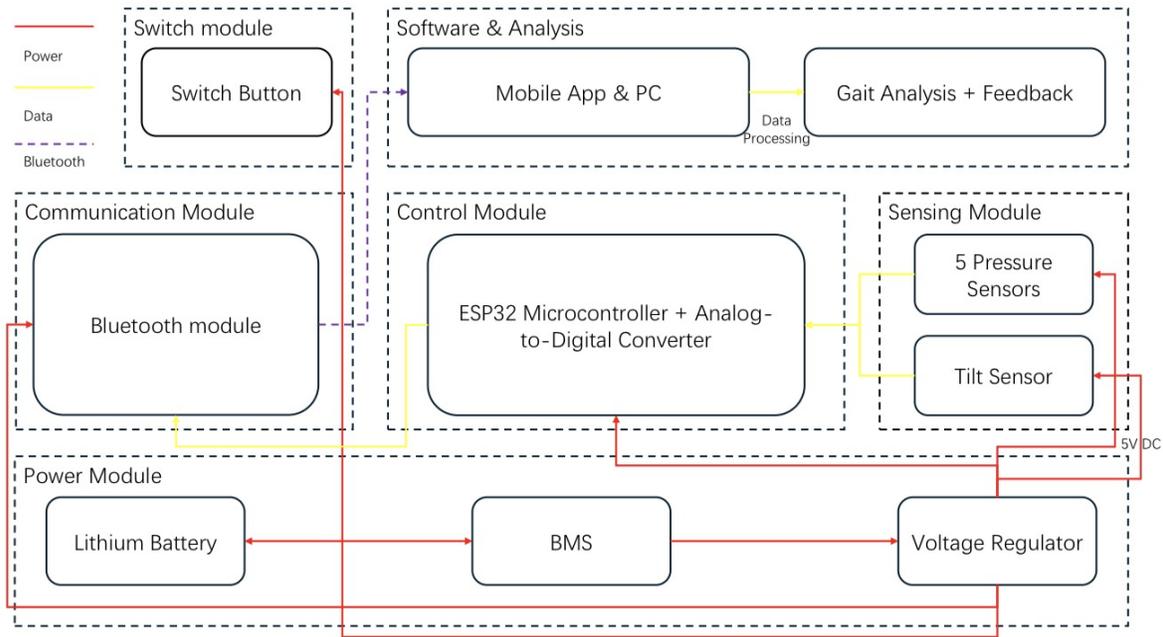


Figure 2: StepWise block diagram.

2. The block diagram shall show the end-to-end data path from sensing to output metrics.

### 2.3.1 Power Module

The power module manages the energy requirements of the system, providing regulated DC voltage to the MCU and sensor array.

- **Energy Storage:** A high-energy-density Lithium-Polymer (Li-Po) battery (minimum 150–300 mAh) is utilized to support multiple discrete diagnostic sessions.
- **Voltage Regulation:** A high-efficiency Low Dropout (LDO) regulator steps down the battery voltage to a stable 3.3V for digital logic and analog reference.
- **Protection:** An integrated Protection Circuit Module (PCM) ensures safety against over-discharge, over-charging, and short-circuit conditions.

### 2.3.2 Control Module

The control module serves as the central processing unit, managing data acquisition, signal conditioning, and local buffering.

- **Processing:** An ESP32 series microcontroller (e.g., ESP32-WROOM) operating at up to 240 MHz handles concurrent sampling of the sensor inputs and manages wireless communication.

- **Interfacing:** The module utilizes five 12-bit Analog-to-Digital Converter (ADC) channels for pressure sensing and one  $I^2C$  bus for spatial orientation data.
- **Form Factor:** A QFN or Wafer-level package is specified to minimize PCB surface area for integration within the insole architecture.

### 2.3.3 Sensing Module

The sensing module converts mechanical interactions and foot orientation into digitized electrical signals.

- **Pressure Array:** Five Force-Sensitive Resistors (FSRs) are strategically positioned to capture plantar pressure distribution from 0.1N to 100N.
- **Spatial Orientation:** A tri-axial ( $XYZ$ ) inclinometer (IMU) provides angular data with an accuracy of  $\pm 1^\circ$  to detect inversion/eversion (valgus/varus) pathologies.
- **Sampling Dynamics:** All channels are sampled at a minimum rate of 50 Hz to accurately reconstruct the human gait cycle.

### 2.3.4 Bluetooth Module

Wireless connectivity is managed via a Bluetooth Low Energy (BLE) subsystem, often integrated into the MCU System-on-Chip (SoC).

- **Standard:** BLE 5.0 or higher is utilized to ensure high throughput during data burst transfers while maintaining low standby power.
- **Communication Range:** Stable data transmission is maintained within a 2–5 meter radius between the insole and the mobile diagnostic application.

### 2.3.5 Transmission Protocols

The system employs a dual-layer protocol architecture to facilitate internal hardware communication and external wireless data synchronization.

#### Internal Data Acquisition Protocols

- **$I^2C$  (Inter-Integrated Circuit):** The tri-axial inclinometer communicates with the master MCU via the  $I^2C$  protocol. The bus operates in **Fast Mode (400 kbps)** using a standard Master-Slave architecture to pull 16-bit data from the sensor registers.
- **Analog Sampling (ADC):** The five pressure sensors are interfaced via Successive Approximation Register (SAR) ADCs. The analog voltage from the resistive divider circuits is converted into a 12-bit digital value representing local pressure magnitude.

**External Wireless Protocol: BLE GATT** Wireless transmission follows the **Generic Attribute Profile (GATT)** standard, organizing the diagnostic data into specific Services and Characteristics:

- **Gait Diagnostic Service:** A custom primary service is defined with a unique 128-bit UUID to encapsulate all diagnostic operations.
- **Data Encapsulation:** Sensor data is packaged into **Notification Packets**. Once a test is initiated, the insole (Server) pushes data to the mobile app (Client) without the latency associated with manual polling.
- **Characteristic Mapping:**
  - **Diagnostic Data Characteristic (Read/Notify):** Streams a composite payload containing the 5 pressure values (2 bytes each) and the 3-axis inclinometer data.
  - **Command Characteristic (Write):** Enables the mobile application to send control signals, such as “Start Test,” “Stop Test,” or “Trigger Calibration.”

## 3 Ethics and Safety

### 3.1 Ethics

StepWise is intended as a wearable tool for gait screening and rehabilitation support. Because it collects plantar-pressure signals, gait-phase information, and foot-orientation data, the project must address privacy, fairness, and the responsible use of algorithmic outputs. Wearable health technologies can provide useful insights, but they also introduce clear ethical risks, including sensitive data exposure, reduced user autonomy, and uneven performance across user groups [1], [2]. All design and testing procedures will align with the IEEE Code of Ethics [3], with priority given to public safety, user welfare, and harm prevention.

First, StepWise follows the principle of *data minimization*. The system only collects data needed for gait assessment and rehabilitation guidance, instead of storing unnecessary personal information. Users should be informed about what is collected, why it is collected, how long it is retained, and whether it may be used for future model improvement. Users should also be able to view, export, and delete their own records. This is important because wearable data can still carry re-identification risk even after de-identification [2].

Second, StepWise should avoid exaggerated medical claims. Smart insoles show promise for gait monitoring, disease-related assessment, and rehabilitation, but current evidence remains mixed across application settings [4], [5]. In this project, StepWise is positioned as a *screening and rehabilitation-support tool*, not a standalone clinical diagnostic device. Its outputs are meant to improve users' understanding of their gait and support safer training behavior, not replace professional medical judgment.

Third, fairness should be considered during data collection and algorithm evaluation. Reviews in digital health note that wearable performance is affected by data quality, representativeness, and health equity [1]. For this reason, the StepWise team should test users with different foot sizes, walking patterns, and body conditions as much as project scope allows. If the dataset remains limited, that limitation should be stated explicitly. Reporting only overall accuracy can hide weak performance for specific groups, so subgroup-level behavior should be examined and reported transparently.

Finally, user autonomy should remain central. The app should explain results in plain language, for example by showing pressure maps or gait-phase changes instead of only reporting a vague "abnormal" label. Users should be able to mute app notifications and stop a session at any time. These choices improve transparency and trust, and make the system more ethically responsible [1], [2].

### 3.2 Safety

Because StepWise is worn inside the shoe during walking, safety must be addressed at material, electrical, mechanical, software, and user-interaction levels. Unlike lab-only

systems, this prototype is intended for everyday environments, where usage conditions are less controlled [6].

First, the insole structure should not cause discomfort or injury. Since the device contacts the foot for extended periods, materials should reduce skin irritation risk. The 3D-printed body should avoid sharp edges, hard protrusions, and localized pressure points that could alter gait or cause pain.

Second, electrical and battery safety are essential because StepWise uses low-power electronics, Bluetooth communication, and a LiPo battery. The circuit should include basic protection against over-charge, over-current, and short circuit. Electronics should be insulated from sweat and repeated loading. The device should also avoid unsafe heat during operation or charging, and it should never be charged while worn [6].

Third, the current prototype does not include in-shoe vibration correction during walking. Because StepWise is an offline screening and rehabilitation-support tool, posture guidance is delivered after each session through app reports and exercise suggestions, rather than through real-time actuation. This design lowers distraction risk during walking and keeps behavior easier to validate for safe use.

Fourth, software and communication failures should be handled conservatively. Since StepWise depends on sensor signals, Bluetooth transmission, and app-side analysis, it should use a clear fail-safe strategy. If signals become unstable, battery level is too low, or Bluetooth disconnects, the system should stop the session and mark the data as invalid, instead of producing potentially misleading recommendations.

Finally, safety should be checked through practical prototype tests. Relevant tests include repeated compression and bending, structural inspection, short walking comfort trials, battery temperature checks, and Bluetooth stability checks. The current target of “500 compression cycles” is too low for realistic use and should be treated only as an early screening threshold, not a final durability claim. A stronger durability target would better match the intended use of a smart insole system [4]. Overall, the prototype should favor conservative behavior, clear warnings, and cautious interpretation of results to reduce avoidable risk.

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