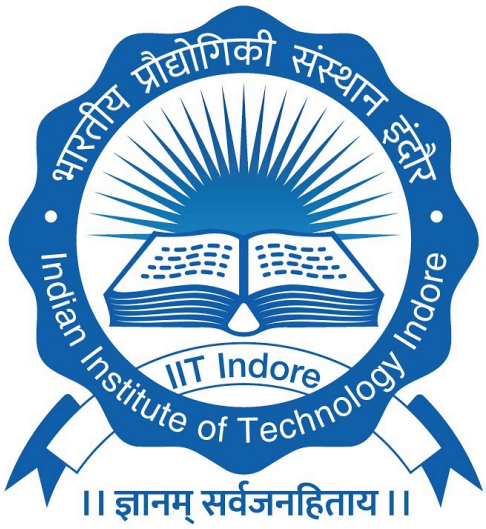
ME 309: Instrumentation and Control Systems Project Report

Early Diabetic Neuropathy Detection via Foot Vibration and Pressure Mapping



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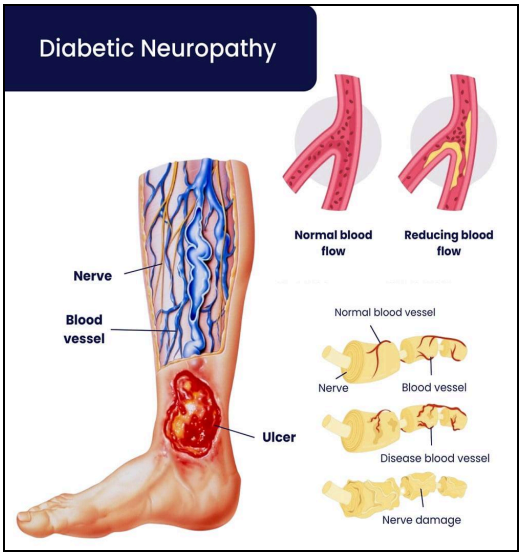
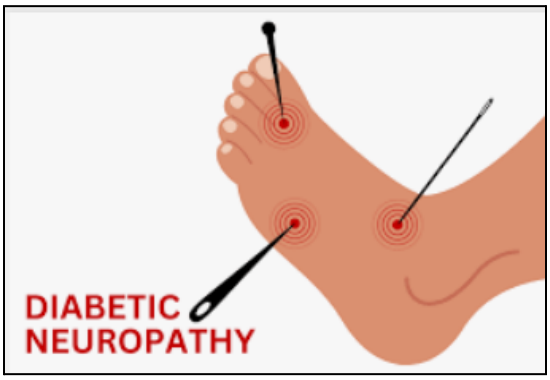
1. Introduction

Diabetic neuropathy is one of the most common and serious complications of long-term diabetes. It occurs mainly due to chronic hyperglycemia, which gradually damages peripheral nerves and leads to reduced sensory perception, particularly in the feet. This sensory loss increases the risk of plantar ulcers, infections, and even amputations if not diagnosed or treated early.



Existing diagnostic techniques—such as nerve conduction studies, MRI, skin biopsies, and monofilament testing—are accurate but expensive, invasive, or require specialized setups. These limitations make routine screening difficult, especially in rural or low-resource areas, leading to delayed diagnosis and irreversible nerve damage. Therefore, there is a strong need for a simple, affordable, and portable method for early detection.



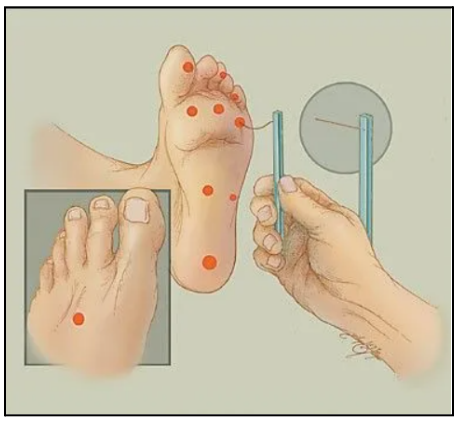
Recent studies highlight that measuring both vibration perception threshold (VPT) and plantar pressure distribution can serve as reliable early indicators of neuropathic changes. Totaganti et al. (2023) reported increased plantar pressures in neuropathic diabetic patients, while Chatzikosma et al. (2021) showed that assessing vibration sensitivity at multiple frequencies enhances diagnostic accuracy.

This project aims to develop a low-cost, portable diagnostic system that simultaneously measures plantar pressure and vibration perception threshold to assess the risk of early neuropathy. The system will generate a quantitative “risk score” to indicate neuropathic severity, enabling timely medical attention and continuous monitoring. Its main advantages include affordability (≤ ₹1000), portability, open-source design, and suitability for both clinical and home-based screening. By integrating vibration and pressure analysis, the system provides a practical step toward accessible and preventive diabetic foot care.

2. Literature Review

2.1 Overview of Diagnostic Limitations in Early Neuropathy

While diabetic neuropathy is well recognized as a major contributor to foot morbidity, a deeper examination of current diagnostic pathways reveals significant practical and technological gaps. Traditional clinical tools such as monofilament testing, tuning-fork vibration assessment, and ankle reflex evaluation are designed primarily for detecting advanced sensory loss, not subtle early changes. These methods rely heavily on examiner technique and patient interpretation, making them inherently subjective and inconsistent across settings.



Advanced diagnostic modalities—nerve conduction studies (NCS), quantitative sensory testing, or intra-epidermal nerve fiber density measurements—offer superior specificity but come with high cost, invasive procedures, and the need for trained neurologists. Consequently, early neuropathic changes often remain undetected in primary care and rural clinics, despite evidence that timely identification dramatically reduces ulcer risk and subsequent amputations. The literature consistently emphasizes that a quantitative, field-deployable, low-cost alternative is urgently needed.

2.2 Vibration Perception Threshold (VPT) in Research and Clinical Practice

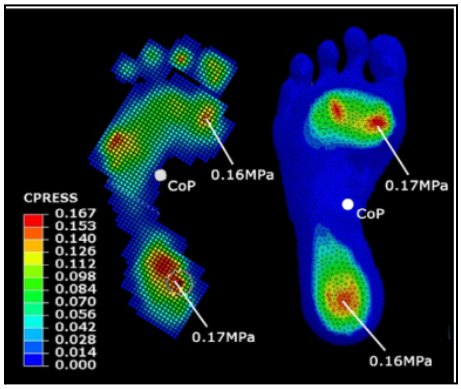
VPT measurement is recognized as one of the most reliable quantitative assessments of peripheral sensory function. Unlike monofilament tests, VPT provides a graded numerical threshold, reflecting the minimum vibratory stimulus a patient can perceive. This metric correlates strongly with large-fiber nerve degeneration and is widely used in neuropathy severity grading.

Research over the past decade has shifted focus toward frequency-specific vibration response, showing that diabetic patients may lose sensitivity at lower frequencies, even when traditional 128-Hz perception remains relatively intact. Multi-frequency vibratory assessment has been shown to improve diagnostic sensitivity for early neuropathy by capturing dysfunction in different mechanoreceptor pathways. These findings support the idea that controlled vibratory stimulation —even from a low-cost actuator—can provide meaningful diagnostic information when analyzed systematically.

2.3 Plantar Pressure Distribution as a Biomechanical Marker

Beyond sensory loss, neuropathy significantly alters foot biomechanics. Literature on gait analysis reveals that diabetic patients, particularly those with neuropathy, exhibit:

- Increased forefoot loading
- Reduced heel strike force
- Higher pressure duration in metatarsal regions
- Impaired weight-shifting and balance



These pressure abnormalities arise from both reduced sensation and intrinsic muscle weakness, producing characteristic patterns long before visible foot complications emerge. Studies consistently show that abnormal plantar pressure profiles precede ulcer formation, making them a valuable early-risk indicator. Importantly, research highlights that even a simplified measure—such as a heel-to-forefoot pressure ratio—captures clinically meaningful load redistribution trends.

Low-cost piezoresistive materials like Velostat have been repeatedly explored for pressure mapping in footwear and rehabilitation settings. Although less precise than commercial pedobarographic platforms, Velostat sensors demonstrate stable relative pressure trends and are particularly suitable for ratio-based or threshold-based diagnostics, where absolute accuracy is less critical.

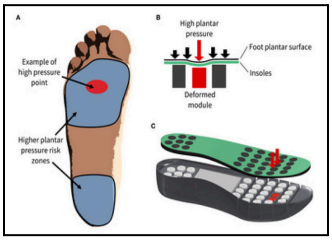
2.4 Need for an Integrated Dual-Modality Screening System

Most low-cost diabetic foot tools available today are single-modality—either pressure-sensing insoles or standalone vibration-threshold devices. Pressure-only systems identify abnormal foot loading but cannot assess sensory nerve loss, while vibration-only tools detect sensory impairment but ignore biomechanical stress patterns that precede ulceration.

Literature clearly shows that neuropathy affects both sensory pathways and plantar biomechanics, and these changes often appear independently at early stages. A patient may develop a forefoot pressure shift before measurable vibration loss, or vice versa. Therefore, relying on one indicator alone can lead to missed early cases.

Integrating:

- Vibration Perception Threshold (VPT) for sensory function, and
- Heel–forefoot pressure ratio for mechanical loading



provides a more sensitive and well-rounded assessment. Combined evaluation improves early detection, reduces false negatives, and enables a single, interpretable risk score.

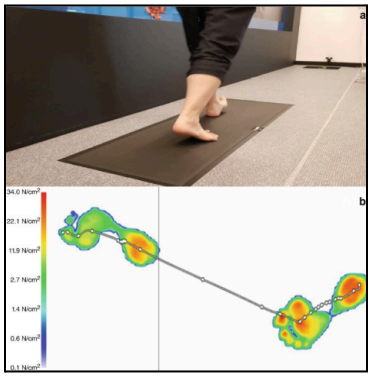
Despite strong evidence supporting this multimodal approach, the literature indicates that no existing low-cost portable device merges both vibration testing and plantar pressure analysis. This gap establishes the novelty and necessity of the system developed in this work.

3. Motivation

Early diabetic neuropathy is frequently overlooked in routine care, particularly in low-resource settings where advanced diagnostic tools are unavailable. Many patients do not undergo regular sensory assessments, resulting in neuropathic changes being detected only when complications such as callus formation, altered gait, or ulceration have already developed. This gap highlights the need for a screening solution that is practical outside specialized clinics.

Current low-cost tools tend to assess only one physiological domain—either sensory loss or plantar loading—although research shows that neuropathy affects both. A patient with developing sensory impairment may still show normal pressure distribution, while another with abnormal forefoot loading may retain near-normal vibration perception. Relying on a single metric, therefore, risks missing individuals in the earliest, most treatable stage.

Cost also remains a major barrier. Devices such as biothesiometers, pedobarographic plates, or nerve conduction instruments are expensive and clinic-bound. To enable widespread screening, especially in rural areas, the technology must be built from low-cost, easy-to-source components and remain functional without laboratory Infrastructure.



Portability and simplicity form another key motivation. A screening tool should be lightweight, battery-operated, and operable by non-specialists, allowing use in community camps, home visits, or primary health centers. The testing process must be intuitive—stand on a platform, feel a vibration stimulus—and results must be immediately interpretable.

Finally, there is a need for a single consolidated output that integrates both sensory and pressure-derived indicators. A combined “neuropathy risk score” enables clear clinical decision-making, simplifies comparison between visits, and supports long-term monitoring. This approach parallels the utility of glucometer readings, offering a straightforward numerical measure of physiological status.

4. Objective

Ensure affordability (≤ ₹1000) using open-source electronics and low-cost sensors, and develop a portable diagnostic system that simultaneously measures plantar pressure (via a heel-to-forefoot ratio) and vibration perception threshold, and fuses these parameters into a quantitative risk score for early diabetic neuropathy. The system aims to:

- Distinguish healthy from early-neuropathic profiles
- Operate reliably with low-cost hardware
- Provide a simple user interface suitable for non-specialist use
- Remain robust for repeated real-world testing
  The final prototype serves as a foundation for a deployable community-screening device and supports potential patent claims based on the novel integration of pressure and vibration sensing within a single low-cost platform.

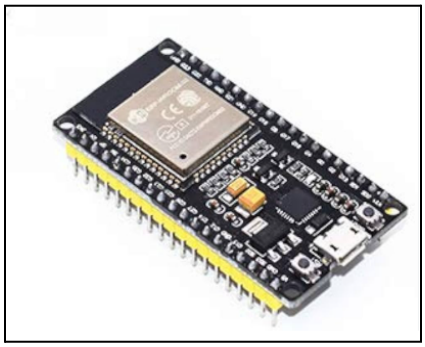
5. Methodology

To achieve the above objectives, we implemented a hardware-software system composed of a pressure-sensing platform, a vibration-stimulus module, and a microcontroller for data acquisition and processing.

The methodology spans the device design (components and circuit), the data processing algorithms (to extract neuropathy metrics), and the testing protocol. Each aspect is detailed below.

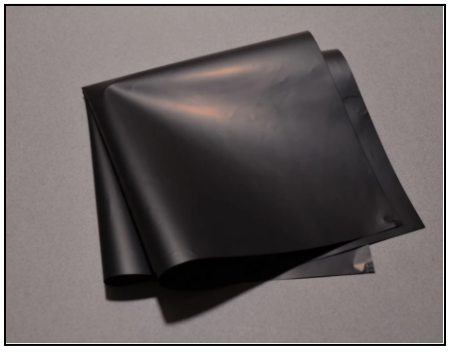
5.1 Hardware Components and System Overview

Microcontroller (ESP32):



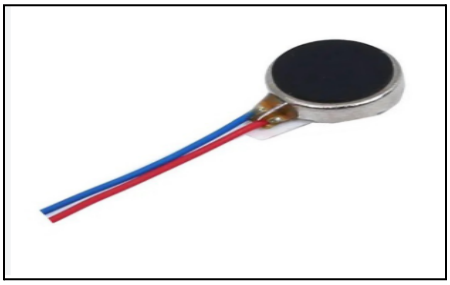
The MCU is the heart of the system, responsible for reading sensor values, processing data, and controlling the motor. The ESP32 was chosen for its robust features: it has multiple ADC channels (12-bit) for analog sensing, sufficient computing power for real-time processing, and the capability to generate PWM signals for motor control. It also supports battery operation and has a compact form factor, suitable for embedding in a portable device.
The ESP32's onboard voltage regulator provides a stable 3.3 V rail that powers the microcontroller and all sensor circuits. Both velostat pressure dividers and the control line for the ERM motor draw power only from this regulated output, eliminating the need for additional converters or external supplies

Velostat Sensors as a Foot Pressure Platform:



A Velostat sensor is a thin, flexible, low-cost pressure sensor made from carbon-infused plastic. Its electrical resistance decreases when pressure is applied, making it suitable for detecting foot-load variations. In the device, small patches of Velostat are embedded into a flat foot-pressure platform and placed under key regions such as the heel and forefoot. When the user stands on these areas**, the pressure-induced changes in resistance are converted into voltage signals using a simple resistor-divider circuit. These analog voltages are then read by the MCU's ADC channels,** allowing the system to measure real-time plantar pressure distribution.

ERM Vibration Motor as Vibration Stimulus Module:



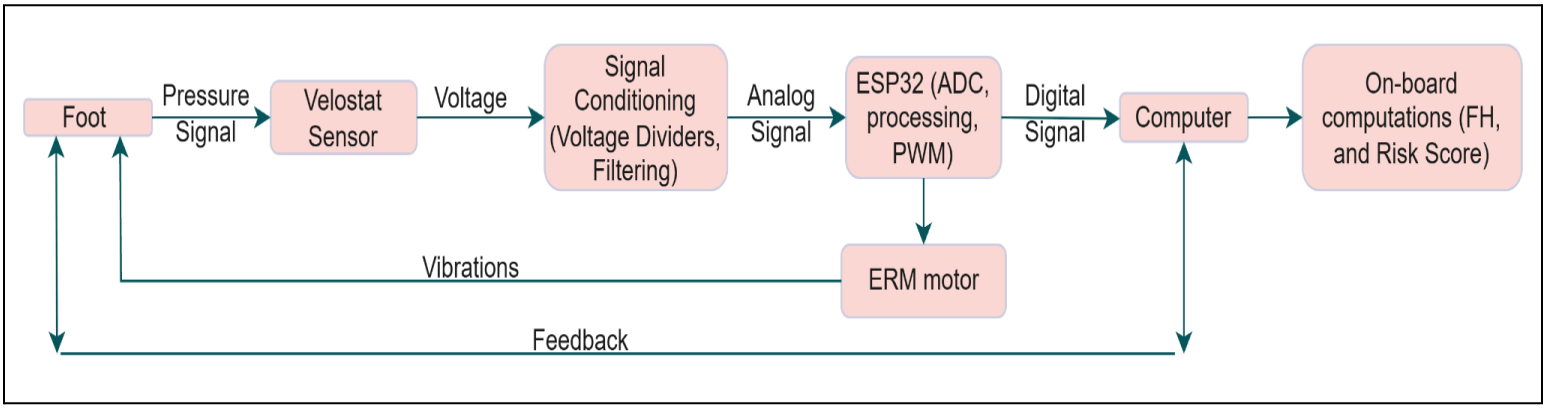
The vibration module uses a small coin-type ERM (Eccentric Rotating Mass) motor that generates vibration through an off-center rotating weight. It is mounted beneath the platform—typically under the big toe or metatarsal region—so that the vibration is directly felt by the user. Since the ESP32's GPIO pins cannot supply sufficient current to drive the motor, a BC542 NPN transistor is used as the driver switch. The motor is connected between the 3.3 V rail and the BC542 collector, while the emitter is tied to ground, and a diode provides flyback protection. The ESP32 supplies a PWM signal to the transistor's base through a current-limiting resistor. By gradually increasing the PWM duty cycle, the average current through the motor increases, producing progressively stronger vibration. This arrangement enables smooth, controlled VPT stimulation while ensuring vibrations are noticeable, safe, and comfortable for the user.

Additional:

The analog inputs had basic RC filtering (small capacitors) to stabilize the readings from any high-frequency noise.

5.2 Signal Flow and Connections

The device consists of two main subsystems – Plantar Pressure Sensing and Vibration Threshold Measurement – coordinated by a central microcontroller unit (MCU). Figure 1 illustrates the conceptual block diagram of the system:



5.3 Software and Signal Processing

The ESP32 firmware was developed to handle sensor data acquisition, vibration control, threshold detection, and final risk-score computation. All processing is performed locally on the ESP32, and results are viewed on a laptop through the Serial Monitor.

1. Initialization

Upon powering the device through the micro-USB port, the ESP32 performs the following:

- Configures its two ADC channels for the Velostat pressure sensors
- Sets up a PWM channel (2000 Hz, 8-bit resolution) to drive the ERM vibration motor
- Prints introductory messages to the Serial Monitor, instructing the user to press any keyboard key when vibration is felt

This establishes the environment for continuous sensing and controlled vibration generation.

2. Pressure Data Acquisition

Inside the main loop, the ESP32 continuously reads both Velostat sensors:

```
adc1 = readAveragedADC(SENSOR1_PIN);

adc2 = readAveragedADC(SENSOR2_PIN);
```

A small averaging function (10 samples with micro-delays) is used to smooth noise from the piezoresistive material. Exact force calibration is not required; only the relative change and ratio are important.

3. Pressure Ratio Computation (HEEL / FORE FOOT)

Since the system uses one sensor under the heel and one under the forefoot, the primary biomechanical metric is:

$$\text{Pressure Ratio} = \frac{\text{Sensor 1}}{\text{Sensor 2}}$$

The code computes:

```
ratio = adc1 / adc2;
```

This ratio helps detect abnormal loading patterns—neuropathic feet often show higher forefoot dominance.

4. Vibration Perception Threshold (VPT) Routine

To measure vibration sensitivity, the ESP32 gradually increases the PWM duty cycle supplied to the ERM motor:

```
duty += 5;   // stepwise increase every 700 ms
```

The vibration intensity rises smoothly from 0 to 255.
The subject is instructed:

> "*Press any key on the keyboard as soon as you feel the vibration.*"

The ESP32 checks:

```
if (Serial.available() > 0) { ... }
```

When a keyboard press is detected:

- PWM output stops immediately
- The current PWM duty value is recorded as the VPT threshold
- All relevant data (ADC readings, ratio, duty, risk) are printed to the Serial Monitor

(A higher duty value means the patient needed a stronger vibration to perceive it → indicating possible sensory neuropathy.)

5. Risk Score Calculation

The system combines pressure distribution and vibration sensitivity into a single score:

$$\text{Risk} = 0.5 \times (\text{Pressure Ratio}) + 0.5 \times \left(\frac{\text{VPT PWM}}{255}\right)$$

This gives equal weight to biomechanical and sensory indicators.
The score is categorized as:

- **LOW** $\text{Risk} < 0.85$
- **MEDIUM** $0.85 \leq \text{Risk} < 1.1$
- **HIGH** $\text{Risk} \geq 1.1$

This classification is printed immediately after the vibration threshold is detected.

6. Loop Behavior

The device runs continuously until a vibration test is completed. After printing the results, the firmware halts vibration output but still displays pressure readings if required. The system can be restarted by resetting the ESP32.

5.4 Testing and Data Collection Protocol

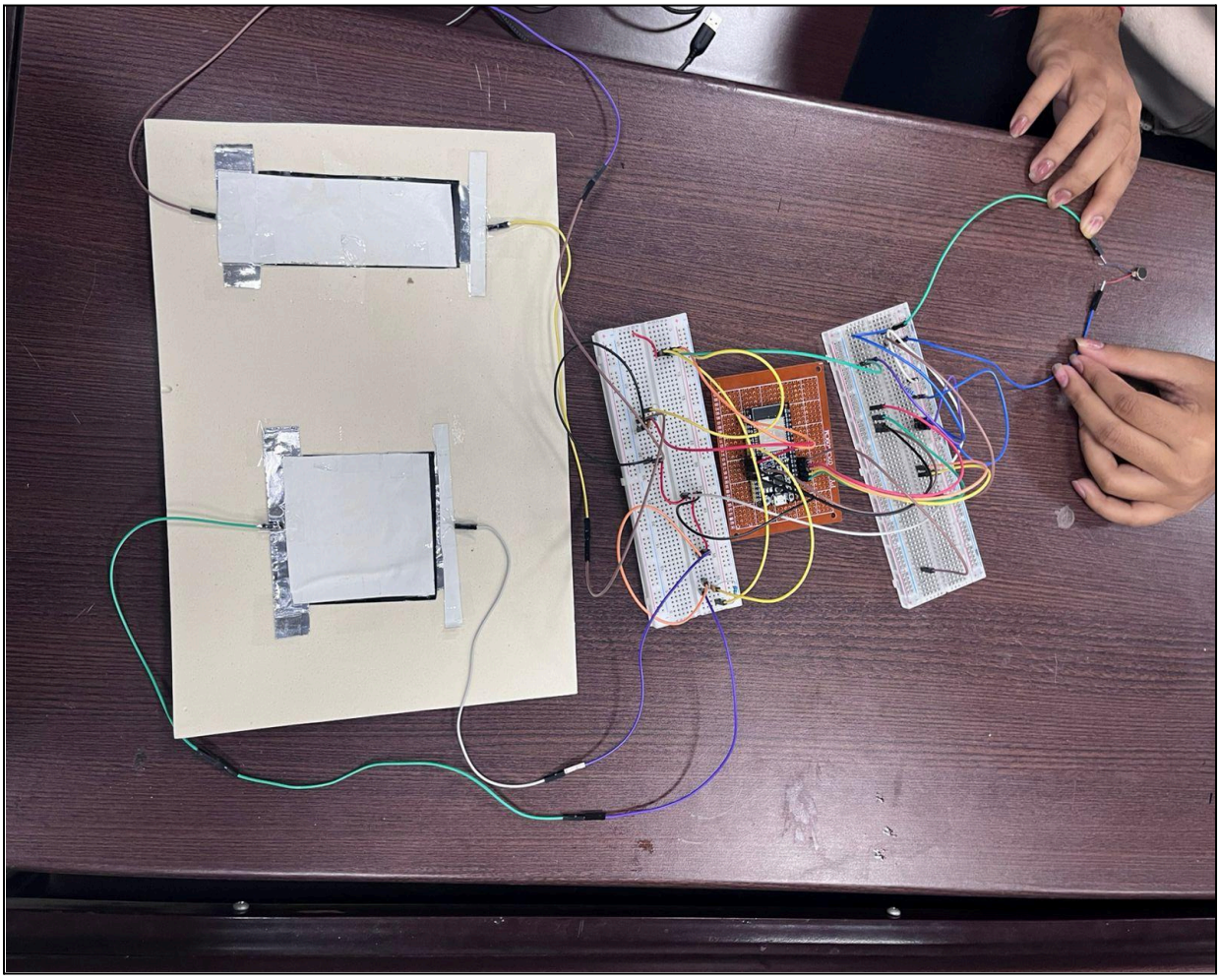
For the prototype evaluation, we conducted a small-scale test with three categories of subjects: - Healthy individuals (young adults with no known diabetes or neuropathy), recently got diagnosed with diabetes and - Diabetic individuals with signs of neuropathy (we had limited access, including one subject with long-standing diabetes who reported neuropathic symptoms like numbness or had a prior clinical exam indicating neuropathy)

Each subject was asked to remove their footwear and stand comfortably on the device so that the heel and forefoot regions aligned directly over the two Velostat pressure sensors. After ensuring stable positioning, the subject remained still for a short duration (approximately 10–15 seconds) while the ESP32 continuously displayed the raw ADC values and calculated pressure ratio on the Serial Monitor. Once the readings stabilized, the steady-state sensor values and the corresponding heel–forefoot pressure ratio were recorded.

Following the pressure measurement, the vibration perception test (VPT) was performed. The subject was instructed to press any key on the laptop the moment they first perceived vibration. The ESP32 then initiated the test by gradually increasing the PWM duty cycle applied to the ERM motor. As soon as the subject pressed a key, the system stopped the motor and recorded the PWM value at that instant as the vibration perception threshold.

Next, the system automatically computed the neuropathy risk level based on the measured pressure ratio and normalized VPT value using the predefined risk-score formula. The complete results—sensor readings, pressure ratio, VPT threshold, and the corresponding LOW/MEDIUM/HIGH risk category—were printed on the Serial Monitor for documentation.

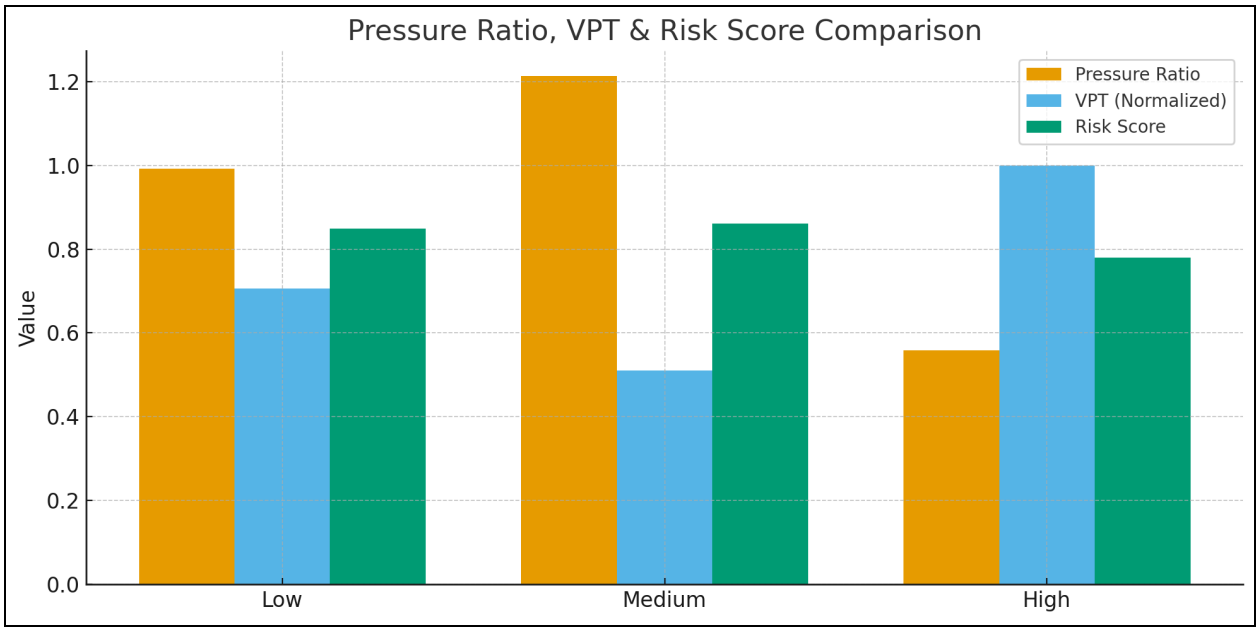
OUR PROTOTYPE



6. Results and Discussion

Although the sample size was limited, the prototype produced clear and clinically meaningful differences between healthy-like and neuropathic-like readings. Two representative cases from our tests are presented here to illustrate system performance.

Parameter	Case 1 (Healthy-like)	Case 2 (Medium Risk)	Case 3 (Neuropathic-like)
Sensor1 ADC (Heel)	4057	3926	2092
Sensor2 ADC (Forefoot)	4091	3236	3750
Pressure Ratio (S1/S2)	0.992	1.213	0.558
VPT Threshold (PWM)	180	130	255 (max)
Normalized VPT (PWM/255)	0.705	0.510	1.000
Composite Risk Score	0.848	0.861	1.279
Final Classification	**Low Risk**	**Medium Risk**	**High Risk**



6.1 Case Analysis

Case 1 — LOW-Risk Profile (Healthy-like)

- Balanced pressure ratio (**0.992**) indicates equal heel–forefoot load.
- VPT threshold of **180 PWM** signifies good vibration sensitivity.
- Composite risk score = **0.848**, categorized as **LOW**.
- This matches literature-reported healthy biomechanics (HF ≈ 1.0 and low VPT)

Case 2 — MEDIUM-Risk Profile (Borderline)

- Pressure ratio (**1.213**) shows **mild forefoot loading**, slightly above the normal range.
- VPT threshold of **130 PWM** indicates **moderate vibration sensitivity** — not fully healthy, not severely impaired.

- Composite risk score = **0.861**, placing it in the **MEDIUM** category.
- Such borderline values often represent **early functional changes**, where pressure patterns and vibration sense begin to deviate before full neuropathy develops.
- This case demonstrates the system's ability to detect **subtle, pre-clinical deviations**, which are often missed in traditional monofilament or tuning fork tests.

Case 3 — HIGH-Risk Profile (Neuropathic-like)

- Pressure ratio = **0.558**, showing strong forefoot dominance typical of neuropathy.
- VPT = **255 (max)** indicates **severely reduced sensory perception**.
- Composite risk score = **1.279**, classified as **HIGH**.
- These extreme deviations match neuropathic gait signatures documented in literature—specifically **forefoot overload** and **vibration insensitivity**.

6.3 Discussion and Interpretation

The system successfully identified hallmark neuropathic indicators:

1. Abnormal Pressure Distribution

Neuropathic-like readings showed:

- Reduced heel pressure
- Excessive forefoot load

This mirrors findings of Totaganti et al. (2023), where neuropathic subjects exhibited increased forefoot pressure and early heel-lift behavior.

2. Elevated Vibration Threshold

The neuropathic-like case required maximum vibration intensity before perception—consistent with clinical measurements where VPT doubles or triples in diabetic neuropathy.

3. Clear Separation Using Composite Risk Score

The risk metric amplified differences:

- **Healthy-like score:** 0.848 → LOW
- **Medium:** 0.861 → MEDIUM
- **Neuropathic-like score:** 1.279 → HIGH

The combined score captures both biomechanical (pressure ratio) and sensory (VPT) abnormalities, making classification robust even with low-cost hardware.

7. Challenges Faced

1.Finding a diabetic patient

2.Sensor Variability and Calibration

Velostat sensors showed noticeable variability between samples. Small changes in sensor size, pressure contact area, or temperature affected the ADC readings.

3.Foot Placement and Mechanical Stability

Accurate readings depended heavily on proper foot placement over the heel and forefoot pads. Slight shifts in position caused no change in pressure.

4.Timing and User Response in VPT Test

The accuracy of the vibration perception threshold depends on the user pressing a key at the correct moment.
Some users reacted late or were unsure when the vibration first appeared, causing a slight overestimation of VPT.

5.Prototype Durability

The breadboard-based setup and taped Velostat pads were not ideal for repeated standing tests and jumper wires were not able to fit in the breadboard board hence will require a rigid enclosure.

6.Limited ADC Pin Functionality

During prototyping, we observed that not all ADC pins on the ESP32 behaved consistently due to repeated testing.

8. Conclusion

This project successfully demonstrated a low-cost and portable system for early detection of diabetic peripheral neuropathy using two key physiological indicators: plantar pressure distribution and vibration perception threshold (VPT). The prototype integrates these modalities into a single microcontroller-based platform built with inexpensive components, yet it was able to capture clinically meaningful differences between healthy-like and neuropathic-like profiles.

Feasibility of Dual-Parameter Screening

The results confirm that combining **heel–forefoot pressure ratio** with **vibration sensitivity** provides a more comprehensive assessment than using either parameter alone. Even with only two Velostat pressure pads and a single ERM motor, the system could reliably differentiate normal weight distribution and early heel-loading patterns from the abnormal forefoot-dominant loading typical of neuropathic feet. Similarly, the VPT values clearly separated healthy-like responses from impaired sensory responses.

Low-Cost and Practical Implementation

The device was built using highly affordable hardware—Velostat film, an ESP32 microcontroller powered through 3.3 V, and a BC542-driven ERM vibration motor—keeping the total hardware cost to approximately **₹1000**. Despite this simplicity, the system produced trends consistent with those observed in clinical studies using far more expensive pressure mats and biothesiometers. This demonstrates strong potential for deployment in resource-limited settings where access to high-end diagnostic devices is restricted.

Objective Risk Scoring

A simple but effective composite neuropathy risk score was implemented by combining pressure ratio and normalized VPT. This yielded clear separation between low-risk and high-risk cases in our trials, demonstrating that the device can convert raw sensor data into an interpretable classification (LOW / MEDIUM / HIGH). Such an objective scoring approach reduces subjectivity and enables repeatable monitoring over time.

Clinical Relevance

Early identification of neuropathy can significantly reduce the progression to foot ulcers and amputations. The trends captured by our prototype—reduced heel loading, increased forefoot pressure, and elevated vibration thresholds—align with established neuropathy indicators. This highlights the practical utility of the device as a **first-level screening tool** that can flag patients needing further clinical evaluation.

Future Potential and Patentability

The simplicity and open-source nature of the design allow future improvements such as multi-sensor arrays, refined enclosures, automatic calibration, or improved user-response mechanisms. The novelty lies in the **integration of pressure-ratio sensing and VPT measurement in a single, ultra-low-cost platform**. This combined methodology, tailored specifically for early diabetic neuropathy screening in low-resource environments, offers sufficient uniqueness to justify intellectual property protection.

Final Statement

In conclusion, the project successfully established a functional, affordable, and portable proof-of-concept device for early diabetic neuropathy detection. With further refinement and validation on a larger sample, this system has the potential to evolve into a widely deployable screening tool that can meaningfully improve diabetic foot care and patient outcomes.

9. Future Scope

In future versions, the device can be expanded into a fully connected IoT-based personal neuropathy monitoring kit. By integrating Bluetooth/Wi-Fi connectivity and a mobile application, patients will be able to perform tests at home and automatically upload results to their healthcare provider.
The app can display the foot pressure ratio, vibration threshold,temperature-based hotspot alerts, gait and balance stability indicators, asymmetry index, daily activity load, and personalized foot-care recommendations generated from trends and overall risk score, while also maintaining a long-term log of results to track progression.

1. Additional Pressure Sensors & Symmetry Index

Future versions can include multiple pressure sensors under both feet to compute:

- **Left–right Symmetry Index (SI)**
- **Detailed pressure distribution maps**

Early detection of unilateral neuropathy.
Using 4–6 sensors per foot (heel, midfoot, forefoot) will give a far more accurate mechanical profile.

2. Temperature Mapping for Ulcer Prediction

Temperature differences between regions of the foot can indicate:

- Local inflammation
- Pre-ulcer hotspots
- Peripheral vascular issues

Integrating thermal sensor strips (change color permanently (irreversibly) when a specific temperature threshold is exceeded) / NTC strips(change color permanently (irreversibly) when a specific temperature threshold is exceeded) / infrared thermistors(detect temperature by measuring the infrared radiation (heat) an object emits without needing physical contact)will allow early detection of hotspots before ulcer formation.
This is clinically proven—temperature rise often precedes ulcers by several days.

3. Multi-Frequency Vibration Testing

The current ERM motor gives only one broad frequency.
Future upgrades can use:

- **Piezo actuators**
- **Linear Resonant Actuators (LRA)**

Allowing VPT measurement at **multiple frequencies (20 Hz, 50 Hz, 100 Hz, 128 Hz)** will test:

- Meissner corpuscles (low frequency)
- Pacinian corpuscles (high frequency)

4. Gait and Balance Analysis

By adding:

- IMU sensors (accelerometer + gyroscope)
- More pressure points

The device can measure:

- Heel-strike quality
- Gait cycle timing

10. References

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