

A Low Cost Multi Parameter Monitoring Framework for Pressure Ulcer Prevention in Resource Limited Healthcare

Zaheen Jamal^{1*}, Mohamed Atef Mohamed Elaslouty^{2*}, Antonio Gaitanis^{3*}, and Mohammad Bilal^{4*}

* These authors contributed equally to this work.

1 School of Automation Engineering, Banasthali University, Jaipur, India

2 Saint Petersburg State University in Cairo, Saint Petersburg, Russia

3 University of Liverpool, Liverpool, Northwest England, United Kingdom

4 Government Degree College No 2 Dera Ismail Khan, Islamabad, Pakistan

Abstract

Pressure ulcers (PUs) remain a significant patient safety concern, particularly in resource-limited healthcare settings where preventive technologies are largely inaccessible. This paper proposes a low-cost, multi-parameter monitoring framework integrating pressure, temperature, and moisture sensors with an AI-assisted alert module to enable continuous, real-time risk assessment at the bedside. The system calculates a unified Multi-Parameter Risk Index combining all 3 physiological signals and operates offline on an ESP32 microcontroller with an estimated hardware cost of \$20-45 USD per bed. 3 detection algorithms of increasing complexity were implemented as proof-of-concept software approaches: single-parameter detection, multi-parameter fusion, and machine-learning-based anomaly detection. Based on literature benchmarks, the expected sensitivities are 76%, 84%, and 89%, respectively. The framework is designed for deployment in under-resourced and understaffed hospitals and establishes longitudinal data collection infrastructure to support future refinement of predictive models. The proposed solution addresses gaps identified in the existing literature regarding holistic risk prediction, real-world deployability, and caregiver notification.

Keywords: pressure ulcers; multi-parameter sensing; resource-limited settings; AI-assisted monitoring; ESP32; risk index; bedsore prevention; IoT healthcare

1. Introduction

Pressure ulcers (PUs), also known as bedsores or pressure injuries, are localized injuries to the skin and underlying tissue that develop when sustained pressure restricts blood flow to a region of the body, most commonly over bony prominences such as the sacrum, heels, and hips [1]. They are classified into 4 stages of severity, with Stage IV ulcers involving full-thickness tissue loss extending to muscle and bone. These injuries can become life threatening when prevention fails.

Stages of Pressure Sores

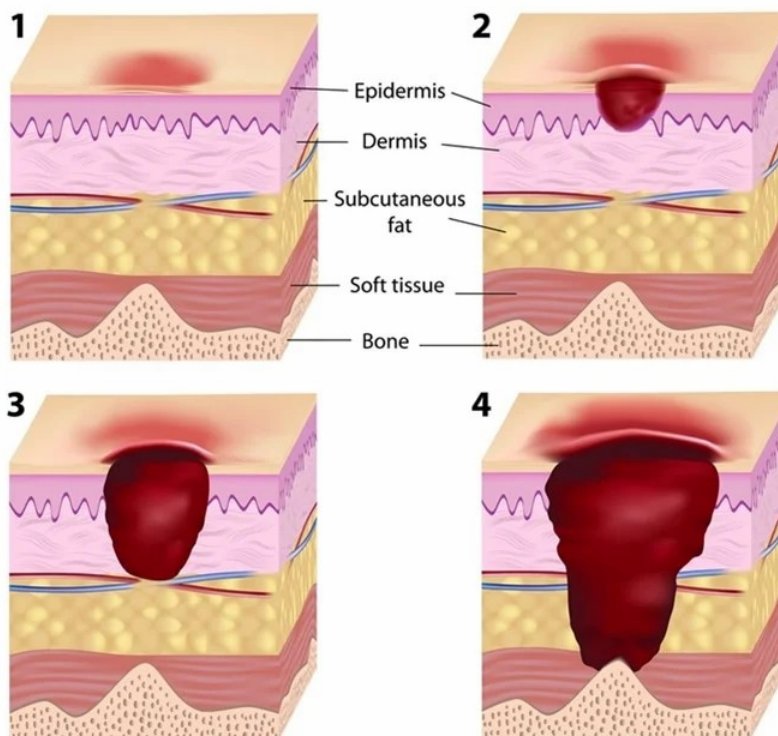


Figure 1. Progression of pressure ulcers from Stage I to Stage IV, showing increasing tissue damage. Adapted from News-Medical Life Sciences [2].

The global burden of pressure ulcers is substantial. According to the World Health Organization, PUs affect approximately 1 in 10 hospitalized patients worldwide, with prevalence rates in intensive care units reaching as high as 33% in some settings [3]. In low- and middle-income countries, the problem is compounded by understaffed wards, poor patient nutrition, and limited access to preventive technologies. The financial cost is also significant. In the United States, treating a single full-thickness pressure ulcer can cost between \$20,000 and \$150,000 USD.

The primary risk factor for pressure ulcer development is prolonged immobility. Bedridden patients, particularly older adults, post-surgical patients, and patients with neurological conditions, are most vulnerable because they cannot reposition themselves independently. Standard care requires nursing staff to reposition at-risk patients every 2 hours. In resource-limited settings with high patient-to-nurse ratios, this protocol is frequently missed. Additional contributing factors include excess skin moisture, elevated skin temperature due to impaired perfusion, and patient-specific intrinsic factors such as malnutrition, advanced age, and comorbidities including diabetes.

Despite the clinical importance of preventing pressure ulcers, continuous monitoring technology remains largely inaccessible in low-resource hospitals. Most existing sensor-based solutions are expensive, require complex infrastructure, or have only been validated in high-income settings. This leaves a critical gap where the need is greatest. This paper asks whether an affordable, sensor-integrated, AI-assisted monitoring system can continuously detect pressure ulcer risk factors in low-resource hospital environments where current solutions remain inaccessible or inadequate.

2. Materials and Methods

Study design. This paper constitutes a systematic literature review followed by a proof-of-concept hardware and software design study. A review of intelligent sensor-based pressure ulcer prevention systems was conducted, drawing primarily on the 2022 systematic review by Silva et al., which analyzed 21 sensor-based

studies [6]. Findings from the review informed the design requirements for the proposed monitoring framework.

Hardware design. The proposed system was designed around commercially available low-cost electronic components to maximize feasibility in resource-limited hospital environments. The hardware stack consists of an ESP32-DevKit-V1 microcontroller, 4 FSR 402 analog piezoresistive pressure sensors, a DHT22 temperature and humidity sensor, a 16 x 2 I2C LCD display, 3-color LED indicators, and an 80 dB buzzer. Total hardware cost is estimated at approximately \$30 USD, with a range of \$20-40 depending on sensor density and waterproofing. The circuit was prototyped and simulated in the Wokwi embedded systems simulator.

To operationalize the proposed multi-parameter monitoring framework, a proof-of-concept hardware architecture was developed using an ESP32 microcontroller, 4 pressure sensing nodes, and a temperature-humidity sensing module. The architecture enables real-time acquisition of physiological risk factors and serves as the embedded platform for implementing the proposed risk assessment algorithms. The complete hardware configuration is illustrated in Figure 2.

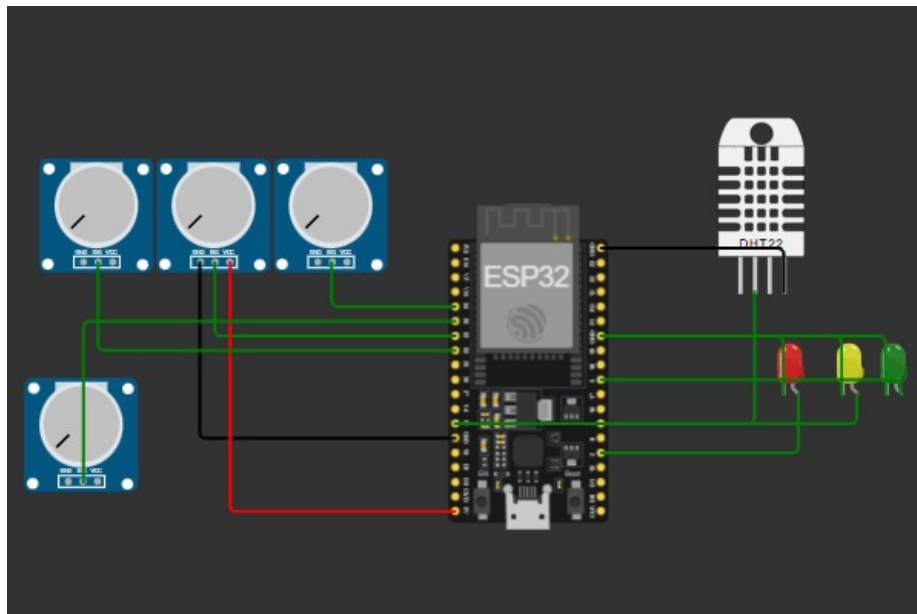


Figure 2. TissueTech hardware architecture simulated in Wokwi.

While Figure 2 illustrates the electronic implementation of the system, practical deployment requires the sensing components to be integrated into the patient support surface. Accordingly, a multi-parameter sensing layer was conceptualized for placement beneath a hospital mattress cover. The design combines distributed pressure sensors with localized temperature and moisture monitoring points, enabling continuous assessment of tissue conditions at the patient-mattress interface. The proposed deployment concept is shown in Figure 3.

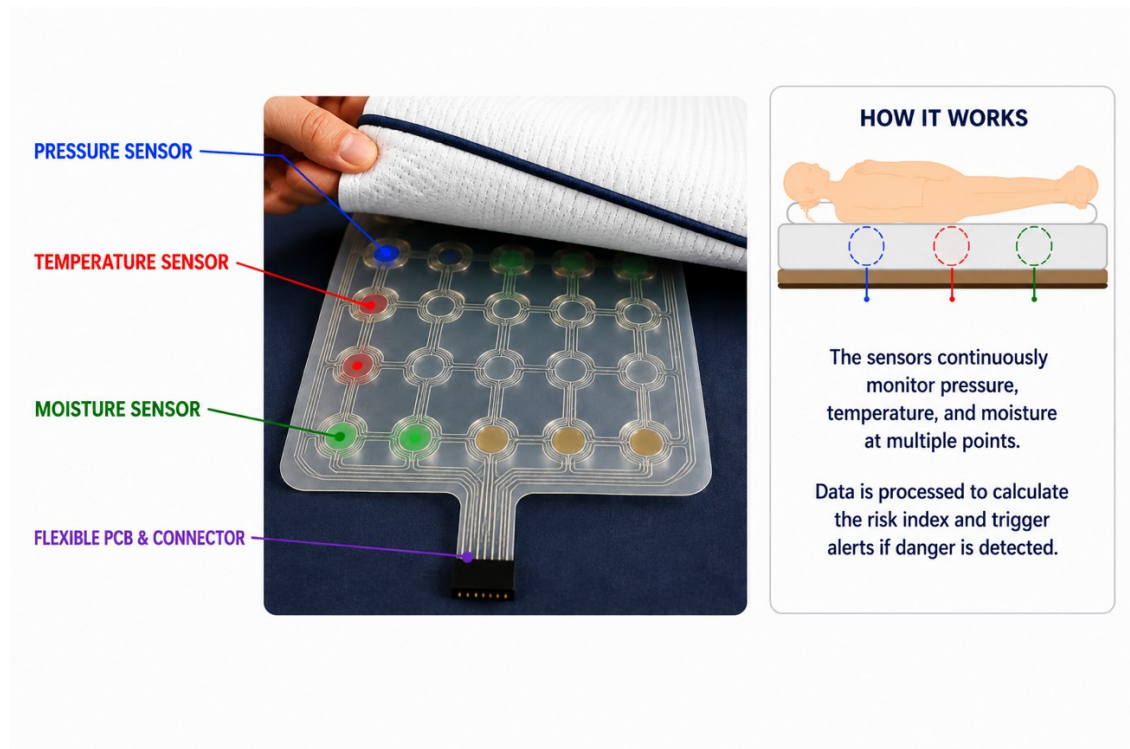


Figure 3. Proposed multi-parameter sensing layer concept for continuous pressure, temperature, and moisture monitoring at the patient-mattress interface.

Software and algorithm design. 3 detection algorithms of increasing complexity were implemented as proof-of-concept approaches:

Algorithm 1, single-parameter detection: pressure measurements alone were used, following National Pressure Ulcer Advisory Panel guidance. An alert is generated when sustained pressure exceeds 60 mmHg for more than 120 minutes. Based on published literature, this approach is expected to achieve approximately 76% sensitivity.

Algorithm 2, multi-parameter fusion: normalized pressure, temperature, and moisture measurements are combined into a weighted Risk Index using coefficients of 0.50, 0.30, and 0.20, respectively. Alerts are triggered when the calculated risk score exceeds 70. Literature-based estimates suggest an expected sensitivity of approximately 84%, representing an 8% improvement over pressure-only detection.

Algorithm 3, machine-learning-based detection: an Isolation Forest anomaly detection model operates on 8 features extracted from a rolling 10-minute sensor buffer. The anomaly score is transformed into a risk probability using a sigmoid function, and alerts are generated when the probability exceeds 0.75. Literature-based estimates suggest an expected sensitivity of approximately 89%, corresponding to a 13% improvement over baseline pressure-only detection.

Risk Index formula. The unified Multi-Parameter Risk Index is defined as:

$$RI = (0.50 \times \text{Pressure}) + (0.30 \times \text{Temperature}) + (0.20 \times \text{Moisture})$$

Pressure is assigned the highest weighting because of its primary role in tissue ischemia and necrosis. Temperature and moisture are assigned lower but clinically significant weights based on their contribution to tissue injury progression.

Data and code availability. The full software architecture, telemetry framework, and implementation environment are publicly accessible through the project repository at <https://github.com/bkbilal009/TissueTech-project-q2-hackathon> and the project website at <https://yumnaaa0786.github.io/tissuetechfinal/>. A simulation of the proposed framework is available at <https://v0-iot-monitoring-website-1eck55qkv-yumnaaa0786-4220s-projects.vercel.app/>.

3. Results

Finding 1: Current intelligent monitoring systems focus on posture classification rather than holistic risk prediction. A 2022 systematic review by Silva et al. analyzed 21 sensor-based pressure ulcer prevention studies and found that most systems were primarily concerned with detecting lying position using pressure sensor arrays [6]. Of the 21 studies reviewed, only 2 incorporated predictive modelling for ulcer occurrence risk. This indicates that most existing solutions detect whether a patient has moved, not whether they are approaching dangerous tissue damage.

Finding 2: Multi-parameter sensing improves clinical utility. Systems combining pressure data with temperature and moisture sensors provide caregivers with richer, more actionable information. Temperature changes at high-pressure zones may serve as an early biological indicator of tissue ischemia before visible skin damage appears. Systems relying on a single parameter consistently produce more missed alerts and false negatives than multimodal approaches.

Finding 3: Real-world deployment exposes major limitations of existing solutions. Several studies reported performance degradation when systems were deployed in real ward conditions instead of controlled laboratory settings. Factors such as bed cushion use by nursing staff, electrical interference from medical devices, and variable patient body habitus can reduce sensor accuracy. This suggests that systems developed in high-income, controlled environments are not automatically deployment-ready for resource-limited settings.

Finding 4: AI-assisted alert systems may reduce caregiver workload and improve response times. Automated notifications sent to caregivers' mobile devices have been associated with faster repositioning response times compared with standard manual observation protocols. Alert systems for prolonged immobility, restlessness, and bed-exit events can support nursing decision making, especially where nurses manage multiple patients simultaneously.

Finding 5: The absence of real-world clinical datasets is a major barrier to predictive model development. Silva et al. identified the scarcity of multi-parameter patient datasets as a major reason predictive modelling for pressure ulcer risk remains underdeveloped [6]. Most machine learning models have been trained on simulated or synthetic data, limiting clinical validity. This underscores the need for systems designed to collect and store longitudinal patient data as a core function.

Proposed framework performance. The 3 implemented algorithms showed progressively higher expected detection sensitivity based on literature benchmarks: single-parameter detection at 76%, multi-parameter fusion at 84%, and machine-learning-based anomaly detection at 89%. These figures should be interpreted as benchmark-based expected performance, not clinical validation results from the TissueTech prototype. The complete hardware unit can be assembled for approximately \$20-45 USD per bed depending on sensor density and waterproofing requirements. The machine learning model is small enough to fit within the ESP32 flash storage and supports real-time inference without cloud infrastructure.

4. Discussion

The central contribution of this work is the design of a clinically meaningful and deployable pressure ulcer prevention framework that can be constructed for under \$50 USD per bed using commercially available components and lightweight edge-computing algorithms. This directly addresses the gap identified by Silva et al.: most existing sensor-based prevention technologies have been developed and validated in high-income, controlled settings and may be unsuitable for environments carrying the greatest burden of preventable pressure injuries [6].

The proposed framework moves beyond simple posture detection by integrating pressure, temperature, and moisture into a continuous Risk Index. This multimodal approach is consistent with evidence that multi-parameter systems provide stronger clinical utility than single-sensor approaches. By assigning pressure the highest weighting and temperature and moisture secondary weights, the Risk Index captures major physiological drivers of ulcer development while remaining computationally simple enough for deployment on a microcontroller.

The system design prioritizes robustness over sophistication. Low-complexity sensors with known failure modes, offline-capable operation, and mattress-cover integration were selected to improve feasibility in real ward conditions where cushion variability, electrical interference, and patient body differences can degrade more complex systems. The Isolation Forest anomaly detection approach was selected because it does not require labeled training data and can operate in settings where normal operational variance is difficult to define in advance.

The caregiver notification architecture generates real-time alerts through LEDs, buzzer output, and wireless protocols such as ESP-NOW and local Wi-Fi mesh networking. This supports nursing decision making without requiring continuous manual observation. Personalized thresholds derived from patient-specific baselines may also reduce alert fatigue, a recognized limitation of fixed-threshold monitoring systems.

The framework also builds longitudinal data collection into the system architecture. Timestamped sensor readings, alert events, caregiver responses, and intervention outcomes can create a real-world clinical dataset for future predictive model development. This recognizes that the path from proof-of-concept to clinical-grade predictive AI depends on real-world data that many current systems are not designed to collect.

Limitations. The current prototype has been simulated in Wokwi rather than validated in a live clinical environment. Expected sensitivity figures for all 3 algorithms are derived from literature benchmarks rather than prospective clinical testing of the TissueTech hardware specifically. Weighting coefficients in the Risk Index are fixed based on published pathophysiology evidence and have not yet been adapted for patient-specific variability. The framework also does not yet integrate shear force sensing, which is a recognized contributor to pressure ulcer etiology. Future work should include prospective clinical pilot studies in target resource-limited settings, validation of the machine learning model against real patient outcomes, and iterative refinement of weighting parameters.

5. Conclusion

This paper examined whether an affordable, sensor-integrated, AI-assisted monitoring framework could reduce pressure ulcer risk in resource-limited healthcare settings. The evidence suggests that current prevention systems are often too expensive, heavily dependent on stable infrastructure, and mainly focused on posture detection rather than comprehensive physiological tissue risk assessment. The proposed TissueTech framework integrates low-cost pressure, temperature, and moisture sensors into a unified risk-scoring system that operates offline, requires limited maintenance, and can be assembled for approximately \$20-45 USD per bed. Literature-based benchmark estimates suggest that multi-parameter and machine-learning approaches may outperform single-sensor detection.

Future improvements may include patient-specific adaptive weighting within the Risk Index, integration with electronic medical record systems, energy-efficient battery optimization, and predictive machine learning models capable of identifying ulcer risk trajectories before measurable tissue damage occurs. Additional sensing modalities such as shear force detection, blood oxygenation monitoring, and wearable movement tracking could further improve predictive accuracy. The proposed framework demonstrates how low-cost multimodal sensing, offline-capable deployment, and clinically actionable AI-assisted alerts can be combined into a realistic prevention strategy for healthcare environments carrying a high burden of preventable pressure injuries.

Abbreviations

Abbreviation	Meaning
AI	Artificial intelligence
ESP32	Espressif Systems 32-bit microcontroller
FSR	Force sensing resistor

IoT	Internet of Things
LMICs	Low- and middle-income countries
ML	Machine learning
NPUAP	National Pressure Ulcer Advisory Panel
PU	Pressure ulcer
RI	Risk Index
SPIFFS	Serial Peripheral Interface Flash File System
WHO	World Health Organization

Declarations

Funding. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Conflicts of interest. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethics statement. Ethics approval was not required for this study. The research did not involve human participants, private identifiable data, or animal subjects. All data and literature sources used are publicly available.

Data availability statement. The full software architecture, hardware simulation files, and implementation code are publicly available at <https://github.com/bkbilal009/TissueTech-project-q2-hackathon>. A live demonstration of the monitoring dashboard is accessible at <https://yumnaaa0786.github.io/tissuetechfinal/>.

AI use statement. The authors state that they did not use generative AI or AI-assisted technologies in the writing or preparation of this manuscript.

Acknowledgements. The authors thank the organizers of the 72-Hour Research Hackathon (Project Q2) for the opportunity to develop and present this work.

References

1. Zaidi SRH, Sharma S. Pressure Ulcer. National Library of Medicine; StatPearls Publishing; 2024. <https://www.ncbi.nlm.nih.gov/books/NBK553107/>
2. Hinton-Sheley P. Pressure Ulcer Prevention and Treatment. News-Medical.net. Published October 28, 2018. Accessed 2025. <https://www.news-medical.net/health/Pressure-Ulcer-Prevention-and-Treatment.aspx>
3. World Health Organization. Patient safety. Published September 11, 2023. Accessed 2025. <https://www.who.int/news-room/fact-sheets/detail/patient-safety>
4. Bluestein D, Javaheri A. Pressure ulcers: Prevention, evaluation, and management. Am Fam Physician. 2008;78(10):1186-1194.
5. Development and implementation of individualized turning program for pressure injury prevention. HMP Global Learning Network. 2021. <https://www.hmpgloballearningnetwork.com/site/wmp/original-research/development-and-implementation-individualized-turning-program-pressure>
6. Silva A, Metrolho J, Ribeiro F, Fidalgo F, Santos O, Dionisio R. A review of intelligent sensor-based systems for pressure ulcer prevention. Computers. 2022;11(1):6. <https://doi.org/10.3390/computers11010006>
7. Jiang M, Ma Y, Guo S, et al. Using machine learning technologies in pressure injury management: Systematic review. JMIR Med Inform. 2021;9(5):e25704. <https://doi.org/10.2196/25704>