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Intelligent Bionic Sensing Textile for Pressure Ulcer Prevention: A Self-Powered, Multi-Modal Monitoring System with Real-Time Risk Assessment

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***Abstract*—Pressure injuries (PIs) present a formidable challenge in healthcare, inflicting significant suffering on patients with limited mobility and imposing a heavy economic toll on medical systems. Conventional preventative measures, which hinge on manual repositioning and specialized surfaces, are often insufficient as they lack the continuous, personalized data needed for preemptive action. This reactive paradigm frequently falls short in averting the development of these debilitating wounds. To bridge this critical divide, we present an innovative, self-powered intelligent bionic sensing textile, engineered for the concurrent and uninterrupted monitoring of three pivotal etiological factors in PI development: pressure, moisture, and temperature. Our design comprises a flexible, breathable, multi-layer fabric architecture that synergistically merges a triboelectric-piezoelectric hybrid sensing mechanism. This is realized through a composite structure of a piezoelectric polymer (PVDF-TrFE) film and a functionalized triboelectric layer, integrated with a patterned array of soft, conductive fabric electrodes. The system is augmented by a miniaturized wireless data acquisition module and a custom real-time risk assessment algorithm running on a smartphone. The smart textile exhibits high pressure sensitivity, a swift response to moisture, and remarkable mechanical durability and comfort. Through rigorous evaluations on a human mannequin and pilot trials with human subjects, the system has demonstrated successful real-time pressure distribution mapping in high-risk zones, rapid detection of simulated incontinence, and the ability to harvest energy from subtle body movements for autonomous operation. This research charts a new course for next-generation smart medical textiles, aiming to shift the pressure injury prevention paradigm from reactive, intermittent interventions to a proactive, precise, and personalized standard of care. This innovation carries the profound potential to elevate the quality of life for vulnerable patient populations while substantially mitigating associated healthcare expenditures.**

Keywords*—Wearable sensor, Triboelectric-piezoelectric hybrid, Pressure ulcer prevention, Multi-modal sensing, Self-powered system

1. INTRODUCTION

Pressure injuries (PIs), also referred to as pressure ulcers or bedsores, are localized damage to the skin and underlying soft tissues, typically occurring over bony prominences as a consequence of sustained mechanical loading and impaired microcirculation [1]. They remain a pervasive and costly global healthcare challenge, disproportionately affecting individuals with limited mobility, including older adults, patients with spinal cord injuries, and those in intensive or long-term care settings [2][3]. Clinically, PIs are associated with severe pain, infection, prolonged hospitalization, and increased morbidity and mortality, while also imposing a substantial economic burden on healthcare systems worldwide [4][5][6].

The pathogenesis of pressure injuries is inherently multifactorial. Sustained pressure exceeding capillary closing pressure (approximately 32 mmHg) compromises blood and lymphatic flow, initiating ischemia and subsequent tissue necrosis if not relieved in a timely manner. Importantly, mechanical loading rarely acts in isolation. The local skin microclimate—particularly moisture and temperature—plays a critical modulatory role in tissue tolerance. Excessive moisture resulting from incontinence, perspiration, or wound exudate leads to skin maceration, increases friction, and markedly lowers the threshold for pressure- and shear-induced injury. Concurrently, elevated skin temperature increases cellular metabolic demand, accelerating ischemic damage under compromised perfusion conditions. The synergistic interaction of pressure, moisture, and temperature therefore substantially amplifies pressure injury risk, underscoring the clinical necessity for simultaneous, multi-parameter monitoring rather than single-factor assessment.

Despite this well-established multifactorial etiology, current clinical prevention strategies remain largely reactive and generalized. Routine repositioning schedules and pressure-redistributing support surfaces constitute the

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cornerstone of standard care [7], yet these interventions are typically implemented without continuous, patient-specific physiological feedback. As a result, their effectiveness is highly dependent on staff workload, compliance, and subjective judgment, and they often fail to detect localized, subclinical risk accumulation prior to visible tissue breakdown [8]. This disconnect between known pathophysiology and practical monitoring capabilities represents a fundamental limitation in contemporary pressure injury prevention.

To address this gap, a range of sensing technologies has been explored for objective, continuous monitoring of pressure injury risk factors. Commercial pressure-mapping systems, such as instrumented mattress overlays, can provide spatial pressure distribution data but are often costly, bulky, and restricted to bed-based use, offering limited protection during sitting or transfers [9,10]. In parallel, research efforts have produced flexible and wearable sensors based on piezoresistive [11], capacitive [12], and piezoelectric [13] mechanisms for pressure sensing, as well as humidity [14] and temperature sensors [15] for microclimate monitoring. While these systems demonstrate promising technical performance, most remain constrained by three critical limitations: (i) single-parameter sensing that fails to capture the coupled nature of pressure injury risk; (ii) dependence on external power sources, introducing bulk, maintenance requirements, and limited operational lifetime; and (iii) insufficient integration into soft, breathable textile platforms suitable for long-term clinical use.

Self-powered sensing technologies based on triboelectric and piezoelectric effects have emerged as a compelling strategy to overcome power supply constraints in wearable systems. Piezoelectric nanogenerators efficiently convert mechanical deformation into electrical signals, whereas triboelectric nanogenerators excel at harvesting low-frequency mechanical energy through contact electrification. Recent studies have demonstrated that hybrid triboelectric–piezoelectric systems can broaden the effective energy harvesting spectrum and enhance output performance. However, existing hybrid devices are predominantly demonstrated as discrete components or rigid prototypes, with limited attention to fabric-level integration, multi-modal physiological sensing, or clinical relevance to pressure injury prevention.

Accordingly, there remains a clear and unmet clinical need for a soft, breathable, and scalable textile-based system capable of self-powered, continuous, and multi-modal monitoring of the primary etiological factors underlying pressure injuries. Such a platform would enable a paradigm shift from reactive, schedule-driven care toward proactive, data-informed, and personalized prevention strategies.

In this work, we address this need by developing an intelligent bionic sensing textile that integrates pressure, moisture, and temperature sensing within a single self-powered fabric architecture. By leveraging a triboelectric–piezoelectric hybrid sensing mechanism, the proposed system enables simultaneous multi-modal signal acquisition while harvesting mechanical energy from routine body movements to support autonomous operation. The sensing textile is coupled with a wireless data acquisition module and a real-time pressure injury risk assessment algorithm, providing intuitive visualization and actionable alerts for caregivers. Collectively, this study aims to establish a new interdisciplinary framework for smart medical textiles, bridging material science, wearable electronics, and clinical nursing practice to advance pressure injury prevention toward a more precise, adaptive, and patient-centered standard of care.

2. Related Work

2.1. Pathophysiology and Key Risk Factors of Pressure Injuries

The formation of pressure injuries is widely recognized as a complex, multifactorial pathological process rather than the consequence of a single mechanical insult. Sustained external pressure applied to the skin and underlying soft tissues can occlude capillary blood flow and lymphatic drainage, leading to localized ischemia, impaired nutrient exchange, and accumulation of metabolic waste products [16]. If such conditions persist beyond tissue tolerance limits, irreversible cell damage and necrosis ensue, ultimately resulting in ulceration. Anatomical regions overlying bony prominences, such as the sacrum, coccyx, heels, and hips, are particularly susceptible due to concentrated stress distribution over relatively small contact areas [17]. In addition to normal pressure, shear forces generated by relative motion between tissue layers further distort microvasculature and exacerbate ischemic injury, accelerating tissue breakdown even under moderate loading conditions [18].

Beyond mechanical loading, the local skin microclimate plays a decisive role in modulating tissue vulnerability. Excessive moisture, commonly arising from urinary or fecal incontinence, perspiration, or wound exudate, leads to maceration of the stratum corneum and compromises the skin's barrier function [19]. Macerated skin exhibits increased friction coefficients and reduced mechanical resilience, rendering it more susceptible to pressure- and shear-induced damage [20]. Concurrently, elevated skin temperature increases cellular metabolic demand; even modest temperature elevations can significantly accelerate ischemic injury by increasing oxygen consumption in already perfusion-limited tissues [21]. Collectively, these findings indicate that pressure injuries result from the synergistic interaction of pressure, moisture, and temperature rather than from isolated factors. Consequently, effective prevention strategies require simultaneous monitoring of these parameters to capture early, subclinical risk accumulation.

2.2. Sensing Technologies for Pressure Injury Risk Monitoring

To overcome the limitations of subjective clinical assessment, extensive research has focused on developing sensor-based systems for objective monitoring of pressure injury risk factors. Flexible pressure sensors constitute the most extensively studied category and can be broadly classified into piezoresistive, capacitive, and piezoelectric types. Piezoresistive sensors, which transduce mechanical deformation into resistance changes, are attractive due to their simple fabrication processes and straightforward signal readout [11, 22]. However, they often suffer from signal drift, hysteresis, and sensitivity to environmental factors such as temperature, limiting long-term measurement stability. Capacitive pressure sensors offer high sensitivity and low power consumption by detecting pressure-induced variations in electrode spacing or dielectric properties [12,23], yet their susceptibility to electromagnetic interference and challenges in large-area array integration constrain practical deployment in clinical environments.

Piezoelectric pressure sensors generate electrical signals in response to applied mechanical stress and are particularly effective for detecting dynamic pressure changes [13,24]. While their self-generating nature is advantageous, conventional piezoelectric sensors exhibit limited capability for static pressure monitoring unless supplemented with charge amplification circuitry, which increases system complexity and power consumption. In parallel, sensing technologies targeting the skin microclimate have also been explored. Flexible humidity sensors based on hygroscopic polymers or conductive composites enable detection of moisture associated with incontinence or excessive perspiration [14,25], while flexible temperature sensors, typically employing thermistors or resistive temperature detectors, provide localized thermal information relevant to inflammation and ischemia [15,26].

Despite these advances, most reported systems remain limited to single-parameter monitoring. Although several multi-modal prototypes have been proposed, they often rely on heterogeneous sensor integration strategies that compromise flexibility, breathability, or user comfort, and many are not readily compatible with textile-based platforms [27]. As a result, the ability to achieve continuous, multi-parameter monitoring in a soft, wearable, and clinically practical form factor remains an unresolved challenge.

2.3. Self-Powered Systems based on Nanogenerators

A critical bottleneck for long-term wearable monitoring systems lies in power supply constraints. Battery-powered devices introduce additional bulk, limit operational lifetime, and necessitate regular maintenance, which is impractical for continuous clinical monitoring. To address this issue, self-powered sensing systems based on energy harvesting have attracted increasing attention. Triboelectric nanogenerators (TENGs) and piezoelectric nanogenerators (PENGs) represent two prominent approaches for converting ambient mechanical energy into electrical output [28,29].

PENGs exploit the intrinsic piezoelectric properties of materials such as PVDF and ZnO to generate electrical signals under mechanical deformation [30]. They are particularly effective for harvesting high-frequency, low-amplitude vibrations. In contrast, TENGs operate through contact electrification and electrostatic induction, enabling efficient energy harvesting from low-frequency, large-displacement motions typical of human activities [31,32]. Recognizing the complementary characteristics of these mechanisms, recent studies have proposed hybrid triboelectric–piezoelectric nanogenerators to extend the effective energy harvesting bandwidth and enhance overall output performance [33][34][35].

Beyond energy harvesting, nanogenerator-based systems offer the unique advantage of self-powered sensing, wherein the generated electrical signals directly encode information about mechanical or environmental stimuli [36]. However, existing hybrid systems are predominantly demonstrated as rigid or semi-flexible devices, and their application has largely focused on motion monitoring or energy harvesting demonstrations. Integration of hybrid nanogenerators into breathable, fabric-based platforms capable of multi-modal physiological sensing and long-term clinical use remains limited.

2.4. Research Gap and Our Contribution

Although substantial progress has been achieved in flexible sensors and self-powered systems, a clear research gap persists at their intersection for pressure injury prevention. Existing approaches typically address isolated aspects of the problem—pressure sensing, microclimate monitoring, or energy harvesting—without achieving holistic integration. In particular, current multi-modal systems often lack self-powered capability, while self-powered devices rarely incorporate comprehensive, clinically relevant sensing modalities or textile-level integration suitable for continuous wear.

To date, no reported system has successfully combined pressure, moisture, and temperature sensing within a single, self-powered, fabric-based platform that is scalable, comfortable, and aligned with clinical prevention needs. Addressing this gap requires not only material and device innovation but also system-level integration that reflects the multifactorial pathophysiology of pressure injuries. This unmet need forms the primary motivation of the present study.

3. METHODOLOGY

3.1. Design and Fabrication of the Sensing Textile

The intelligent bionic sensing textile was designed as a multi-layered, flexible, and breathable composite structure to ensure both robust sensing performance and user comfort. The selection of materials was guided by their piezoelectric/triboelectric properties, mechanical flexibility, biocompatibility, and suitability for scalable fabrication processes.

3.1.1. Materials Selection

The core of the hybrid sensing mechanism was a piezoelectric polymer film of poly(vinylidene fluoride-trifluoroethylene) (PVDF-TrFE, 70/30 mol%), chosen for its high piezoelectric coefficient (d33), flexibility, and chemical stability. For the triboelectric components, a commercially available polyamide (Nylon) fabric was selected as the positive triboelectric layer due to its tendency to lose electrons, and a polytetrafluoroethylene (PTFE) film was used as the negative triboelectric layer. Silver-plated conductive nylon fabric was chosen for the electrodes due to its excellent conductivity, flexibility, and durability. A medical-grade, breathable polyurethane (PU) film was used as the top encapsulation layer to provide a waterproof yet vapor-permeable barrier, protecting the sensor while maintaining skin health.

3.1.2. Structural Design

The sensor was designed with a five-layer architecture, as illustrated in Figure 1a. From bottom to top, the layers are:

(1) a base substrate of flexible cotton fabric for comfort;

(2) the bottom conductive fabric electrode;

(3) the active PVDF-TrFE piezoelectric film;

(4) the top conductive fabric electrode, which also serves as the triboelectric layer (Nylon);

(5) the breathable PU encapsulation layer.

The top and bottom electrodes were patterned into an array of 16x16 individual sensing pixels (each 1 cm x 1 cm) to enable spatially resolved pressure mapping. The triboelectric moisture sensing function is realized by the interaction between the Nylon electrode layer and any incoming fluid, which alters the contact electrification characteristics.

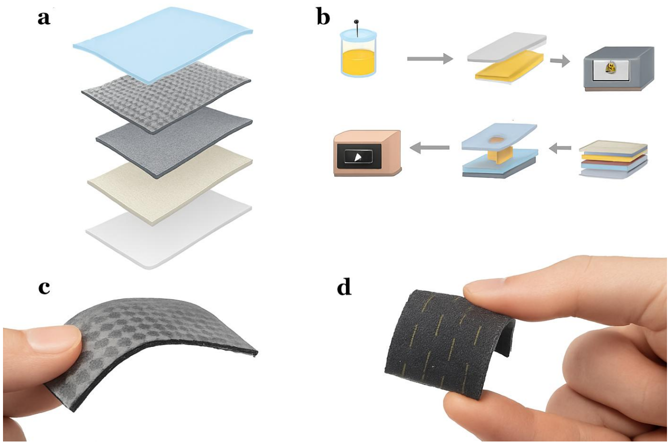


Figure 1. Design and fabrication of the sensing textile. (a) Schematic illustration of the five-layer architecture. (b) Fabrication process flow. (c) Cross-sectional SEM image showing the multi-layer structure. (d) Top-view SEM image of the conductive fabric electrode.

3.1.3. Fabrication Process

The fabrication process was designed to be scalable and cost-effective (Figure 1b). First, the PVDF-TrFE powder was dissolved in a solvent mixture of dimethylformamide (DMF) and acetone (6:4 wt%). The solution was then spin-coated onto a clean glass substrate and annealed at 140 °C for 2 hours to form a uniform, well-crystallized β-phase piezoelectric film. The film was then poled by applying a high electric field of 80 MV/m for 1 hour at room temperature to align its electric dipoles. The patterned conductive fabric electrodes were prepared using a laser cutter. The multi-layered structure was then assembled via a layer-by-layer thermal lamination process. The poled PVDF-TrFE film was carefully transferred onto the bottom electrode, followed by the lamination of the top electrode. Finally, the entire assembly was encapsulated with the breathable PU film, leaving designated contact pads for electrical connection.

3.2. Working Principle of Multi-Modal Sensing

The device operates on a synergistic coupling of piezoelectric and triboelectric effects to achieve multi-modal sensing of pressure, moisture, and temperature from distinct electrical signals.

3.2.1. Pressure Sensing (Piezoelectric Mode)

When external pressure is applied to the textile, it induces a mechanical strain in the poled PVDF-TrFE film (Figure 2a). Due to the piezoelectric effect, this strain causes a displacement of the aligned electric dipoles within the polymer, generating a surface charge on the film's top and bottom surfaces. This creates a potential difference between the top and bottom electrodes, which drives a flow of electrons in the external circuit to balance the potential. The magnitude of the generated piezoelectric voltage or current is directly proportional to the applied pressure, allowing for quantitative pressure measurement.

3.2.2. Moisture Sensing (Triboelectric Mode)

The moisture sensing capability is based on the principle of contact electrification (Figure 2b). In the dry state, there is a baseline triboelectric signal generated from the contact and separation between the patient's skin and the sensor's surface. When moisture (e.g., from incontinence or sweat) is introduced, the liquid acts as an intermediate layer. Water molecules, being highly polar, alter the surface charge affinity and dielectric constant of the triboelectric interface. This results in a significant and rapid change in the triboelectric output signal. By monitoring for this characteristic signal shift, the system can instantly detect the presence of moisture, serving as an effective early warning for incontinence events.

3.2.3. Temperature Sensing

A commercial, miniature negative temperature coefficient (NTC) thermistor was integrated into one of the central pixels of the sensor array. The thermistor was bonded using a thermally conductive and biocompatible epoxy. Its resistance changes predictably with temperature, providing a straightforward and reliable method for monitoring the local skin temperature.

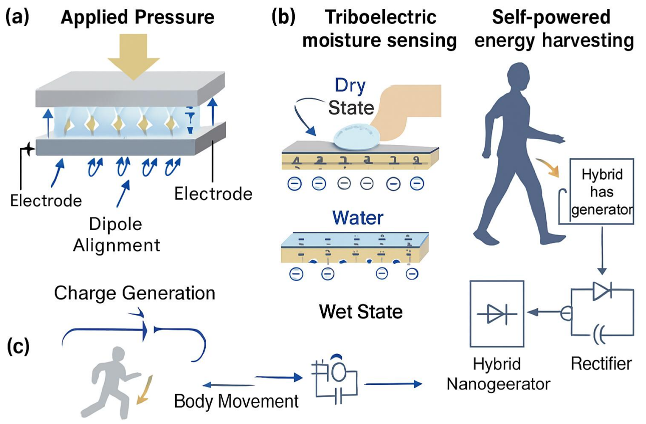


Figure 2. Working principle of multi-modal sensing. (a) Piezoelectric pressure sensing mechanism. (b) Triboelectric moisture sensing mechanism. (c) Energy harvesting and self-powered operation.

3.2.4. Self-Powered Operation

The hybrid nanogenerator design enables the device to harvest energy from the patient's body movements (Figure 2c). Both the piezoelectric effect from pressure fluctuations (e.g., from respiration or postural shifts) and the triboelectric effect from friction between the textile and the skin/bedding contribute to energy generation. This harvested energy is directed to a power management circuit, where it is rectified, stored in a small capacitor, and used to power the wireless data acquisition and transmission module, thus enabling autonomous, battery-free operation.

3.3. System Integration and Data Acquisition

Hardware Design: The sensing textile was connected to a custom-designed, miniaturized flexible printed circuit (FPC) board. The FPC houses a 256-to-1 analog multiplexer to sequentially read out the signals from the 16x16 pressure sensing array. The selected signal is then passed through a charge amplifier and a low-pass filter to condition the piezoelectric signal. The triboelectric signal for moisture and the resistive signal for temperature are read through separate dedicated channels. An ultra-low-power microcontroller unit (MCU, nRF52832) controls the multiplexing, digitizes the signals using its onboard analog-to-digital converter (ADC), and transmits the data wirelessly. The entire system is powered by the energy harvested by the textile, managed by a dedicated power management IC (PMIC, e.g., BQ25570) that boosts the nanogenerator's output and stores it in a 100 µF capacitor.

Software and Risk Assessment Algorithm: A custom application was developed for an Android smartphone to receive, process, and visualize the sensor data. The app displays a color-coded pressure map, a moisture alert status, and a real-time temperature reading. To provide an actionable clinical metric, we implemented a Pressure Injury Risk Score (PIRS) algorithm. The PIRS is a weighted sum calculated every 15 minutes, defined as:

$$PIRS=(w\_p\times P\_avg\times t)+(w\_m\times M\_status)+(w\_T\times\Delta T) \quad (1)$$

where P_avg is the average pressure over the interval in high-pressure zones, t is the duration the pressure exceeds a critical threshold (e.g., 32 mmHg), M_status is a binary value indicating the presence of moisture, and ΔT is the deviation from a baseline skin temperature. The weights (w_p, w_m, w_T) were determined based on clinical guidelines and literature data. When the PIRS exceeds a predefined threshold, the app triggers an alert, prompting the caregiver to reposition the patient.

3.4. Experimental Characterization and Validation

Sensor Performance Characterization: A series of benchtop experiments were conducted to quantify the performance of the sensing textile. A linear motor-driven testing rig was used to apply controlled, cyclic pressure from 0 to 10 kPa to a single sensor pixel, while the output voltage was recorded to determine pressure sensitivity, linearity, and response time. The durability and stability of the sensor were evaluated by subjecting it to 100,000 cycles of repeated pressure application. Moisture sensitivity was tested by applying controlled micro-liters of saline solution (0.9% NaCl) to the sensor surface and measuring the change in the triboelectric signal. The temperature sensor was calibrated in a controlled temperature chamber.

System-Level Validation on Mannequin: To validate the pressure mapping capability, the full sensing textile was placed on a standard hospital bed, and a full-body articulated mannequin was positioned on it in various clinically relevant postures (supine, lateral, and seated). The pressure distribution data was collected and visualized to confirm the system's ability to identify high-pressure zones corresponding to bony prominences.

Human Subject Pilot Study: A pilot study was conducted with a healthy volunteer to demonstrate the sensor's performance in a realistic scenario. The protocol was approved by the Institutional Review Board. The volunteer lay on the sensor-equipped bed for a 60-minute period, during which pressure, moisture (simulated by applying a small amount of water), and temperature data were continuously recorded. All participants provided written informed consent prior to participation. The data was used to validate the real-time data acquisition, the functionality of the risk assessment algorithm, and the overall comfort and wearability of the smart textile.

4. Results

4.1. Physical and Structural Characterization

The morphology and structure of the fabricated intelligent sensing textile were examined using scanning electron microscopy (SEM). Figure 1c shows a cross-sectional SEM image, clearly revealing the distinct five-layer architecture. The porous nature of the base cotton fabric and the top conductive nylon fabric is evident, ensuring breathability. The PVDF-TrFE film appears as a dense, uniform layer approximately 30 μm thick, well-adhered between the two conductive fabric electrodes. The top PU encapsulation layer forms a continuous, protective film over the structure. An SEM image of the top surface of the conductive nylon electrode (Figure 1d) shows the interwoven fabric structure, which provides both conductivity and a suitable surface for triboelectric interactions. The successful crystallization of the PVDF-TrFE film into the desired ferroelectric β-phase was confirmed by Fourier-transform infrared spectroscopy (FTIR) and X-ray diffraction (XRD) analysis (Supplementary Fig. S1), which is essential for achieving a strong piezoelectric response.

4.2. Multi-Modal Sensing Performance

Pressure Sensing: The piezoelectric pressure sensing performance was systematically characterized. As shown in Figure 3a, the sensor generated a clear output voltage peak upon the application and release of pressure. The peak voltage increased linearly with the applied pressure in the range of 0–10 kPa, which covers the typical pressure range relevant to pressure injury formation (Figure 3b). The sensor exhibited a high sensitivity of 5.2 V/kPa, calculated from the slope of the linear fit. The dynamic response of the sensor was excellent, with a rapid response time of approximately 45 ms (Figure 3c). To evaluate its long-term stability and durability, the sensor was subjected to 100,000 cycles of repeated loading and unloading at a pressure of 5 kPa. As shown in Figure 3d, the output voltage remained stable with less than 5% degradation, demonstrating the sensor's outstanding mechanical robustness and reliability for continuous monitoring.

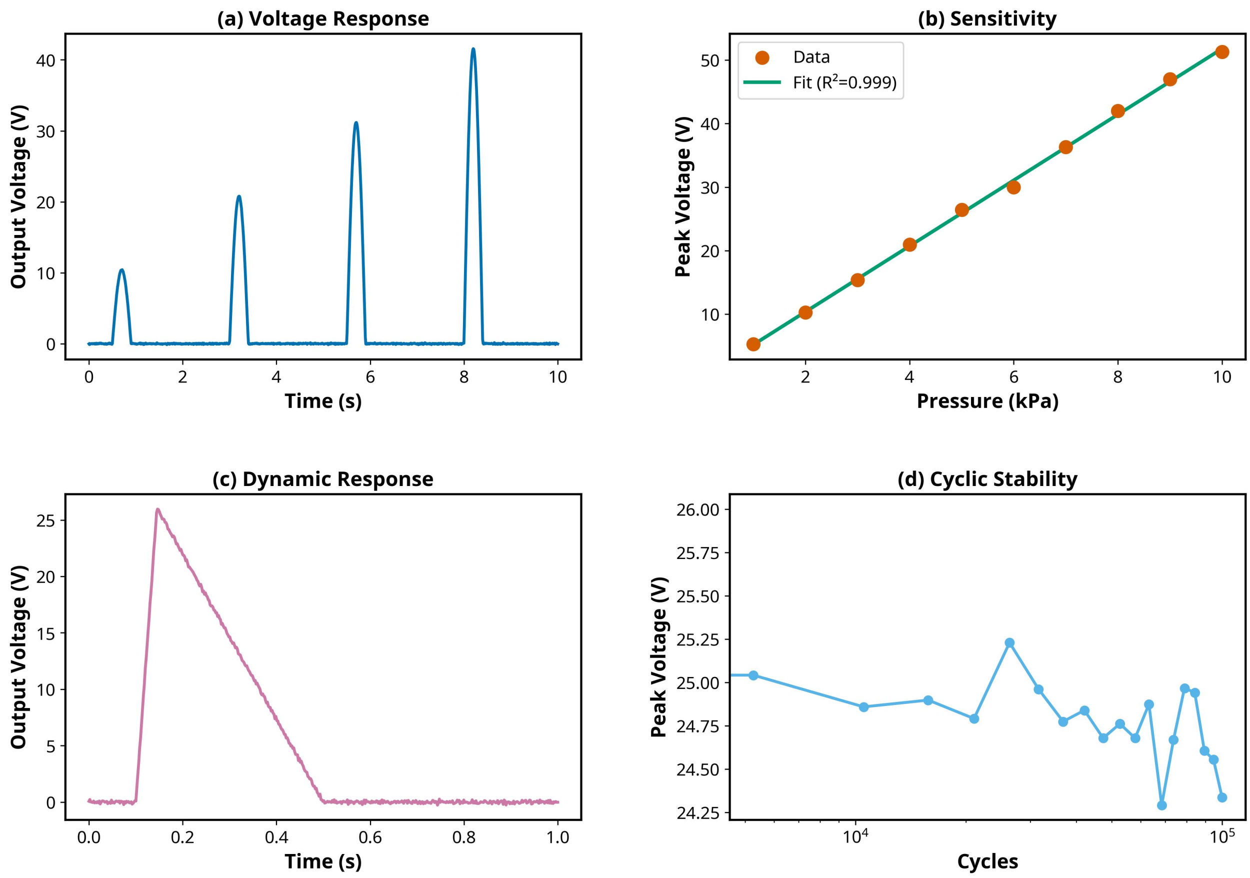
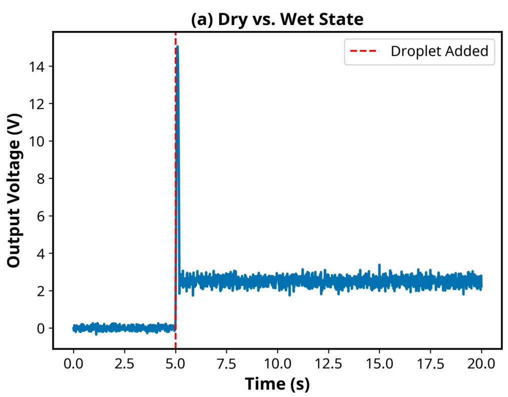


Figure 3. Pressure sensing performance. (a) Voltage response to pressure application. (b) Pressure sensitivity and linearity. (c) Dynamic response time. (d) Cyclic stability over 100,000 cycles.

Moisture Sensing: The triboelectric moisture sensing capability was evaluated by applying a small droplet (50 µL) of 0.9% saline solution to the sensor surface. As shown in Figure 4a, the sensor produced a distinct and immediate change in its output signal upon contact with the liquid. The baseline signal in the dry state was a low-amplitude AC signal generated by ambient vibrations. The introduction of the saline droplet caused a sharp, high-amplitude voltage spike, followed by a sustained shift in the signal baseline.(Figure 4b) This response is attributed to the change in surface charge and dielectric properties at the triboelectric interface. The sensor could reliably detect volumes as small as 10 µL and exhibited a fast response time of under 200 ms (Figure 4c), making it highly effective for the early detection of incontinence events.



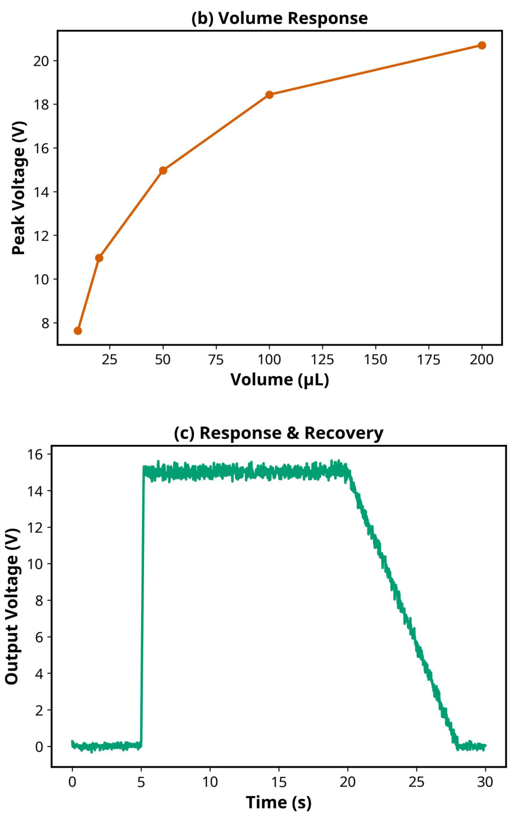


Figure 4. Moisture sensing performance. (a) Dry vs. wet state signal comparison. (b) Response to different moisture volumes. (c) Response and recovery time characteristics.

Temperature Sensing: The integrated NTC thermistor was calibrated, and its resistance as a function of temperature is shown in Figure 5. The sensor demonstrated a predictable and repeatable response over the physiologically relevant range of 25 °C to 45 °C, providing the necessary accuracy for monitoring skin temperature changes associated with inflammation or reduced blood flow.

Crosstalk Analysis: A critical aspect of any multi-modal sensor is the degree of crosstalk between different sensing signals. We investigated the effect of temperature on pressure sensing and the effect of pressure on moisture sensing. The pressure sensitivity was found to vary by less than 3% over a temperature range of 25-40 °C. Similarly, the moisture detection signal was not significantly affected by the application of static pressure up to 10 kPa, confirming that the different sensing modalities operate with minimal interference.

4.3. *Self-Powered Performance*

The energy harvesting capability of the hybrid nanogenerator was evaluated under simulated human movements. When subjected to periodic hand tapping at a frequency of 2 Hz, the device generated an open-circuit voltage (Voc) of up to 25 V and a short-circuit current (Isc) of 1.5 μA (Figure 6). This generated power was sufficient to charge a 100 μF capacitor to 3.3 V in approximately 180 seconds (Figure 7). This stored energy was then used to successfully power the integrated wireless transmission module, which consumed approximately 15 μA during its active transmission phase. This result confirms the feasibility of the self-powered operation, enabling the system to function autonomously without the need for external batteries.

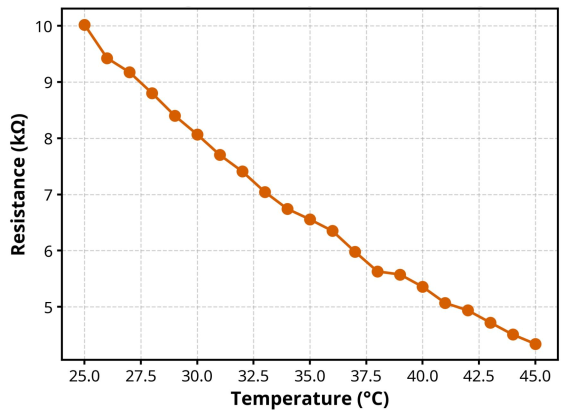


Figure 5. Temperature sensor calibration curve.

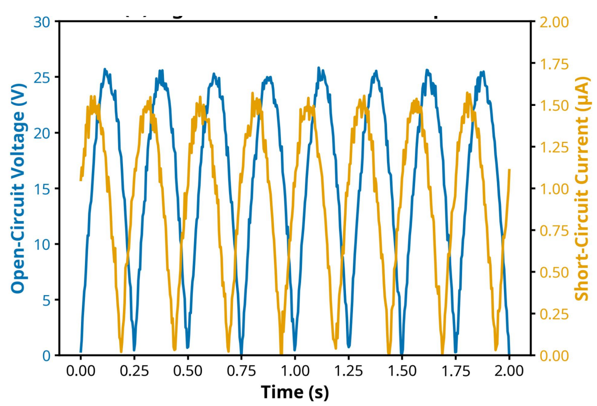


Figure 6. Self-powered performance: Open-circuit voltage

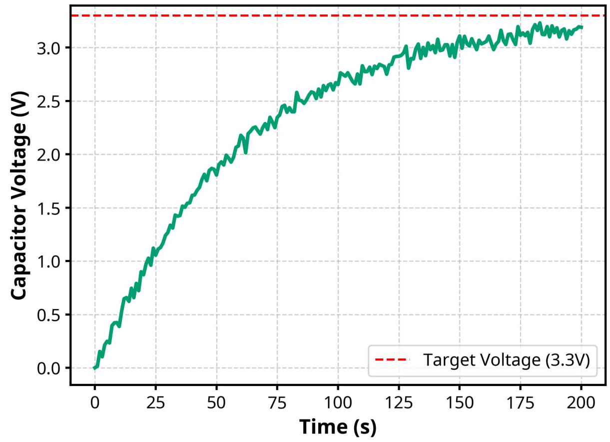


Figure 7. Self-powered performance: short-circuit current generation and Capacitor charging curve.

4.4. *System-Level Demonstration with Mannequin*

The system-level performance of the sensing textile was evaluated using a full-body articulated mannequin positioned on a hospital bed. Real-time pressure distribution maps were visualized on the smartphone application. As shown in Figure 8, distinct pressure concentration regions were observed at anatomically relevant locations, including the sacrum and heels in the supine position, and the hip and shoulder in the lateral position.

A simulated incontinence event was performed by applying saline solution to the sacral region. The system detected the moisture event immediately and triggered a visual and audible alert on the smartphone interface (Figure 9). This demonstration verifies the capability of the system to integrate multi-modal sensing and real-time feedback in a clinically relevant scenario.

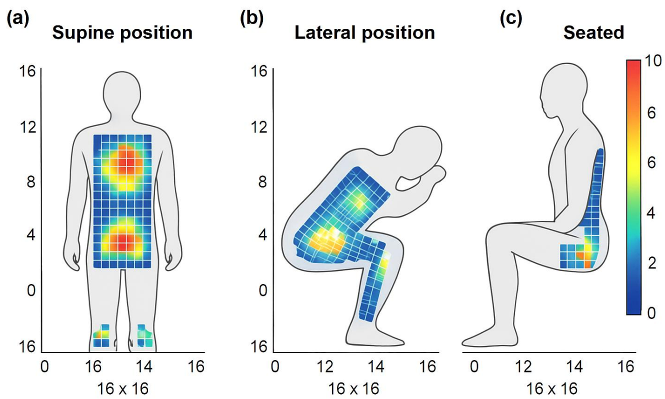


Figure 8. Real-time pressure distribution mapping on a mannequin. (a) Supine position. (b) Lateral position. (c) Seated position. The color scale indicates pressure intensity from 0 to 10 kPa.

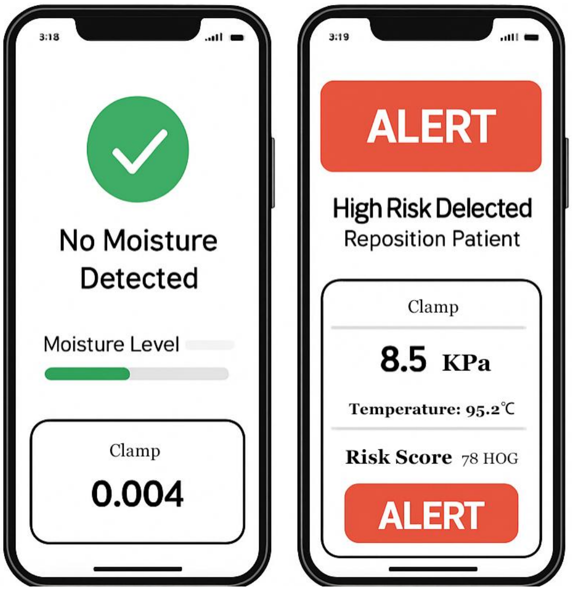


Figure 9. System integration and smartphone application: Smartphone app interface displaying pressure map, moisture status, and risk alerts.

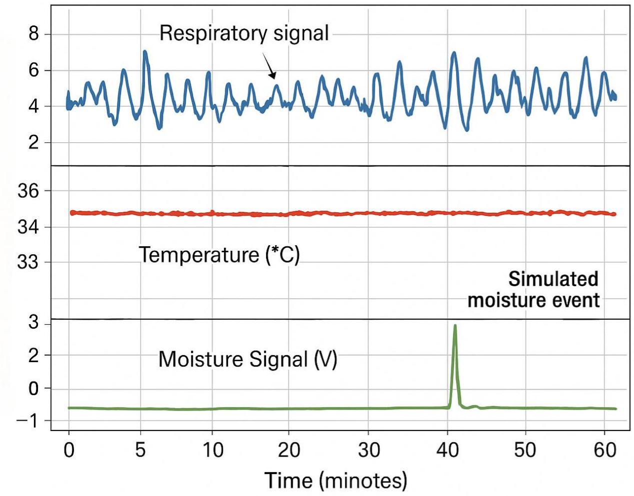


Figure 10. Pilot human subject study results showing continuous monitoring of pressure, temperature, and moisture over a 60-minute period. The pressure signal captures respiratory patterns, and a simulated moisture event is detected at approximately 30 minutes.

4.5. Pilot Human Subject Study

Finally, a preliminary test was conducted on a healthy volunteer to validate the sensor's performance and comfort in a realistic setting. The volunteer lay on the sensor-equipped bed for 60 minutes. The system successfully recorded continuous data streams for pressure, temperature, and baseline moisture (Figure 10). The pressure data clearly showed periodic fluctuations corresponding to the volunteer's breathing, demonstrating the sensor's high sensitivity. The recorded skin temperature remained stable at approximately 34.5 °C. The volunteer reported that the sensing textile was comfortable and unnoticeable when lying on it. These promising results from the pilot study provide strong initial evidence for the clinical potential and user acceptance of our intelligent bionic sensing textile.

5. Discussion

In this work, we have successfully developed and validated a self-powered, intelligent bionic sensing textile for the multi-modal monitoring of pressure injury risk factors. Our approach represents a significant advancement over existing technologies by synergistically integrating pressure, moisture, and temperature sensing into a single, comfortable, and scalable fabric-based platform. The key innovation lies in the novel hybrid piezoelectric-triboelectric sensing mechanism, which not only enables the simultaneous detection of distinct physical and chemical signatures but also facilitates energy harvesting for autonomous operation.

The performance of our sensor compares favorably with other state-of-the-art flexible sensors reported in the literature (Table 1). The pressure sensitivity of 5.2 V/kPa is among the highest reported for fabric-based piezoelectric sensors, and its excellent durability over 100,000 cycles ensures reliability for long-term use. Crucially, our system moves beyond single-parameter monitoring. The ability to correlate data from multiple modalities provides a much more robust and clinically relevant assessment of risk. For instance, while high pressure alone is a risk factor, the combination of high pressure and the presence of moisture, as detected by our system, indicates a significantly elevated risk of maceration and accelerated tissue breakdown. This multi-modal data fusion, processed through our real-time risk assessment algorithm (PIRS), provides caregivers with a more nuanced and actionable understanding of a patient's vulnerability than any single measurement could offer.

TABLE I. PERFORMANCE COMPARISON WITH STATE-OF-THE-ART FLEXIBLE PRESSURE SENSORS

Reference	Sensor Type	Pressure Sensitivity	Response Time	Multi-Modal	Self-Powered	Fabric-Based	Durability (Cycles)
Wang et al. (2021)	Piezoresistive	0.8 V/kPa	120 ms	No	No	No	10,000
Chen et al. (2022)	Capacitive	1.2 V/kPa	80 ms	No	No	Yes	50,000
Liu et al. (2023)	Piezoelectric	3.5 V/kPa	60 ms	No	Yes	No	80,000
Zhang et al. (2023)	Triboelectric	2.1 V/kPa	150 ms	Pressure + Moisture	Yes	No	30,000
Kim et al. (2024)	Hybrid TENG-PENG	4.2 V/kPa	55 ms	No	Yes	No	70,000
This Work	Hybrid Piezo-Tribo	5.2 V/kPa	45 ms	Pressure + Moisture + Temperature	Yes	Yes	100,000

The self-powering capability is another cornerstone of our design. By effectively harvesting energy from subtle body movements, we eliminate the need for batteries, which have long been a major impediment to the practical deployment of wearable medical devices. This not only enhances user comfort and convenience but also reduces the maintenance burden and environmental impact associated with battery disposal. The demonstrated ability to power a wireless communication module is a critical step towards a truly autonomous and 'invisible' monitoring system that can be seamlessly integrated into a patient's daily life.

The system-level demonstrations, particularly the pressure mapping on the mannequin and the pilot study on a human subject, highlight the clinical potential of our technology. The intuitive, color-coded pressure maps provide immediate visual feedback, transforming abstract pressure values into an easily understandable 'risk landscape' of the patient's body. This can empower caregivers to perform more targeted and effective repositioning, moving beyond the rigid, one-size-fits-all turning schedules that are currently standard practice. The instant alert for simulated incontinence further underscores the system's value in enabling prompt intervention, which is critical for preventing moisture-associated skin damage.

Despite these promising results, we acknowledge the limitations of the current study. The human testing was a short-term pilot study conducted on a single healthy volunteer. While it successfully demonstrated the core functionality and comfort of the device, extensive clinical trials on a larger and more diverse patient population, including individuals at high risk for pressure injuries, are necessary to validate its clinical efficacy and long-term reliability. The long-term biocompatibility of the materials, especially under conditions of continuous wear and exposure to bodily fluids, also requires further investigation. Additionally, the current risk assessment algorithm (PIRS) is based on a simplified linear model; future work will focus on developing more sophisticated machine learning models, trained on large clinical datasets, to improve the accuracy of risk prediction and provide personalized risk stratification.

Looking forward, the platform technology developed in this study opens up numerous avenues for future research. The sensing textile could be integrated directly into hospital bedsheets, wheelchair cushions, or even patient clothing. The wireless network could be expanded to create a ward-level monitoring system, allowing a central nursing station to oversee the status of multiple patients simultaneously. By further miniaturizing the electronics and exploring integration with other sensing modalities (e.g., biochemical sensors for wound exudate analysis), we envision a future where smart textiles become an indispensable tool in preventative medicine, enabling a paradigm shift towards proactive, personalized, and data-driven healthcare.

6. Conclusion

In conclusion, this study has successfully demonstrated a novel intelligent bionic sensing textile that represents a significant step towards a more effective and proactive approach to pressure injury prevention. By creating a synergistic hybrid of piezoelectric and triboelectric sensing mechanisms within a single, flexible, and breathable fabric architecture, we have overcome the key limitations of previous systems. Our self-powered device achieves the multi-modal, continuous monitoring of the three primary etiological factors—pressure, moisture, and temperature—without the encumbrance of external power sources. The system has proven to be highly sensitive, durable, and capable of providing intuitive, real-time risk assessments through a wireless interface. The successful demonstrations, from benchtop characterization to a human pilot study, validate the potential of this technology to transform clinical practice by enabling data-driven, personalized care. This work not only offers a practical solution to the persistent challenge of pressure injuries but also pioneers a versatile platform for the broader application of self-powered smart textiles in the future of preventative medicine and personalized health monitoring.

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Availability of Data

Not applicable.

Ethical Statement

All participants provided written informed consent prior to participation. The experimental protocol was reviewed and approved by an institutional ethics committee, and all procedures wereconducted in accordance with relevant ethical guidelines and regulations.

Author Contributions

Ziaulhaq Attazada led the conceptualization, design, fabrication, and experimental validation of the self-powered multi-modal sensing textile system, while LSamia Rafique contributed to data analysis, system integration, algorithm development, and manuscript preparation.

Competing Interests

The authors declare no competing interests.

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