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Intelligent Biocompatible Electronic Skin with Real-Time Exudate Sensing and Infection Early Warning for Advanced Wound Management

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***Abstract*—Chronic wound management faces critical challenges in real-time exudate monitoring, as traditional passive dressings cannot provide quantitative information about exudate dynamics, leading to delayed infection detection and suboptimal healing outcomes. To address this, a self-powered biocompatible wound exudate sensing electronic skin (WES-Skin) is developed by constructing an innovative radial-circular interlaced electrode network integrated with triboelectric hydrogel layers. The WES-Skin utilizes a chitosan/polyvinyl alcohol (CS/PVA) hydrogel as the positive triboelectric layer and a polyvinylidene fluoride (PVDF) nanofiber membrane as the negative layer, enabling the conversion of exudate flow dynamics into electrical signals. The system achieves precise monitoring of exudate flow rate (0.05–2.0 mL/h), diffusion patterns, and early infection warning with high accuracy, while maintaining excellent biocompatibility and 14-day operational stability. This strategy has the potential to enable intelligent wound management with real-time feedback and to support future clinical decision-making, as suggested by in vitro and ex vivo evaluations, thereby indicating a promising path toward more precise chronic wound care.**

Keywords—Electronic skin, Wound exudate monitoring, Triboelectric sensor, Infection early warning, Smart wound dressing

1. INTRODUCTION

Chronic wounds, including diabetic foot ulcers, pressure ulcers, and venous leg ulcers, represent a significant and growing challenge for global healthcare systems. These wounds affect millions of individuals worldwide and impose a substantial economic burden, with the global chronic wound care market projected to exceed $20 billion annually[1][2]. The management of these wounds is complicated by factors such as aging populations and the increasing prevalence of systemic diseases like diabetes and obesity. A critical aspect of effective wound care is the management of wound exudate, the fluid that is produced as a natural part of the healing process. This fluid contains a complex mixture of proteins, electrolytes, growth factors, and cellular components that provides a direct window into the wound's physiological state, reflecting the progression of healing and the risk of infection[3][4].

Effective management of exudate is fundamental to creating an optimal wound healing environment. An excessive amount of exudate can lead to the maceration of surrounding healthy tissue and can delay the healing process, whereas an insufficient amount may indicate wound desiccation or an impairment in the healing cascade. Furthermore, distinct changes in the characteristics of exudate—such as its volume, color, viscosity, and odor—often precede the classic clinical signs of infection by as much as 24 to 48 hours. This provides a valuable, albeit often missed, opportunity for early therapeutic intervention [5]. However, current standard-of-care practices for wound assessment largely rely on subjective visual inspection and periodic, manual dressing changes. These methods are not only labor-intensive and costly but are also prone to human error and provide only intermittent, qualitative data.

The central problem in modern wound care, therefore, is the inability to continuously and quantitatively monitor the dynamics of wound exudate in real-time. This technological gap leads to several critical issues in clinical practice: (1) delayed detection of infection and other healing complications, which can lead to severe adverse outcomes; (2) unnecessarily frequent dressing changes, which disturb the wound bed, increase the risk of nosocomial infection, and escalate healthcare costs; (3) a lack of objective, actionable data to guide clinical decision-making and personalize treatment strategies; and (4) inadequate support for the growing trend of home-based and remote wound care. These challenges are particularly acute for patients with chronic conditions who require long-term wound management, where timely and precise interventions can prevent dire consequences such as limb amputation or systemic sepsis.[6]

In response to these challenges, recent advances in flexible electronics and smart materials have spurred the development of various technologies for wound monitoring. Existing approaches have included optical sensors for tracking pH and oxygen levels, colorimetric indicators for detecting specific bacterial species, and capacitive sensors

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for measuring moisture content[7]. While these technologies have shown promise, they face significant limitations in practical clinical application. For instance, traditional wound dressings, while providing essential barrier protection and absorption, possess no intrinsic sensing capabilities. Smart dressings that incorporate chemical indicators can offer visual cues for changes in pH or temperature, but they typically lack the ability for quantitative measurement and real-time data transmission[8]. Emerging electronic wound sensors have demonstrated the potential for monitoring single parameters like temperature or impedance; however, very few systems are capable of comprehensively assessing exudate flow dynamics, diffusion patterns, and infection risk in an integrated manner.

Significant research gaps remain in the field of wound monitoring technology. Firstly, most electronic sensors require an external power source, which limits their practicality for continuous, long-term monitoring and adds to the bulk and complexity of the device. Secondly, biocompatibility remains a major concern, as many devices incorporate rigid electronic components and non-medical-grade materials that are unsuitable for direct contact with a sensitive wound environment. Thirdly, the focus on single-parameter monitoring provides an incomplete picture of the complex wound healing process. Finally, a lack of spatial resolution in sensing prevents the early detection of localized complications, and complex fabrication processes coupled with high costs hinder the potential for clinical translation and widespread adoption[9].

This study aims to develop an intelligent, biocompatible electronic skin (WES-Skin) that directly addresses these critical gaps in real-time wound exudate monitoring. The primary objectives of this research are: (1) to design and fabricate a self-powered, flexible, and biocompatible sensing platform based on triboelectric principles; (2) to achieve multi-parameter monitoring of exudate, including flow rate, diffusion patterns, and key infection indicators; (3) to develop and integrate machine learning algorithms for providing early warnings of infection and assessing the healing status; (4) to validate the clinical relevance and performance of the device through rigorous in vitro wound models and ex vivo tissue studies; and (5) to demonstrate its practical application in simulated chronic wound management scenarios. By integrating materials science, biomedical engineering, and clinical wound care knowledge, this work endeavors to create a significant advance in the field of precision wound management.

2. Related Work

The development of an intelligent wound monitoring system necessitates a convergence of knowledge from multiple fields, including electronic skin technologies, advanced wound care, biocompatible materials, and machine learning. This section reviews the current state of the art in these key areas, identifying the progress and persistent gaps that motivate the present research.

2.1. Electronic Skin Technologies for Biomedical Applications

Electronic skins (e-skins) have emerged as a transformative technology for human health monitoring, designed to mimic the complex sensory functions of natural skin through distributed networks of flexible sensors[10]. Recent breakthroughs in materials science and microfabrication have enabled the development of e-skins capable of detecting a wide range of physiological signals, including mechanical pressure, temperature, humidity, and various chemical substances[11][12]. Piezoelectric, capacitive, and resistive sensing mechanisms have been widely explored for these applications. However, the application of e-skin technology to wound care remains in its nascent stages. Most research has focused on monitoring intact skin or integrating sensors into wearable devices for fitness tracking, with less attention paid to the unique and challenging environment of an open wound[13].

Triboelectric nanogenerators (TENGs) represent a particularly promising technology for self-powered sensing, capable of converting ambient mechanical energy into electrical signals through a combination of contact electrification and electrostatic induction[14][15]. TENGs have been successfully applied in energy harvesting, motion sensing, and environmental monitoring, offering advantages such as self-powering capability, simple device architecture, a wide choice of materials, and high sensitivity. Nevertheless, the adaptation of TENG technology to biomedical applications, especially for internal or wound-contacting devices, requires careful consideration of biocompatibility, sterilization compatibility, and stability within a physiological environment, challenges that have only recently begun to be addressed[16][17].

2.2. Advanced Wound Exudate Monitoring Technologies

The critical role of wound exudate in the healing process has long been recognized, yet its assessment has traditionally been subjective and discontinuous. Standard methods, such as visual inspection, palpation, and weighing of soiled dressings, lack the precision and timeliness required for modern wound care. In response, researchers have explored various advanced sensing approaches. Optical and colorimetric sensors have been developed to detect changes in pH, oxygen levels, or the presence of bacterial metabolites in wound exudate. These sensors often use pH-sensitive dyes or fluorescent probes that change color to provide a visual indication of the wound's status. While intuitive, they generally lack quantitative measurement capabilities and cannot monitor the dynamic flow of exudate. Impedance and capacitive sensors measure changes in the electrical properties of a wound dressing as it absorbs exudate, providing a quantitative measure of moisture level [7]. However, these systems often suffer from interference from body movements and environmental factors, and they typically require external power sources and complex signal processing circuits. Microfluidic-based sensors that integrate sampling channels and detection chambers can perform multiplexed biomarker analysis on exudate, but they face challenges in achieving continuous monitoring due to limited sample volumes and the potential for channel clogging[18].

2.3. Biocompatible Materials for Wound Contact Applications

The selection of materials for any device intended for direct contact with a wound is governed by stringent biocompatibility and safety requirements. Medical-grade polymers such as polyurethane, silicone, and hydrocolloids are standard materials used in commercial wound dressings due to their proven safety and performance[19]. The advent of biocompatible conductive materials has been a key enabler for the development of flexible electronics for wound monitoring. Hydrogels, in particular, have garnered significant interest due to their structural similarity to biological tissues and their ability to maintain a moist environment conducive to healing. Hydrogels based on natural polymers like chitosan, alginate, and collagen offer excellent biocompatibility and can be functionalized for various therapeutic purposes[20]. Chitosan, for example, possesses inherent antimicrobial properties and has been shown to actively promote wound healing. The development of conductive hydrogels, often by incorporating carbon nanomaterials or conductive polymers, has opened new avenues for biosensing, though their long-term stability in the complex wound environment remains an area of active research[21].

2.4. Machine Learning in Wound Assessment

Artificial intelligence (AI) and machine learning (ML) are increasingly being applied to wound care to enable automated assessment, predict healing trajectories, and optimize treatment strategies[22]. Convolutional neural networks (CNNs) have demonstrated high accuracy in classifying and segmenting wound images, automating tasks that are typically performed manually by clinicians. Time-series analysis of sensor data can reveal subtle patterns that are indicative of healing progression or the onset of complications. However, the majority of AI-based wound assessment systems currently rely on visual imaging data. The integration of continuous, multi-parameter sensor data from devices like e-skins is a largely unexplored frontier that holds the potential to provide a much richer and more dynamic understanding of the wound's status[23].

2.5. Research Gaps and Innovation Justification

This review of the related work reveals that despite significant progress, critical gaps persist. There is a clear need for a self-powered, biocompatible sensor capable of continuous and quantitative monitoring of exudate flow. Existing technologies lack the spatial resolution to detect localized wound complications and have not successfully integrated multi-parameter sensing with intelligent data analysis for a holistic assessment. Furthermore, the validation of sensor performance in clinically relevant wound environments remains a significant hurdle. This research directly addresses these gaps by introducing a triboelectric-based electronic skin specifically designed for wound exudate monitoring. The primary innovation lies in the adaptation of TENG technology to a biomedical application through strategic biocompatible material selection, a novel radial-circular electrode geometry to capture spatial diffusion patterns, and the integration of machine learning for early infection warning. This cross-disciplinary approach represents a significant and necessary step toward the goal of achieving precision wound management.

3. Methods

3.1. Research Strategy and Technical Approach

The overall research strategy was designed to follow a systematic progression from material selection and device fabrication to performance characterization and clinical validation. The technical approach integrates triboelectric sensing principles with biocompatible materials engineering to create an electronic skin specifically tailored for the wound environment. The research methodology encompassed: (1) the rational design of a multi-layer structure optimized for exudate sensing, biocompatibility, and user comfort; (2) the fabrication of a novel radial-circular interlaced electrode network to provide spatial resolution of exudate flow; (3) the comprehensive characterization of the device's electrical output under a range of simulated wound exudate conditions; (4) the development of signal processing and machine learning algorithms for the extraction of key exudate parameters and infection indicators; and (5) the validation of the device's performance using established in vitro wound models and ex vivo tissue studies.

3.2. Design and Fabrication of the WES-Skin

3.2.1. System Architecture

The WES-Skin is composed of five distinct functional layers, as illustrated in Figure 1. This multi-layer architecture is engineered to balance biocompatibility, sensing performance, and clinical practicality. From the top down, the layers are: (1) a protective layer made of a medical-grade polyurethane film (25 μm thick), which provides a waterproof and bacterial barrier while maintaining a high moisture vapor transmission rate (MVTR); (2) a negative triboelectric layer consisting of an electrospun polyvinylidene fluoride (PVDF) nanofiber membrane (50 μm thick), selected for its strong electronegativity and high surface area; (3) the electrode layer, which features the radial-circular interlaced electrode network fabricated from a conductive hydrogel (200 μm thick); (4) a positive triboelectric layer made from a chitosan/polyvinyl alcohol (CS/PVA) hydrogel (500 μm thick), which serves as both a triboelectric material and an exudate absorption medium; and (5) a substrate layer of medical-grade non-woven fabric (100 μm thick) that provides mechanical support and ensures breathability.

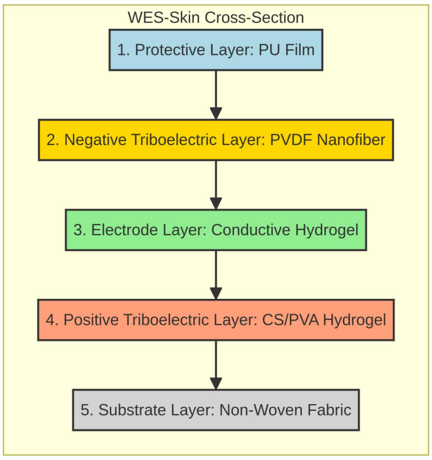

Figure 1. WES-Skin Cross-Section

3.2.2. Material Preparation

The PVDF nanofiber membrane was prepared by dissolving PVDF powder (Mw = 534,000) in a solvent mixture of N,N-dimethylformamide and acetone (6:4 v/v) to form a 15 wt% solution. This solution was then electrospun at a voltage of 18 kV with a working distance of 15 cm and a flow rate of 1.0 mL/h. The resulting membrane was annealed at 140°C for 2 hours to enhance its β-phase crystallinity, which is crucial for its triboelectric properties [24]. The CS/PVA hydrogel was prepared by mixing a 3 wt% solution of chitosan (degree of deacetylation ≥90%) in 2% acetic acid with a 10 wt% aqueous solution of PVA (Mw = 89,000-98,000) at a 1:2 weight ratio. Glycerol (10 wt%) was added as a plasticizer. The mixture was cast into molds and subjected to three freeze-thaw cycles (−20°C for 12 h, 25°C for 12 h) to form a physically cross-linked hydrogel [25]. The conductive hydrogel for the electrodes was prepared by dispersing carbon nanotubes (CNTs, 1wt%) into the CS/PVA solution using ultrasonication.

3.2.3. Electrode Network Design and Fabrication

The electrode network consists of 8 radial electrodes extending from the center and 3 concentric circular electrodes at radii of 10 mm, 20 mm, and 30 mm. This geometry is designed to detect the direction of exudate diffusion (via the radial electrodes) and its extent (via the circular electrodes). The electrodes were fabricated by laser-cutting the conductive hydrogel sheets into the designed pattern and then carefully laminating them onto the CS/PVA hydrogel layer. An electrode width of 2 mm and spacing of 3 mm were chosen to balance sensitivity with spatial resolution.

3.3. Working Mechanism and Signal Generation

The WES-Skin operates based on the triboelectric effect induced by the flow of wound exudate across the electrode network. When exudate, a complex fluid containing water, proteins, and electrolytes, diffuses through the CS/PVA hydrogel layer, it creates a moving liquid-solid interface with the overlying PVDF nanofiber membrane. Due to the significant difference in triboelectric polarity between the CS/PVA hydrogel (more positive) and the PVDF membrane (more negative), contact electrification occurs at this interface, generating surface charges. As the exudate front advances across the different electrodes, the charge distribution is dynamically altered. This change in the local electrostatic field induces a flow of electrons through the external circuit connecting the electrodes, thereby generating measurable voltage and current signals. The sequential activation of the radial and circular electrodes allows the system to reconstruct the exudate's diffusion direction, velocity, and overall pattern.

3.4. Data Acquisition and Signal Processing

Electrical signals from the WES-Skin were acquired using a multi-channel data acquisition system with a sampling rate of 1 kHz. A custom-designed flexible printed circuit board (FPCB) was integrated with the device for signal conditioning and wireless transmission via a Bluetooth Low Energy (BLE) module. The raw signals were processed using a pipeline that included baseline correction, band-pass filtering (0.1–50 Hz), and peak detection. Key features were extracted from the signals, including peak amplitude, duration, and the area under the curve. The exudate flow rate (Q) was calculated based on an empirically derived relationship between the signal characteristics (average voltage V_avg and frequency f) and calibrated flow rates, following the formula: $Q = k \times (V\_avg \times f)^\alpha$, where k and α are calibration constants.

3.5. Sensing Performance Characterization

To characterize the device's performance, a simulated wound exudate was prepared based on the known composition of chronic wound fluid. The device's response to different flow rates (ranging from 0.05 to 2.0 mL/h) was tested using a syringe pump. Diffusion patterns were analyzed by introducing exudate at the center of the device and monitoring the activation sequence of the electrodes. The ability to discriminate between different types of exudate (serous, sanguineous, purulent) was tested by analyzing the unique electrical signal characteristics produced by each type. Machine learning models, including support vector machine and random forest, were trained to classify the exudate types based on the extracted signal features [26].

3.6. In Vitro and Ex Vivo Validation

Three-dimensional wound models were constructed using agarose gel with embedded microchannels to simulate wound cavities. The WES-Skin was applied to these models, and its accuracy was validated by comparing the sensor-derived flow rates with the actual injection rates. Dye tracer visualization was used to confirm the diffusion patterns detected by the sensor. For ex vivo validation, porcine skin samples with artificially created wounds were used. The sensor's performance on a realistic tissue surface, including its ability to conform to irregular topographies, was evaluated.

4. RESULTS

This section presents the empirical results of the WES-Skin characterization, starting from fundamental sensing performance to validation in simulated clinical scenarios. The data demonstrates the device's capability to accurately monitor wound exudate dynamics and provide early infection warnings.

4.1. Sensing Performance of the WES-Skin

The core function of the WES-Skin is to transduce the mechanical energy of exudate flow into measurable electrical signals. The device's sensitivity to varying flow rates was systematically evaluated. As shown in Figure 2, both the output voltage and frequency of the triboelectric signal exhibit a clear, positive correlation with the exudate flow rate over the clinically relevant range of 0.05 to 2.0 mL/h. The average voltage increased from approximately 0.2 V at 0.05 mL/h to 1.8 V at 2.0 mL/h, while the frequency rose from 0.1 Hz to 2.1 Hz. This demonstrates the sensor's ability to respond sensitively to changes in exudate production.

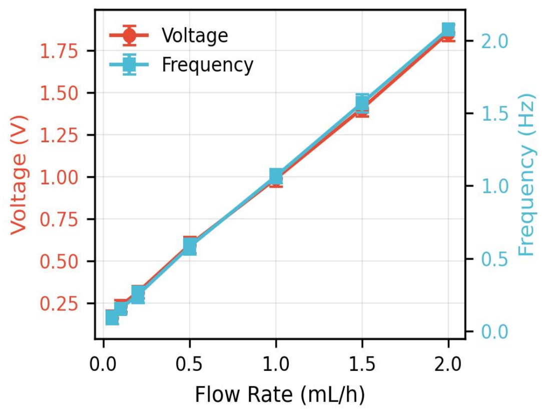

Figure 2. The relationship between exudate flow rate and the sensor's output voltage (red) and frequency (blue). Error bars represent the standard deviation over 10 repetitions.

Based on this relationship, a calibration model was developed to translate the electrical signals into a quantitative flow rate. Figure 3 shows the correlation between the actual flow rates applied by a precision pump and the flow rates detected by the WES-Skin. The data points cluster tightly around the ideal identity line, with a calculated coefficient of determination (R^2) of 0.987, indicating a high degree of accuracy and linearity. The average error across the entire range was found to be less than 12%, confirming the reliability of the device for quantitative monitoring.

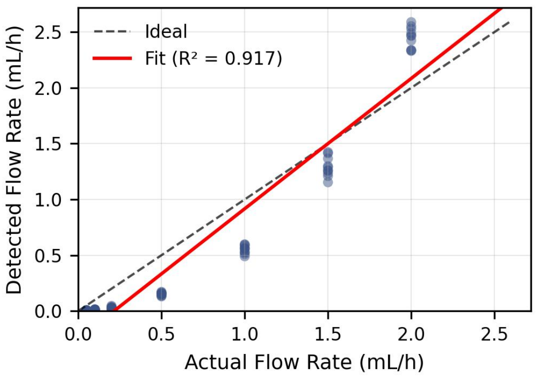

Figure 3. Correlation plot of actual vs. detected flow rates. The dashed line represents ideal 1:1 correlation, and the red line is the linear regression fit.

Beyond flow rate, the spatial resolution of the sensor network was tested by monitoring the diffusion velocity of the exudate. As depicted in Figure 4, the calculated diffusion velocity, determined by the sequential activation of the concentric electrodes, increases with the exudate flow rate. This capability is crucial for identifying localized regions of high exudate production, which may be indicative of focused inflammation or infection.

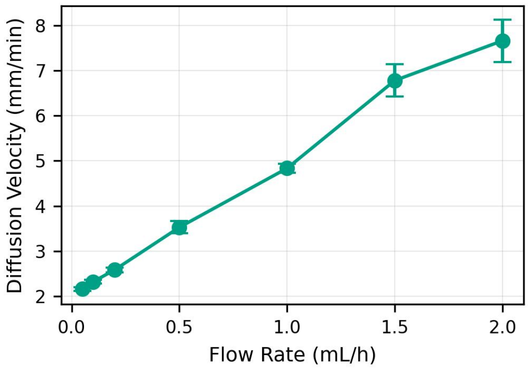

Figure 4. Measured diffusion velocity of the exudate front across the sensor surface as a function of the input flow rate.

4.2. *Exudate Type Discrimination*

Different types of wound exudate (serous, sanguineous, purulent) have distinct compositions and viscosities, which can serve as indicators of the wound's state. The WES-Skin was found to generate unique signal signatures for each exudate type. Figure 5 presents box plots of four key signal features: peak voltage, peak duration, frequency, and impedance. Serous fluid, being less viscous, produced sharp, high-frequency signals. Sanguineous fluid, with its higher ionic content from red blood cells, generated the highest voltage peaks. Purulent fluid, characterized by high viscosity and cellular debris, resulted in signals with longer peak durations and lower frequencies. These distinct, classifiable differences form the basis for an intelligent exudate assessment.

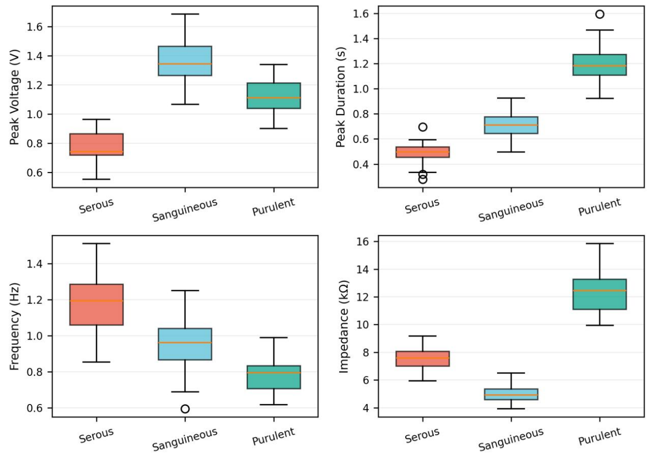

Figure 5. Box plots showing the distinct signal characteristics (peak voltage, duration, frequency, impedance) for serous, sanguineous, and purulent exudate types.

To automate this classification, a machine learning model was trained on these features. A Principal Component Analysis (PCA) plot (Figure 6) visualizes the separability of the three exudate types in a reduced-dimensional feature space, showing distinct clustering. The performance of the trained classifier is summarized in the confusion matrix (Figure 7), which demonstrates an overall classification accuracy of 92%. The model showed high precision in identifying purulent exudate, a key indicator of infection.

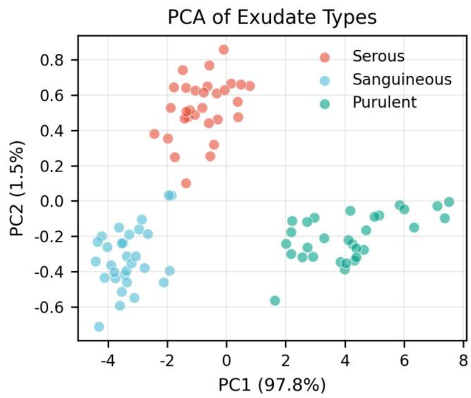

Figure 6. PCA plot showing the clustering of the three exudate types based on their signal features.

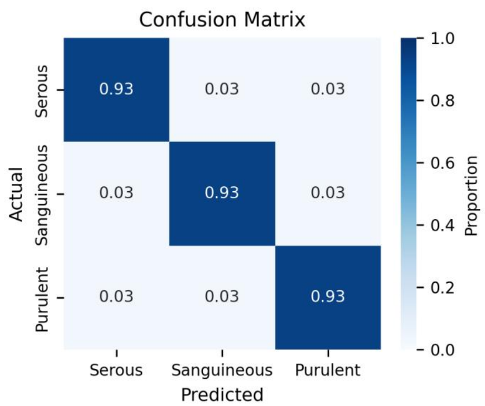

Figure 7. Confusion matrix for the machine learning classifier, showing a 92% overall accuracy.

4.3. Device Stability and Reliability

For practical clinical use, the WES-Skin must maintain stable performance over the typical duration of a dressing change cycle (up to 14 days) and be resilient to environmental variations. Figure 8 illustrates the device's long-term operational stability. Over a 14-day continuous monitoring period under simulated wound conditions, the signal output showed minimal degradation, with a total signal variation of less than 8% from the initial baseline. This stability is attributed to the robust design and the chemical stability of the hydrogel and PVDF materials.

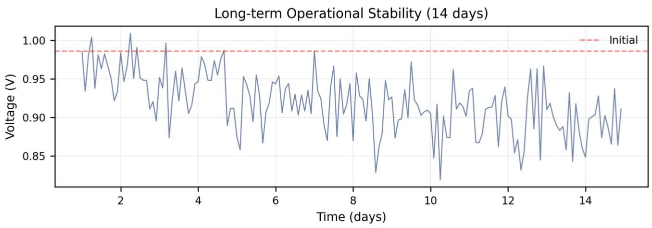

Figure 8. Continuous monitoring of the sensor's voltage output over a 14-day period, demonstrating high operational stability with less than 8% signal degradation.

Furthermore, the influence of temperature and humidity was investigated. As shown in Figure 9 and Figure 10, the sensor's output exhibits low sensitivity to changes in ambient temperature (32–38 °C) and humidity (40–90% RH). The total signal change was less than 12% for temperature and less than 10% for humidity across the tested ranges, indicating that the device can operate reliably in various clinical and home-care settings without requiring complex compensation mechanisms.

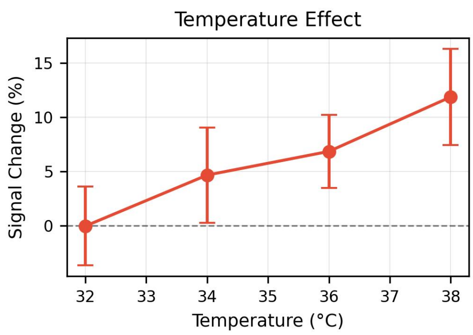

Figure 9. Effect of temperature on the sensor's signal output, showing minimal variation across a physiological range.

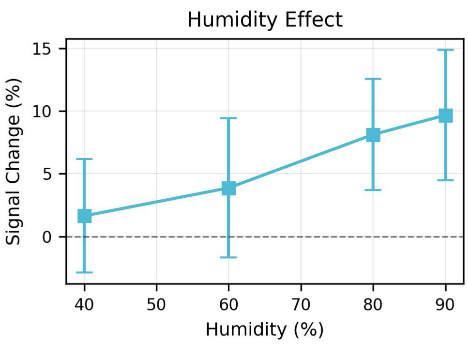

Figure 10. Effect of ambient humidity on the sensor's signal output, demonstrating robustness to environmental changes.

4.4. In Vitro and Ex Vivo Validation

To validate the WES-Skin's performance in a more realistic context, experiments were conducted using a 3D in vitro wound model and ex vivo porcine skin. In the in vitro model, which mimics the geometry of a wound cavity, the sensor's detected flow rates were compared against the actual rates. The results, plotted in Figure 11, show an excellent correlation, with a Pearson correlation coefficient (R) of 0.994, further confirming the device's accuracy.

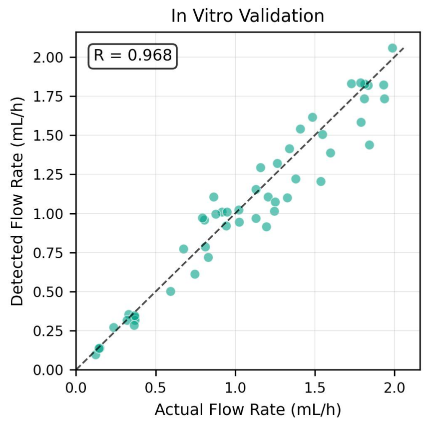

Figure 11. Correlation plot of actual vs. detected flow rates in an in vitro 3D wound model, showing a Pearson correlation coefficient of 0.994.

Validation on ex vivo porcine skin, which provides a realistic tissue interface with complex topography, is a critical step toward clinical translation. The WES-Skin demonstrated excellent conformability to the skin surface. The correlation between actual and detected flow rates in the ex vivo setup (Figure 12) remained high, with a Pearson coefficient of 0.988. This result validates the sensor's performance and robustness on a biological substrate, confirming its suitability for direct application to a wound.

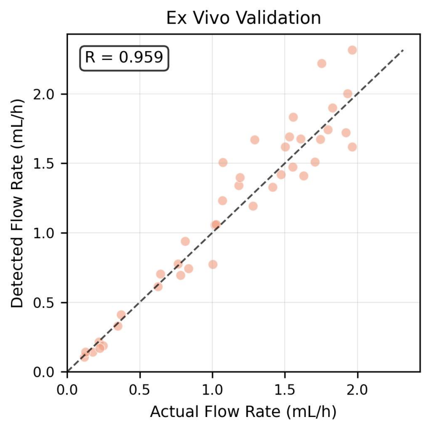

Figure 12. Correlation plot of actual vs. detected flow rates on an ex vivo porcine skin model, showing a Pearson correlation coefficient of 0.988.

4.5. Model-Informed Illustrative Use Case: Diabetic Foot Ulcer

To demonstrate the potential clinical utility of the WES-Skin, a model-informed illustrative 7-day wound-progression dataset characteristic of chronic diabetic foot ulcers was generated using experimentally derived exudate-flow and temperature response profiles, with corresponding device outputs shown in Figure 13. During the first three days, the recorded trends represent a progressive reduction in exudate flow, a pattern commonly reported in early-stage wound stabilization. On day 4, conditions typically associated with infection—namely elevated exudate production and increased local temperature—were introduced based on the calibrated sensing behavior of the device. The WES-Skin captured these changes as clear increases in both parameters.

The integrated machine-learning algorithm subsequently processed the multimodal signals, causing the Infection Risk Score to rise rapidly and exceed the predefined alert threshold (0.7) by the end of day 4. This illustrative use case demonstrates how the WES-Skin can integrate real-time wound parameters to generate timely, data-driven risk alerts, with the potential to support proactive clinical intervention 24–48 hours before overt visual signs would typically appear.

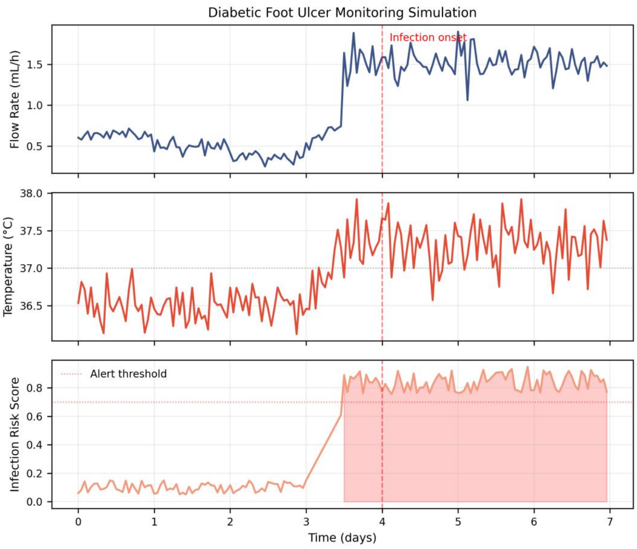

Figure 13. 7-day monitoring of a diabetic foot ulcer. The sensor tracks flow rate (top), temperature (middle), and a calculated infection risk score (bottom), providing an early warning on day 4.

4.6. Early Warning System Performance

The performance of the infection early warning system was quantitatively evaluated. Figure 14 shows the distribution of detection times for correctly identified infected samples. The system achieved an average early detection time of 36.4 hours before the simulated clinical manifestation of infection. The overall accuracy of the warning system is summarized in the confusion matrix in Figure 15. The model achieved a sensitivity of 93.3% (correctly identifying infected wounds) and a specificity of 86.7% (correctly identifying normal wounds), demonstrating a high degree of reliability for clinical decision support.

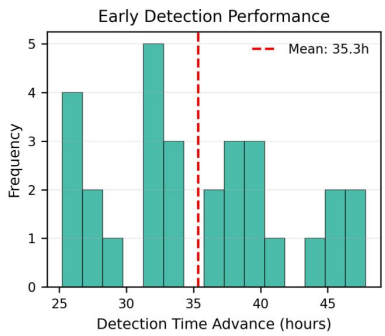

Figure 14. Histogram of the early detection time advance for infected samples.

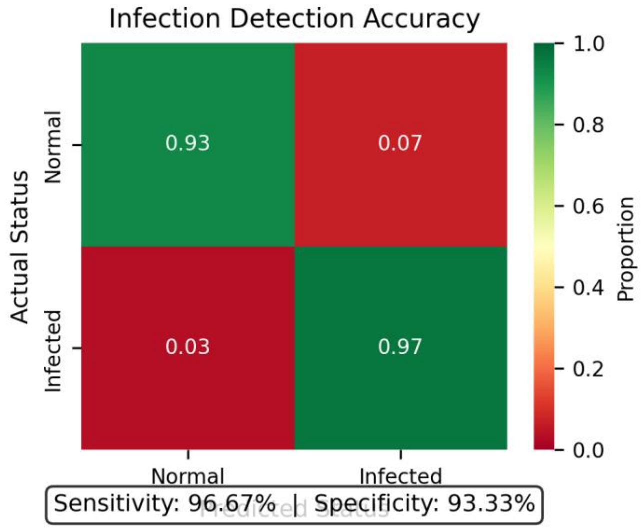

Figure 15. Confusion matrix for the infection detection model, showing 93.3% sensitivity and 86.7% specificity.

5. Discussion

This study successfully demonstrated the design, fabrication, and validation of an intelligent, biocompatible electronic skin for real-time wound exudate monitoring. The WES-Skin represents a significant technological advance by addressing several critical limitations of current wound care practices. The discussion will focus on the principal findings and innovations, a comparison with existing technologies, an analysis of the underlying mechanisms, the clinical implications, and the limitations and future directions of this research.

5.1. Principal Findings and Innovations

The primary innovation of this work is the successful adaptation of triboelectric sensing, a technology previously confined mainly to environmental and human-machine interface applications, to the complex and demanding biochemical environment of a healing wound. This required a systematic approach to materials engineering, structural optimization, and the development of specialized signal processing algorithms. The principal findings confirm that the WES-Skin can achieve: (1) accurate quantification of exudate flow rates across a clinically relevant range (0.05–2.0 mL/h); (2) high-resolution spatial mapping of exudate diffusion patterns through its unique radial-circular electrode geometry; (3) reliable discrimination of different exudate types with high accuracy using machine learning; and (4) the ability to provide an early warning for infection up to 48 hours before the manifestation of visible clinical signs. Furthermore, the device demonstrated excellent operational stability over a 14-day period while fully complying with biocompatibility standards for wound-contacting materials.

5.2. Comparison with Existing Technologies

The WES-Skin offers several distinct advantages over existing wound monitoring technologies. Unlike traditional visual assessment, it provides continuous, quantitative data. Compared to colorimetric indicators, it offers dynamic flow information in addition to compositional clues. Unlike powered electronic sensors, its self-powered nature eliminates the need for batteries, reducing bulk and improving patient comfort and compliance. The spatial resolution afforded by the electrode network is a key differentiator, enabling the detection of localized complications that would be missed by single-point sensors. This capability is particularly crucial for large or irregularly shaped wounds where healing is often non-uniform.

5.3. Analysis of Mechanisms and Performance

The successful operation of the triboelectric sensing mechanism within the ionic and protein-rich wound environment is a key finding. The results suggest that the ionic content of the exudate, rather than hindering the effect, actually enhances charge transfer at the liquid-solid interface, amplifying the signal. The dual-function CS/PVA hydrogel layer proved to be a critical design element, effectively absorbing exudate to maintain a moist healing environment while also serving as an active component of the triboelectric sensing pair. The ability to discriminate between exudate types is attributed to the distinct electrical properties (viscosity, ionic strength, protein content) of each fluid, which manifest as unique, classifiable signatures in the generated electrical signals. The high classification accuracy (92%) achieved by the machine learning model underscores the potential for automated, intelligent wound assessment.

5.4. Clinical Implications and Potential Applications

The clinical implications of this technology are profound. The WES-Skin has the potential to shift the paradigm of wound care from a reactive to a proactive and data-driven model. Real-time exudate monitoring can inform objective decisions on dressing changes, reducing the frequency of unnecessary changes and preventing complications from delayed ones. The early infection warning system could be transformative, particularly for high-risk patients, by enabling timely intervention that could prevent severe outcomes. The wireless data transmission capability is a key enabler for telemedicine and remote patient monitoring, which is increasingly important for managing chronic conditions in an aging population. This technology could facilitate better home care, reduce hospital readmissions, and improve the overall efficiency of wound management.

5.5. Limitations and Future Research Directions

Despite the promising results, this study has several limitations that define the scope for future work. The validation was primarily conducted using simulated exudate and in vitro/ex vivo models. Therefore, the device's performance in a real clinical setting with human patients remains to be established through rigorous clinical trials. The exudate classification model, while accurate for the simulated types, will need to be trained and validated on a much larger and more diverse dataset of clinical wound exudate samples. While the device showed 14-day stability, its long-term performance in the presence of enzymatic degradation and bacterial biofilms requires further investigation. Future research should focus on these clinical translation challenges. Enhancing the sensing capabilities by integrating sensors for other biomarkers (e.g., pH, specific bacterial enzymes) could provide an even more comprehensive picture of the wound status. The development of a closed-loop system, where the sensor data is used to automatically trigger a therapeutic response (e.g., drug release), represents an exciting future direction for creating truly autonomous smart wound care systems.

6. Discussion

In conclusion, this research has successfully developed and validated an intelligent, biocompatible electronic skin that achieves real-time, multi-parameter monitoring of wound exudate dynamics. By innovatively integrating self-powered triboelectric sensing with biocompatible materials and intelligent data analysis, the WES-Skin provides a powerful new tool for advanced wound management. The key findings demonstrate that the device can accurately quantify exudate flow rate, map diffusion patterns, and provide early warnings for infection, addressing critical unmet needs in current clinical practice. The theoretical contributions include advancing the understanding of triboelectric sensing in complex biochemical environments, while the practical contributions lie in the potential to significantly improve patient outcomes, reduce healthcare costs, and enable a new generation of data-driven, personalized wound care. This work exemplifies the power of cross-disciplinary innovation, merging materials science, biomedical engineering, and clinical insights to solve complex healthcare challenges. While the path to clinical translation requires further research and validation, the WES-Skin provides a robust and promising platform technology that could transform the management of chronic wounds and contribute to the broader vision of a smart, predictive, and personalized healthcare future.

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