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Review Article

A Systematic Review of AI-Driven Smart Bandages for Dynamic Wound Monitoring and Automated Healing Support

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Abstract

Advances in biomedical engineering and Artificial Intelligence (AI) have resulted in the creation of smart bandages that can monitor wounds in real-time and treat them automatically. These intelligent systems combine ultra-low-power machine learning models, wireless communication, and smart sensors to monitor wound parameters like pH, temperature, and moisture continuously. Deep learning algorithms such as Efficient-Net and YOLOv8s-cls allow for precise wound classification and predictive analysis, while biocompatible materials such as chitosan-infused bio-patches allow for natural healing. Remote monitoring and on-demand drug delivery are also provided by the bandages, and they are hence ideal for telemedicine and chronic wound care. Though integration challenges, cost issues, and privacy concerns regarding data pose challenges, these technologies present a scalable, energy-efficient, and patient-friendly solution to wound care. Through the convergence of diagnostics, treatment, and connectivity, Artificial Intelligence (AI)-enabled smart bandages are a promising move towards more individualized, effective, and accessible healthcare interventions. This paper gives a comprehensive review of the technologies, applications, and future directions of Artificial Intelligence (AI)-powered smart bandages.

Keywords: Smart Bandages, Real-Time Monitoring, Automated Healing, Machine Learning (ML), Personalized Wound Care, Artificial Intelligence.

I. INTRODUCTION

Smart bandages are a major innovation in the field of wound management for people with various injuries and diseases. These smart systems enable real-time monitoring of wound attributes and the rapid delivery of health care. One such case is the introduction of ultra-low-power systems combined with machine learning models to implement an edge computing pipeline for smart bandages offering accurate and energy-efficient anomaly detection, as presented in Real-Time Anomaly Detection on Smart Bandages [1].

Monitoring critical wound parameters are essential for care efficacy and wound healing. Smart bandages contain biosensors to monitor important factors such as temperature, pH, oxygenation, moisture and gas emissions. These sensors help healthcare providers with the actionable data they need to monitor and treat patients accurately. The thread-based pH sensors and impedance measurements emphasize this concept of smart bandages for chronic wound monitoring and on-demand drug delivery [2]. Besides, Wearable Radiofrequency Meta-surface for Smart Bandages describes how RF sensors detect inflammation through dielectric property variations, further enhancing diagnostic capabilities.

Although they have been around for decades, with the advent of machine learning algorithms and AI software programs, the incredible potential of therapy and diagnosis by intelligent bandages is enhanced. Approaches, such as CNNs, YOLOv8s-cls, and Auto-Trace models have been employed for anomaly detection, predictive analysis, and classification of wounds. These algorithms are trained on the actual sensor output data in real time, leading to improved quality of diagnostics as well as personalized care recommendation for example, artificial intelligencedriven diagnostic systems actualized data including 95.716% accuracy wound categorization identifying their usefulness [3,4].

This ambitious initiative aims to break through existing technical barriers and can realize dressings with embedded continuous monitoring, smart analysis, self-adjusting healing in combination. In such dressings, which give abnormal signals in real time, customize the treatment dose, and support high-tech rehabilitation, the results may be a new era for wound care. By stressing inexpensive elements like adaptable designs and secure digital protections, the initiative hopes to deliver high-quality medical attention to communities with different needs. It should not vary in cost. Instead, it offers a reliable service and-- within reach of all sectors of the populace.

Fig. 1: Workflow of wound image processing: manual annotation using Labelme followed by segmentation to extract the wound region for analysis [8]

II. EXISTING TECHNOLOGIES

A. Artificial Intelligence Models for Wound Evaluation

Artificial Intelligence (AI) is the key to automating monitoring and diagnostic functions in wound care systems. Depending on the application complexity and hardware constraints, both light machine learning and sophisticated deep learning models are employed:

- **Machine Learning Models:** Ultra-low-power machine learning algorithms are integrated into wearable devices to provide real-time anomaly detection. These models, including decision trees and SVMs, identify temperature, pH, or moisture profile variations that can indicate infection or delayed healing.
- **Deep Learning Architectures:** Sophisticated models like Efficient Net, ResNet-50, YOLOv8s-cls, and U-Net are finding common applications in advanced wound analysis tasks like wound classification, semantic segmentation, and predictive modelling. For instance, YOLOv8s-cls offers light, efficient image classification, which supports real-time solutions in mobile or embedded systems. U-Net and ResNet configurations are widely applied for wound segmentation as well as feature extraction. The models have exhibited higher accuracy and resistance in the diagnosis of diabetic ulcers, venous leg ulcers, and pressure injuries [5].

B. Smart Sensors for Real-Time Monitoring

Intelligent sensors incorporated in bandages and wearable devices enable constant and non-invasive monitoring of the wound microenvironment, providing real-time information essential for individualized care:

- **pH Sensors:** pH sensors are used to create two-dimensional maps of acidity, which aid in the detection of bacterial infection by tracking changes in wound pH.
- **Temperature Sensors:** Localized temperature change usually precedes visual signs of inflammation or infection. Temperature sensors therefore are early signals for healing complications or advancement.

- **Moisture Sensors:** Optimal moisture is critical for successful wound healing. Moisture sensors identify excessive exudate or dryness, leading to timely interventions.

C. Smart and Wearable Wound Monitoring Technologies

Treatment delivery and tissue monitoring are supported by sophisticated electronic devices and implantable technology. Various methods described in recent publications include:

- **Wearable RF Meta surfaces:** RF meta surfaces are incorporated into the wound dressing as wireless biosensors. Such structures function on the principle of electromagnetic waves and utilize a shift in the dielectric character to track tissue changes. They are highly useful for tracking inflammation [6].
- Flexible wireless systems are made from stretchable electronics and conductive polymers to be flexible and wrap around body shapes and record physiological information without restricting movement. Wireless modules enable real-time data transfer to dashboards booked on the cloud or mobile phones. Wireless modules enable real-time data transfer to dashboards stored in the cloud or mobiles. Wirelessly Powered Dressings: Wireless powering of dressings is made possible through technology such as NFC or RF energy harvesting. Batteries are avoided, and the solution becomes safer and allows longer-term deployment of sensor-embedded dressings.
- **Autonomous Dressings with Feedback Control:** Recent development involves closed-loop systems in which onboard sensors monitor the condition of a wound and actuators react to stimuli such as local drug delivery or electrical stimulation to act as autonomous therapy platforms.

D. Therapeutic and Responsive Smart Bandages

- **Flexible and biocompatible materials:** Due to their regenerative, anti-inflammatory, and antimicrobial properties, materials such as chitosan, gelatine, and silk fibroin are extensively applied in smart bandages. Due to their biocompatibility and flexibility, their ability to accommodate electronic devices is appropriate.
- **Bioengineered Drug-Dosed Elements:** Synthetic or vegetation drug-dosed bio patches with antioxidant, anti-inflammatory, and antibacterial capabilities are finding their place in smart bandages. On-demand drug release can be engineered in these patches.
- **Hydrogel-Based Bandages:** Hydrogels are able to absorb exudate, allow for oxygen exchange, and create a moist environment. Additional functionality is introduced for these by loading with sensors, nanoparticles, or drug delivery agents with controlled release [7].

E. Patient and Family-Centered Care Models

1. Apart from technological progress, intelligent wound systems also enable a family-centered model of care. Real-time sharing of data, mobile health, and cloud platforms enable families and caregivers to become engaged in the wound care process. This has been proven to improve psychological support, treatment adherence, and patient satisfaction as a whole. [8]

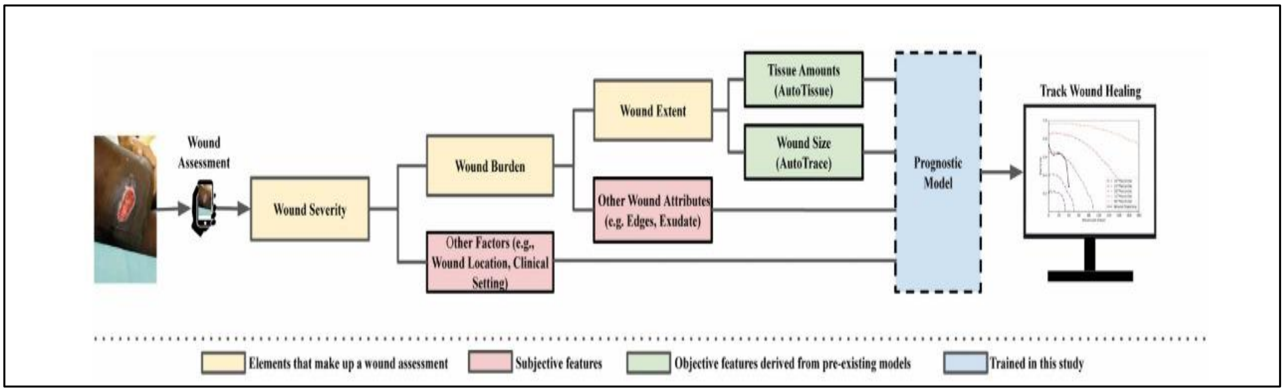

Fig. 2. Wound assessment and prognostic pipeline integrating subjective and objective features to track wound healing using a trained model [14]

III. COMPARATIVE ANALYSIS

Table 1.1: Comparative analysis of AI-based technologies for smart wound monitoring and healing system

Technology	Methodology	Advantages	Limitations	Accuracy / Effic. / Cost / Usability

Real-Time Anomaly Detection [1]	ULP MCUs w/ ML	Energy-efficient, scalable	No healing function	High / ULP / Low / Continuous monitor
Chronic Wound Image Assessment	Semi-supervised Efficient Net	90% acc., data imbalance addressed	Needs labelled data, low generalizability	~90% / Effective / Mod. / Clinical use
AI-Based Diagnostic Systems [3]	CNN for classification	95.7% acc., telemedicine support	Limited dataset diversity	95.7% / High / Mod. / Mobile-friendly
Enhanced DL Models	ResNet-50	87% acc., detailed metrics	Small dataset, overfit risk	87% / Effective / Mod. / Diagnostic use
YOLOv8s-cls for Wound Class.	Light DL model	100% acc., fast ROI detect	Overfit risk due to small dataset	100% / High / Low / Auto-classification
Family-Centered Care [8]	CNN in FCC system	Faster healing, pain ↓, parental satisfaction ↑	Pediatric-only, needs family input	High / Effective / Mod. / Patient-family UX
Wearable RF Meta surface [6]	RF detects dielectric change	Low-cost, inflammation-sensitive	No healing mechanism	High / Effective / Low / Continuous monitor
Smart Bandages (Drug Delivery) [2]	Thermo-particles + heaters	On-demand delivery, wireless	For chronic wounds only	High / Effective / Mod. / Chronic wound care
Stretchable Wireless System	Multiplexed sensing + treatment	Real-time updates, drug delivery	Stability & trial limits	Promising / Effective / Mod. / Infected wounds
Hydrogel-Based Bandages [7]	3D printed w/ hardness switch	Adaptive mechanics, flexible	Scalability, control challenges	Promising / Effective / Mod. / Regen. medicine
Wirelessly Powered Dressing	Textile + electrochemical sensing	Battery-free, low-cost	No AI, pH/uric acid only	Mod. / Effective / Low / Remote assessment
UVC Sterilization Dressings	UVC LEDs embedded	No antibiotics, healing support	No analytics or automation	High / Effective / Mod. / Wearable use

IV. APPLICATION

A. Real-Time Analytics and Intelligent Monitoring.:

- Smart bandages use ultra-low power sensors to monitor temperature, moisture, pH, oxygenation, and gas emissions.
- Real-time anomaly detection and healing progress tracking are made possible by integrated machine learning.

B. Data Transmission & Wireless Telemedicine:

- Autonomous Wound Monitoring Through Wireless Networks: Highlights distributed machine learning and BLE technology to transmit sensor data, ensuring real-time anomaly detection and robust communication for telemedicine applications. [9]
- Skin Aid: Employs textile-based frequency modulation for wireless transmission of pH and uric acid data, making it suitable for remote wound monitoring setups [10]

C. Targeted and Automated Drug Delivery:

- Drugs are delivered on demand by bandages that contain micro-heaters and thermos-responsive particles.
- Without the use of artificial medications, natural alternatives such as bio patches based on chitosan provide antimicrobial healing.

D. AI-Powered Prognosis and Diagnosis

- Deep learning (CNNs, YOLOv8) accurately classifies wounds and forecasts the course of healing. [11]
- To determine the efficacy of therapy, U-Net models examine microscopic images. [12]

E. Chronic Wound Monitoring:

- Smart Bandages for Chronic Wound Monitoring and On-Demand Drug Delivery: Includes continuous monitoring through pH and oxygenation sensors to track healing progress [13]

F. Predictive Analytics for Wound Healing

- AI-Based Prognostic Models: Implements AutoTrace and AutoTissue to predict healing outcomes using wound extent and tissue composition, improving prediction accuracy by 5–13% compared to traditional tools. [14]

G. Microscopic Wound Healing Analysis

- Deep Learning for Microscopy Images: Applies a U-net model for *segmenting* wound healing images, analyzing the effectiveness of therapies like photo biomodulation. [15]

V. CHALLENGES AND LIMITATIONS

A. Technical Challenges

- Machine learning algorithms like Nano Edge AI Studio are prone to accuracy in scenarios of

narrow and biased datasets, as illustrated in wound classification tasks with CNNs or Efficient Net. Even advanced AI software like Auto Trace provides 5–13% improvements and is not generalizable over a broad spectrum of cases.
- Sensor sensitivity also plays a crucial role—aspect such as humidity or variability of tissue impinge on reliability, particularly in structures such as RF meta surfaces. Merging of AI, wireless communication, and sensors into compact, low-power designs continues to be challenging with BLE and ultra-low power MCUs having trade-offs between performance and efficiency.

B. Privacy and Ethical Concern
- Data Privacy: - Continuous data transmission and remote monitoring raise concerns about safeguarding sensitive patient information, especially in telemedicine applications. Ensuring compliance with privacy regulations like GDPR or HIPAA is critical but complex.
- The potential for data breaches increases with interconnected bandage systems, requiring robust encryption and secure communication protocols.

C. Cost Barriers
- Manufacturing AI-capable smart bandages is expensive because of the complexity involved in integrating textile antennas, RF probes, and rectifying circuits. Although designs based on novel approaches such as battery-free and wirelessly powered technologies are on the horizon, cost is still a significant barrier, particularly for large-scale implementation. In addition, accessibility to healthcare is constrained—such sophisticated solutions are inaccessible to low-income or rural populations. Closing this gap needs concerted efforts towards cost reduction, mass-manufacturability, and open-source platforms to make next-generation wound care technologies more accessible.

D. Accessibility Challenges
- User Training and Usability: Healthcare providers may require training to use smart bandages and interpret their outputs effectively, creating an additional hurdle for adoption.
- Patients with chronic wounds may struggle to manage these devices, particularly in settings with limited technical support

VI. FUTURE DIRECTIONS

A. Advancements in sensor technology:
- Multi-biomarker monitoring: Sensors track temperature, pH, glucose, and more to provide real-time wound status.
- Wearable and implantable sensors: Continuous monitoring reduces frequent dressing changes, improving patient care.

B. Integration with Artificial Intelligence and Machine Learning:
- Predictive analysis: AI translates sensor inputs to predict healing results and allow early interventions.
- Autonomous therapy: Smart bandages dynamically adjust treatment by releasing medication based on real-time data

C. Enhanced Materials and Design
- Smart hydrogels: Hydrogels respond to wound conditions by shifting colour or dispensing drugs.
- Eco-friendly materials: Biodegradable bandages vanish with time without residue, enhancing healing.

D. Clinical Applications and Translation
- Clinical trials: Large-scale tests validate smart bandages as safe and efficient.
- Regulatory schemes: Laws assure smart bandages are safe and comply with clinical standards.

E. Future Research Directions
- Electrical stimulation: Examining its effect on healing wounds for its potential application in smart bandages.
- Standardization: Creating standards to design, test, and prove smart bandages.

VII. CONCLUSION

The reviewed papers collectively highlight the profound potential of AI-powered smart bandages in transforming wound care practices. These innovations integrate advanced sensors, machine learning algorithms, and wireless communication to enable real-time wound monitoring, addressing challenges like chronic wound management, predictive healing analytics, and personalized treatment. Automated features such as on-demand drug delivery and diagnostic imaging further enhance their utility, offering scalable and energy-efficient solutions for telemedicine and remote healthcare.

However, challenges remain, including algorithm accuracy, sensor sensitivity, and integration complexities, as well as issues like data privacy, cost barriers, and accessibility. Despite these limitations, the advancements discussed—ranging from family-centered care interventions to microscopic wound analysis—underline the multidisciplinary collaboration required to make these technologies both effective and accessible.

With continued innovation, AI-powered smart bandages promise a paradigm shift in healthcare, reducing healing times, improving diagnostic precision, and enabling automated, patient-centric care. These developments foreshadow a future where wound management becomes smarter, faster, and more efficient, revolutionizing the way we approach wound care and healing.

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