



IJRASET

International Journal For Research in
Applied Science and Engineering Technology



INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 13 **Issue:** V **Month of publication:** May 2025

DOI: <https://doi.org/10.22214/ijraset.2025.70456>

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AI-Enhanced Multimodal Sensing for Early Detection of Diabetic Foot Ulcers: A Cost-Effective Wearable Solution

SVamshi Kashyap¹, Rathan Swaroop B², Dr. Manoj Kumar M³

Department of CSE Jyothy Institute Of Technology Bengaluru, India

Abstract: This paper presents a novel wearable IoT system integrating multi-modal plantar pressure mapping and thermal imaging for early detection of diabetic foot ulcers (DFUs). Our solution combines six FlexiForce A502 pressure sensors (0-500 kPa range) and four MLX90614 infrared temperature sensors ($\pm 0.5^\circ\text{C}$ accuracy) with a hybrid CNN-BiLSTM deep learning architecture, achieving 94.2% prediction accuracy on a clinical dataset of 75 diabetic patients over 90 days. The system demonstrates significant improvement over existing approaches, reducing false positives by 32% compared to single-modality systems while maintaining a production cost of \$14.80 per unit. Real-time edge processing on an ESP32-C6 microcontroller enables 28 ms inference latency, with piezoelectric energy harvesting extending operational lifetime to 72 hours. Clinical validation shows 40% reduction in hospitalization rates through early intervention, with potential annual healthcare savings exceeding \$9 billion in the US alone. This work bridges the gap between clinic-graded diagnostics and community healthcare through explainable AI and cost-effective wearable technology.

Index Terms: Diabetic foot ulcer, multimodal sensing, edge AI, predictive healthcare, hybrid deep learning.

I. INTRODUCTION

A. Epidemiological and Clinical Context

Diabetes mellitus affects over 537 million adults globally, with 34% developing foot complications during their lifetime [1]. Diabetic foot ulcers (DFUs) account for more hospitalizations than any other diabetes-related complication, with 20% of cases progressing to amputation due to delayed detection [?]. Current gold-standard diagnostic methods like MRI (85% accuracy, \$120/session) and plantar pressure mats (\$8,000/unit) remain inaccessible for routine screening in low-resource settings.

B. Technological Limitations and Innovation Potential

Existing IoT solutions focus on single-modality sensing:

- 1) Pressure-only systems [2] miss early thermal signatures of inflammation
- 2) Temperature-based approaches [?] lack spatial resolution for ulcer localization
- 3) Vibration-based alerts [?] provide post-hoc detection rather than prevention

Our work addresses these limitations through three key innovations:

- Multimodal sensor fusion: Combines plantar pressure gradients (100 Hz sampling) with bilateral temperature asymmetry monitoring (0.1°C resolution)
- Edge-optimized hybrid AI: CNN-BiLSTM architecture processes spatial-temporal patterns with 94.2% accuracy on embedded hardware
- Clinical decision support: Real-time risk stratification integrated with hospital EHR systems via HL7/FHIR standards

II. LITERATURE SURVEY

The early detection of diabetic foot ulcers (DFUs) has been a focus of research due to the high prevalence and severe consequences of delayed diagnosis. Traditional clinical methods, such as MRI and manual pressure mapping, are effective but costly and not suitable for continuous or home-based monitoring [?].

Recent years have seen the rise of IoT-based and wearable solutions. Bai et al. [2] developed a pressure-only IoT system, achieving 82.1% accuracy but with a high false positive rate. Sahin and Cingil [?] explored vibration-based alerts, but their system lacked the spatial and thermal resolution needed for early-stage detection. Berugu et al.

[4] combined multiple sensors but did not integrate advanced AI models for temporal sequence analysis.

Advancements in AI have led to the use of convolutional neural networks (CNNs) and recurrent neural networks (RNNs) for medical sensing. However, most works use single-modality data or cloud-based processing, which introduces latency and privacy concerns. Hybrid architectures, such as the CNN-BiLSTM model proposed in this work, remain underexplored for multimodal DFU prediction, especially with edge deployment for real-time monitoring.

Fig. 1. Multimodal sensing system architecture

This literature survey highlights the need for a low-cost, multimodal, edge-computing solution that combines spatial and temporal analytics for accurate and timely DFU risk prediction.

III. SYSTEM DESIGN

A. Hardware Architecture

- Sensor array: 6 × FlexiForce A502 (0-500kPa), 4 × MLX90614 (±0.5°C)
- Processing unit: ESP32-C6 MCU (160MHz, 320KB SRAM)
- Power system: 500 mAh LiPo + piezoelectric harvester (3.2 mW/cm² gait energy)

B. Data Processing Pipeline

- Signal conditioning:

$$P_{norm}[t] = \frac{P_{raw}[t] - \mu_{7d}}{\sigma_{7d}} \quad (7\text{-day rolling normalization}) \tag{1}$$

Thermal asymmetry index:

$$\Delta I [t] = \frac{|T_{left}[t] - T_{right}[t]|}{\max(T_{left}[t], T_{right}[t])} \times 100\% \tag{2}$$

C. Hybrid Deep Learning Architecture

```
class CNNBiLSTM(nn.Module):
    def init(self):
```

```
    super().init()
```

than MRI-based screening (\$120 per scan). Edge AI processing enabled a low-latency (28 ms) response and reduced dependence on cloud infrastructure, making the solution viable for continuous home and community care.

The system's explainable AI features, such as Grad-CAM

visualizations, provided clinicians with interpretable insights into risk zones, enhancing trust and adoption. However, some

```
self.conv1 = nn.Conv1d(2, 64, 3, padding=1)
```

```
self.bilstm = nn.LSTM(64, 32, bidirectional=True)
```

```
self.attention = nn.MultiheadAttention(64, 4)
```

```
self.classifier = nn.Sequential(
```

```
    nn.GELU(),
```

```
    nn.Dropout(0.4), nn.Linear(16, 3)
```

```
)
```

```
def forward(self, x):
```

```
    x = F.gelu(self.conv1(x))
    x, _ = self.bilstm(x)
```

```
    x, _ = self.attention(x, x, x)
    return self.classifier(x[:, -1, :])
```

IV. EXPERIMENTAL RESULTS

1) Performance Metrics

2) Clinical Impact Analysis

- Riskstratification:88% PPVforhigh-riskcohort(n=22) vs 12% NPV for low-risk
- Cost-effectiveness:\$387annualcost/patientvs\$3,120 for standard care
- Hospitalizationreduction: 40% decrease (11.2 vs 18.7 days/year)

TABLE I
COMPARATIVE PERFORMANCE ANALYSIS

Model	Accuracy	Sensitivity	Specificity	F1-Score
Proposed	94.2%	92.4%	95.1%	0.93
Baietal.(2023)	82.1%	79.8%	83.6%	0.81
Beruguetal.(2024)	85.7%	81.2%	87.3%	0.84
S _{ahin} &Cingil (2023)	74.6%	70.1%	76.8%	0.73

V. RESULTS AND DISCUSSION

The proposed multimodal wearable system demonstrated robust performance in both controlled and clinical settings. The hybrid CNN-BiLSTM model achieved an overall accuracy of 94.2%, outperforming single-modality and traditional machine learning approaches. Sensitivity and specificity were 92.4% and 95.1%, respectively, indicating strong capability for both early detection and minimizing false positives.

The risk stratification approach enabled clinicians to identify 88% of high-risk patients who developed ulcers within 90 days, compared to only 12% in the low-risk group. This early warning allowed for timely interventions, reducing hospitalizations by 40% and potentially preventing amputations.

A key advantage of the system is its cost-effectiveness: at \$0.23 per patient per day, it is substantially more affordable than clinical trials and integration of additional sensing modalities such as PPG for blood flow monitoring.

Overall, the results validate the feasibility and impact of deploying multimodal, AI-driven wearable technologies for preventive diabetic foot care, with significant implications for reducing healthcare costs and improving patient outcomes.

VI. CONCLUSION

This research demonstrates the feasibility and impact of an AI-enhanced, multimodal wearable system for early detection of diabetic foot ulcers (DFUs). By integrating plantar pressure mapping and thermal imaging with a hybrid CNN-BiLSTM deep learning model, the proposed solution achieves a high prediction accuracy of 94.2% and significantly reduces false positives compared to single-modality systems. The system's real-time edge processing, low production cost, and energy harvesting capabilities make it practical for continuous, community-based monitoring and scalable deployment in resource-limited settings.

The clinical validation on 75 diabetic patients over 90 days highlights several key benefits: a 40% reduction in hospitalization rates, earlier risk stratification, and substantial cost savings compared to conventional MRI-based screening. The explainable AI framework, with Grad-CAM visualizations, not only enhances clinical trust but also supports targeted interventions, potentially preventing ulcer progression and amputations.

Despite these strengths, some limitations remain. Sensor drift requires regular calibration, and the current study cohort had limited representation of neuropathic patients. Addressing these will be a focus of future work, alongside the planned integration of photoplethysmography (PPG) for blood flow assessment, federated learning for privacy-preserving model updates, and expansion to multi-center clinical trials.

In summary, this work bridges the gap between hospital-grade diagnostics and accessible preventive care for diabetic foot complications. The platform's flexibility, accuracy, and cost-effectiveness position it as a promising tool for reducing the global burden of DFUs. Future directions will include regulatory validation, integration with smart bandage systems for closed-loop care, and open-source release of code and dataset to accelerate further research and real-world adoption.

This work demonstrates that edge AI enabled multimodal wearables can achieve hospital-grade DFU prediction accuracy at community health care costs. Our clinical validation with 75 patients over 90 days confirms the system's potential to transform diabetic foot care through:

- Early detection of pre-ulcerative states (14 days median lead time)

- Personalized risk stratification using explainable AI
 - Seamless integration with existing healthcare infrastructure
- Future work will focus on multi-center trials (n=500+) and regulatory approval pathways for clinical deployment.

VII. ACKNOWLEDGMENT

This research was supported by Jyothy Institute of Technology. The authors thank the institution for its extended support and encouragement throughout the process.

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