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

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 13 Issue V May 2025- Available at www.ijraset.com

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

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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 (±0.5°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 demonstratessignificantimprovementsoverexistingapproaches,reduc- ing false positives by 32% compared to single-modality systems whilemaintainingaproductioncostof$14.80perunit.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% reductioninhospitalizationratesthroughearlyintervention,with potentialannualhealthcaresavingsexceeding$9billionintheUS alone.Thisworkbridgesthegapbetweenclinic-gradediagnostics and community healthcare through explainable AI and cost-effective wearable technology.
IndexTerms: Diabeticfootulcer,multimodalsensing,edgeAI, predictive healthcare, hybrid deep learning.

I. INTRODUCTION

A. EpidemiologicalandClinicalContext

Diabetesmellitusaffectsover537millionadultsglob- ally, 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)remaininaccessibleforroutinescreeninginlow- resource settings.

B. TechnologicalLimitationsandInnovationPotential

ExistingIoTsolutionsfocusonsingle-modalitysensing:
1) Pressure-onlysystems[2]missearlythermalsignatures 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-optimizedhybridAI:CNN-BiLSTMarchitecture processesspatial-temporalpatternswith94.2%accuracy on embedded hardware
- Clinical decision support: Real-time risk stratification integrated with hospital EHR systems via HL7/FHIR standards

II. LITERATURE SURVEY

Theearlydetectionofdiabeticfootulcers(DFUs)has been a focus of research due to the high prevalence andsevere 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. S¸ahinandCingil[**?**]exploredvibration-basedalerts,buttheir system lacked the spatial and thermal resolution needed for early-stage detection. Berugu et al.

[4] combined multiple sensorsbutdidnotintegrateadvancedAImodelsfortemporal sequence analysis.
AdvancementsinAIhaveledtotheuseofconvolu- tional neural networks (CNNs) and recurrent neural networks (RNNs)formedicalsensing.However,mostworksusesingle- modality data or cloud-based processing, which introduces latency and privacy concerns. Hybrid architectures, such asthe CNN-BiLSTM model proposed in this work, remain underexploredformultimodalDFUprediction,especiallywith edge deployment for real-time monitoring.
Fig.1.Multimodalsensingsystemarchitecture
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×FlexiForceA502(0-500kPa),4×MLX90614 (±0.5°C)
- Processingunit:ESP32-C6MCU(160MHz,320KB SRAM)
- Powersystem: 500 mAh LiPo + piezoelectric harvester (3.2 mW/cm^{2}gait energy)

B. Data Processing Pipeline
- Signalconditioning:

$$P_{norm}[t] = \frac{P_{raw}[t]-\mu_{7d}}{\sigma_{7d}} \quad \text{(7-dayrollingnormalization)} \qquad (1)$$

Thermalasymmetryindex:

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

C. HybridDeepLearningArchitecture
classCNNBiLSTM(nn.Module): def init(self):
super().init()
than MRI-based screening ($120 per scan). Edge AI pro- cessing enabled a low-latency (28 ms) response and reduced dependenceoncloudinfrastructure,makingthesolutionviable for continuous home and community care.
Thesystem’sexplainableAIfeatures,suchasGrad-CAM
visualizations, provided clinicians with interpretable insights intoriskzones,enhancingtrustandadoption.However,some

self.conv1=nn.Conv1d(2,64,3,padding=1)
limitationsremain,includingtheneedforperiodicsensor
self.bilstm=nn.LSTM(64,32,bidirectional=True)
recalibrationduetodriftandlimitedvalidationinneuropathic
self.attention=nn.MultiheadAttention(64, 4)
patients.Futureworkwilladdressthesethroughbroader
self.classifier=nn.Sequential(nn.Linear(64, 16),
nn.GELU(),
nn.Dropout(0.4), nn.Linear(16,3)
)
defforward(self,x):
x=F.gelu(self.conv1(x)) x, _ = self.bilstm(x)
x, _ = self.attention(x, x, x) returnself.classifier(x[:,-1,:])

IV. EXPERIMENTAL RESULTS

1) *PerformanceMetrics*
2) *ClinicalImpactAnalysis*

- 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)

TABLEI
COMPARATIVEPERFORMANCEANALYSIS

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

Theproposedmultimodalwearablesystemdemonstratedro- bust performance in both controlled and clinical settings. The hybrid CNN-BiLSTM model achieved an overall accuracy of 94.2%,outperformingsingle-modalityandtraditionalmachine learning approaches. Sensitivity and specificity were 92.4% and 95.1%, respectively, indicating strong capability for both early detection and minimizing false positives.

Theriskstratificationapproachenabledclinicianstoidentify 88% of high-risk patients who developed ulcers within 90 days,comparedtoonly12%inthelow-riskgroup.Thisearly warningallowedfortimelyinterventions,reducinghospital- izations by 40% and potentially preventing amputations.

Akeyadvantageofthesystemisitscost-effectiveness:at $0.23perpatientperday,itissubstantiallymoreaffordable 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

Thisresearchdemonstratesthefeasibilityandimpactof an AI-enhanced, multimodal wearable system for early de- tection 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 continu- ous, community-based monitoring and scalable deployment in resource-limited settings.

The clinical validation on 75 diabetic patients over 90 days highlightsseveralkeybenefits:a40%reductioninhospitaliza- tionrates,earlierriskstratification,andsubstantialcostsavings compared to conventional MRI-based screening. The explain- able AI framework, with Grad-CAM visualizations, not only enhancesclinicaltrustbutalsosupportstargetedinterventions, potentially preventing ulcer progression and amputations.

Despite these strengths, some limitations remain. Sensor drift requires regular calibration, and the current study cohort hadlimitedrepresentationofneuropathicpatients.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.

Insummary,thisworkbridgesthegapbetweenhospitalgradediagnosticsandaccessiblepreventivecarefordiabeticfootcomplications.Theplatform'sflexibility,accuracy,and cost-effectiveness position it as a promising tool for reducing theglobalburdenofDFUs.Futuredirectionswillinclude regulatory validation, integration with smart bandage systems forclosed-loopcare,andopen-sourcereleaseofcodeanddatasetstoacceleratefurtherresearchandreal-worldadoption.

ThisworkdemonstratesthatedgeAIenabledmultimodalwearablescanachievehospitalgradeDFUpredictionaccuracyatcommunityhealthcarecosts.Ourclinicalvalidationwith75patientsover90daysconfirmsthesystem'spotentialtotransformdiabeticfootcarethrough:

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

- PersonalizedriskstratificationusingexplainableAI
- Seamlessintegrationwithexistinghealthcareinfrastruc- ture

Future work will focus on multi-center trials (n=500+) and regulatory approval pathways for clinical deployment.

VII.ACKNOWLEDGMENT

ThisresearchwassupportedbyJyothyInstituteofTechnol- ogy. The authors thank the institution for its extended support and encoragement through out the process.

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