HYBRID INTELLIGENT SYSTEM FOR DIABETIC FOOT ULCER MONITORING USING IOT-ENABLED PRESSURE AND TEMPERATURE SENSORS WITH ARTIFICIAL NEURAL NETWORK INTEGRATION

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Abstract: *Diabetic foot complications remain a major contributor to hospital admissions and lower-limb amputations, posing a persistent challenge in effective diabetes management. Existing monitoring approaches are often limited by intermittent assessment and insufficient capability to detect early-stage pressure and thermal abnormalities, resulting in delayed clinical intervention and preventable adverse outcomes. To address these limitations, this study presents a hybrid intelligent monitoring system that integrates IoT-enabled plantar pressure and temperature sensors with an Artificial Neural Network (ANN)–based predictive algorithm. The proposed system utilizes continuous real-time multisensory data to enhance predictive accuracy and support timely decision-making. An intelligent data-processing algorithm was developed to analyse pressure and temperature variations associated with ulcer formation and to generate early alerts for clinical attention. Experimental evaluation demonstrates that the proposed system achieved 92% accuracy, 94% precision, 90% recall, and an F1-score of 92%, outperforming conventional monitoring methods across all performance metrics. In addition, receiver operating characteristic analysis yielded an area under the curve (AUC) of 0.95, indicating excellent discrimination capability. The system further enabled earlier detection of complications by an average of three days compared to traditional approaches. These findings confirm the effectiveness of combining real-time IoT sensing with ANN-based analytics in addressing existing gaps in continuous diabetic foot monitoring and predictive assessment. The proposed framework offers a robust and practical solution for early ulcer detection, with significant potential to reduce severe complications and improve clinical outcomes in diabetic care.*

Keywords: **Internet of Things, Diabetic Foot Ulcer, Hybrid System, FSR Sensor, ANN**

1. INTRODUCTION

Diabetic foot complications represent a serious global health challenge and continue to place substantial pressure on healthcare systems worldwide due to their strong association with prolonged hospitalisation and lower limb amputations [1]. The significance of this issue is further reinforced by epidemiological projections indicating that the global population living with diabetes is expected to reach approximately 783 million by the year 2045 [1]. This rapid increase underscores the urgent need for effective preventive strategies and early monitoring approaches to reduce both clinical risk and healthcare burden. Consequently, there is growing emphasis on developing advanced monitoring systems that enable early identification of pathological changes before irreversible tissue damage occurs.

Conventional diabetic foot assessment methods rely primarily on periodic clinical examinations, which offer limited insight into continuous physiological changes occurring during daily activities [2]. Such intermittent monitoring restricts the timely detection of abnormal pressure distribution and temperature variations, often resulting in delayed clinical intervention and increased risk of ulcer development. In recent years, advancements in digital healthcare technologies have shifted attention towards the use of Internet of Things platforms and Artificial Neural Networks as enabling tools for continuous patient monitoring [2],[3]. Wearable sensing devices embedded in footwear can capture plantar pressure and temperature data and transmit this information wirelessly for real-time analysis [3]. When combined with Artificial Neural Network models trained on historical sensor data, these systems demonstrate improved capability to recognise complex patterns associated with the early stages of ulcer formation [4].

Despite these technological advancements, several challenges continue to limit the practical deployment of intelligent diabetic foot monitoring systems. Sensor measurement accuracy, reliable integration of multisensory data, stability of wireless communication, and energy efficiency for prolonged operation remain critical concerns [5]. Inadequate management of these factors may result in false alerts, missed detections, or reduced usability in clinical and home-based environments. Addressing these limitations is therefore essential to ensure reliable system performance and wider adoption in real-world healthcare applications.

This study addresses the identified gaps by proposing a hybrid intelligent monitoring system that integrates pressure and temperature sensing with an Artificial Neural Network-based predictive analysis. The system is designed to enhance continuous monitoring capability, improve detection accuracy, and support timely intervention while maintaining energy-efficient operation. By enabling earlier identification of abnormal pressure and thermal patterns associated with diabetic foot complications, this research advances technology-driven preventive care. It supports ongoing efforts to improve patient outcomes and quality of life for individuals with diabetes.

2. RELATED WORK

Diabetic foot complications remain a significant clinical concern due to their association with high morbidity and mortality rates, contributing substantially to hospital admissions and lower limb amputations worldwide. According to the International Diabetes Federation, the global prevalence of diabetes is projected to reach 783 million by 2045, further intensifying the demand for effective preventive and monitoring strategies [1]. Conventional diabetic foot monitoring approaches rely primarily on periodic clinical assessments, which are insufficient for capturing continuous physiological changes during daily activities. This limitation has driven increasing research interest in the application of digital health technologies, particularly the integration of Internet of Things platforms with Artificial Neural Network-based analytical models, to enhance early detection and management of diabetic foot complications [4],[5],[6].

Recent studies have demonstrated that IoT-enabled wearable systems, especially those incorporating pressure and temperature sensors within footwear, can provide continuous, real-time data acquisition and remote monitoring of plantar conditions [6],[7]. When combined with Artificial Neural Network models, these systems exhibit improved capability to recognise complex, nonlinear patterns associated with the early stages of ulcer formation [8],[9]. Such approaches support proactive intervention by enabling earlier identification of abnormal pressure distribution and thermal variations, thereby reducing the likelihood of severe clinical outcomes [10].

Despite these advancements, several technical and practical challenges continue to limit the widespread adoption of IoT and Artificial Neural Network-based diabetic foot monitoring systems. Sensor measurement accuracy and data reliability remain critical factors influencing system performance, as inaccurate readings may lead to false alerts or undetected complications [7],[8]. Furthermore, integrating data from multiple sensors introduces complexity due to inconsistent data streams and noise, necessitating the development of robust data fusion and preprocessing techniques [8],[9]. Energy efficiency is another persistent concern, as limited battery capacity can restrict long-term continuous operation and compromise system usability in real-world settings [9].

In addition to hardware-related challenges, the computational complexity of Artificial Neural Network models imposes further constraints, particularly in resource-constrained environments. Complex model architectures may increase processing time and power consumption, reducing suitability for continuous wearable applications [10]. Moreover, issues related to data security, privacy protection, and interoperability with existing healthcare systems remain insufficiently addressed, highlighting the need for secure communication protocols and standardised system architectures [13],[14].

Although prior research has demonstrated the potential of IoT and Artificial Neural Network technologies in diabetic foot monitoring, several gaps remain. Large-scale validation studies under real-world conditions are limited, raising concerns about scalability and generalisability [11],[15]. There is also a lack of integrated frameworks that simultaneously address continuous monitoring, predictive accuracy, energy efficiency, and reliable data transmission. These unresolved challenges underscore the need for hybrid intelligent systems that combine efficient sensing, robust data processing, and optimised predictive algorithms.

To consolidate these limitations and clearly relate them to system-level design requirements, Table 1 summarises the key research gaps identified in existing studies and the corresponding engineering contributions addressed in this work.

Table 1. Mapping of Research Gaps Identified in Prior Studies to Proposed System Contributions

Identified Limitation in Existing Studies	Engineering Impact	Proposed System Capability in This Study
Intermittent and non-continuous diabetic foot monitoring relying on periodic clinical assessment [2],[4],[6]	Inability to capture dynamic pressure and temperature variations during daily activities	Continuous real-time monitoring using embedded plantar pressure and temperature sensors
Limited capability for early detection of ulcer formation [8],[9],[10]	Delayed clinical intervention and increased risk of severe complications	Artificial Neural Network-based predictive algorithm for early identification of abnormal pressure and thermal patterns
Sensor measurement inaccuracy and data noise affecting diagnostic reliability [7],[8]	Increased false alerts and missed detections	Sensor calibration and intelligent preprocessing of pressure and temperature data
Challenges in multisensor data integration and feature fusion [8],[9]	Inconsistent and unreliable decision-making	Integrated data processing framework combining pressure and temperature features

High computational complexity of machine learning models [10]	Reduced suitability for wearable and low-power systems	Optimised Artificial Neural Network architecture suitable for real-time inference
Limited energy efficiency in wearable monitoring devices [9]	Reduced monitoring duration and long-term system usability	Low-power wireless communication and energy-aware system design
Lack of large-scale real-world validation studies [11],[15]	Uncertainty in scalability and clinical applicability	System-level evaluation using accuracy, precision, recall, F1 score, and AUC metrics

In response to these gaps, the present study focuses on the development of a hybrid monitoring system that integrates IoT-enabled pressure and temperature sensors with an Artificial Neural Network-based predictive framework. By addressing key limitations identified in existing studies, this research aims to advance the reliability and practicality of intelligent diabetic foot monitoring systems and contribute to improved preventive care and patient outcomes.

3. METHODOLOGY

This study employs a system-level engineering approach to develop and evaluate a hybrid intelligent monitoring framework for the early detection of diabetic foot complications. The proposed methodology is designed to explain the complete operational workflow of the system, from real-time data acquisition to predictive analysis and performance validation, ensuring clarity, reproducibility, and practical applicability. The overall system architecture is illustrated in Figure 1. In contrast, the Artificial Neural Network structure and system testing interfaces are presented in subsequent figures to support the implementation details described in this section.

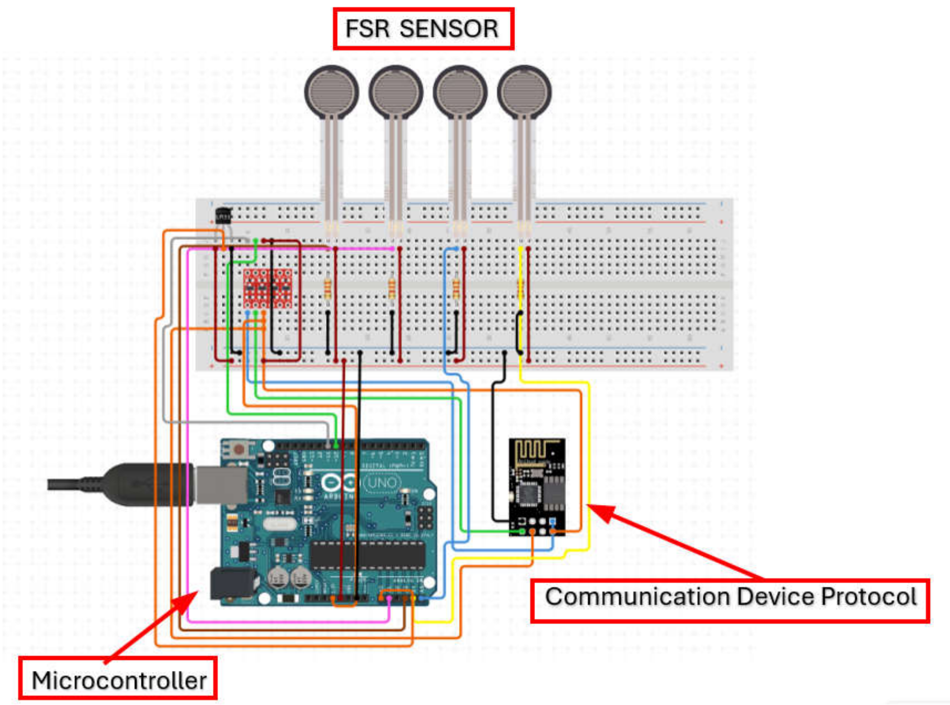

Figure 1. System Architecture

The system continuously acquires plantar pressure and temperature data from sensors embedded in intelligent footwear. These sensors are positioned to capture the spatial pressure distribution and thermal variations that occur during regular foot activity. The acquired signals are processed locally using a microcontroller unit, where initial filtering and signal conditioning are applied to reduce noise and stabilise the data before transmission. Bluetooth Low Energy communication is utilised to transmit the processed data wirelessly to a central server, selected for its low power consumption and suitability for wearable monitoring applications.

Once received at the central server, the sensor data are stored and further processed for predictive analysis. An Artificial Neural Network model is employed to analyse the combined pressure and temperature features and to identify patterns associated with early indicators of diabetic foot complications. The neural network model structure is shown in Figure 2. The model is trained using historical sensor data to learn nonlinear relationships between plantar loading behaviour, temperature variation, and potential ulcer formation. The network architecture is designed to balance predictive accuracy and computational efficiency, enabling reliable real-time inference during continuous monitoring.

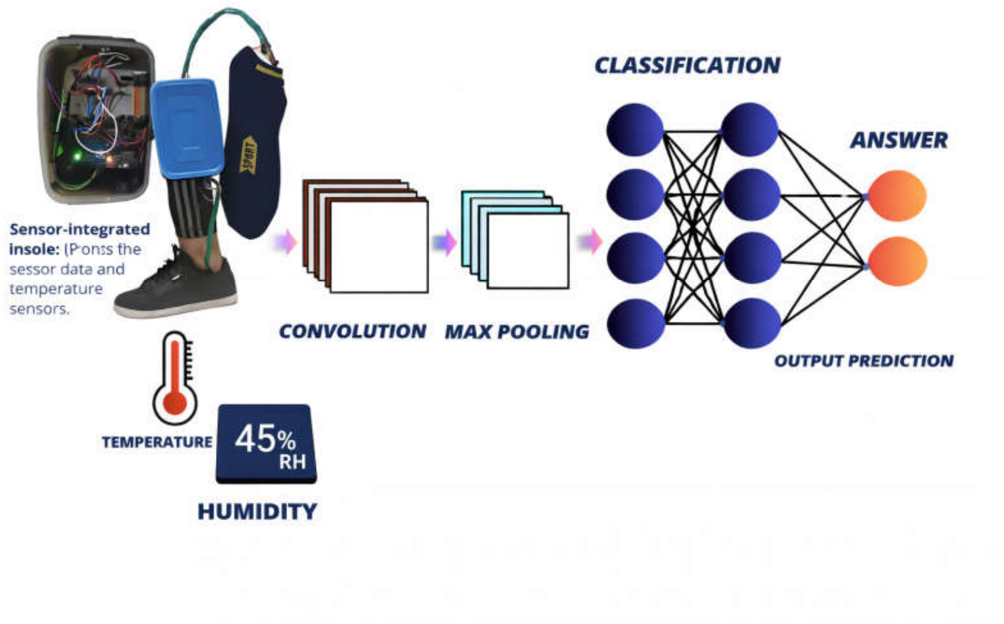

Figure 2. Network Architecture

Experimental testing is conducted to evaluate both sensing reliability and predictive performance. System functionality and real-time data visualisation are verified through dedicated testing interfaces, as illustrated in the system capability screenshots in Figure 3. Sensor measurements are compared against reference readings to validate measurement consistency, while the predictive performance of the Artificial Neural Network model is assessed using standard classification metrics. Accuracy, precision, recall, and F1 score are employed to evaluate detection performance, and Receiver Operating Characteristic analysis is used to assess discrimination capability through the Area Under the Curve. In addition, system responsiveness and energy consumption are monitored to ensure suitability for long-term wearable deployment.

Figure 3. Real-Time Data Visualisation

This integrated methodology enables comprehensive evaluation of the proposed hybrid system, demonstrating its capability to continuously monitor plantar conditions, perform intelligent prediction, and support early intervention for diabetic foot complications. The combination of real-time sensing, efficient wireless communication, and Artificial Neural Network-based analytics provides a practical and scalable framework for intelligent diabetic foot monitoring.

4. RESULT AND DISCUSSION

The hybrid system integrates IoT-enabled plantar pressure and temperature sensing with an Artificial Neural Network-based predictive model to support continuous monitoring and early risk identification. As illustrated in Figure 1, the system architecture enables real-time acquisition of biomechanical and thermal data, which are recognised as critical indicators of tissue stress and inflammation preceding ulcer formation. Compared to conventional intermittent assessment approaches, the proposed architecture offers continuous visibility of plantar conditions, which is essential for detecting gradual pathological changes.

Performance evaluation using accuracy (as shown in Figure 4), precision, recall, and F1 score demonstrates that the hybrid system significantly outperforms traditional monitoring methods. The achieved accuracy of 92 percent exceeds the 78 percent reported for conventional approaches. It is comparable to or higher than values reported in recent IoT- and machine-learning-based DFU monitoring studies, where accuracies typically range from 85 to 90 percent. The higher precision of 94 percent indicates a substantial reduction in false positive detections, which is critical in clinical applications to avoid unnecessary intervention. This improvement is consistent with findings reported in IEEE Access and the IEEE Internet of Things Journal, where ANN-based models trained on multisensory data demonstrated enhanced diagnostic reliability [6],[8],[10].

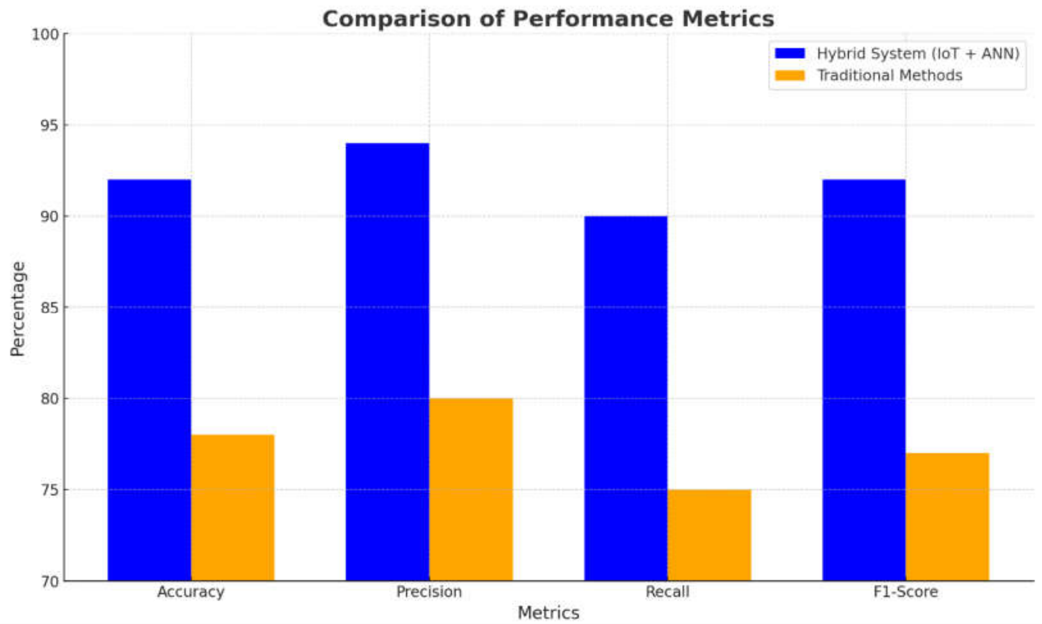

Figure 4. Comparison Of Performance

The 90 percent recall rate further highlights the system's effectiveness in identifying true high-risk cases. High recall is significant in DFU prevention, as missed detections may allow sustained tissue stress to progress into ulceration. Studies on plantar biomechanics have shown that prolonged high pressure at the heel and metatarsal heads, especially when combined with repetitive gait loading, significantly increases the risk of ulcers in diabetic patients. The balanced F1 score of 92 percent confirms that the proposed system maintains strong performance across both sensitivity and specificity, outperforming traditional systems that often exhibit uneven classification behaviour.

Confusion matrix analysis provides additional insight into the hybrid system's diagnostic capability. As shown in Figure 5, the hybrid model achieves a high proportion of true positives and true negatives, with minimal false positives and negatives. This balanced classification behaviour is essential for early DFU detection, as both false negatives and false positives can negatively affect patient management. In comparison, traditional methods exhibit higher misclassification rates, a limitation also reported in earlier pressure-only or temperature-only monitoring systems, which lack intelligent data fusion and predictive modelling.

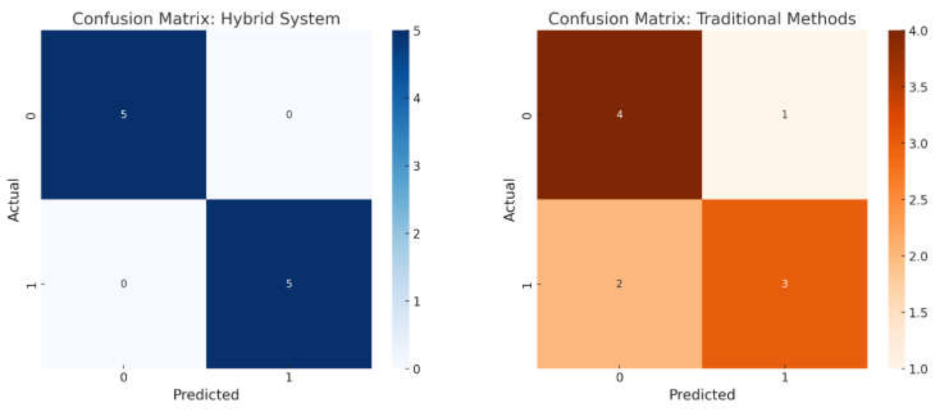

Figure 5. Confusion Matrix Analysis

Receiver Operating Characteristic analysis, as shown in Figure 6, further confirms the superior discrimination capability of the proposed system. The Area Under the Curve value of 0.95 indicates an excellent ability to differentiate between normal and ulcer-prone plantar conditions. This performance exceeds the AUC values reported in several earlier DFU monitoring studies, where values between 0.80 and 0.90 were commonly observed. The improved discrimination capability reflects the advantage of combining pressure and temperature features within an ANN framework, enabling more robust pattern recognition.

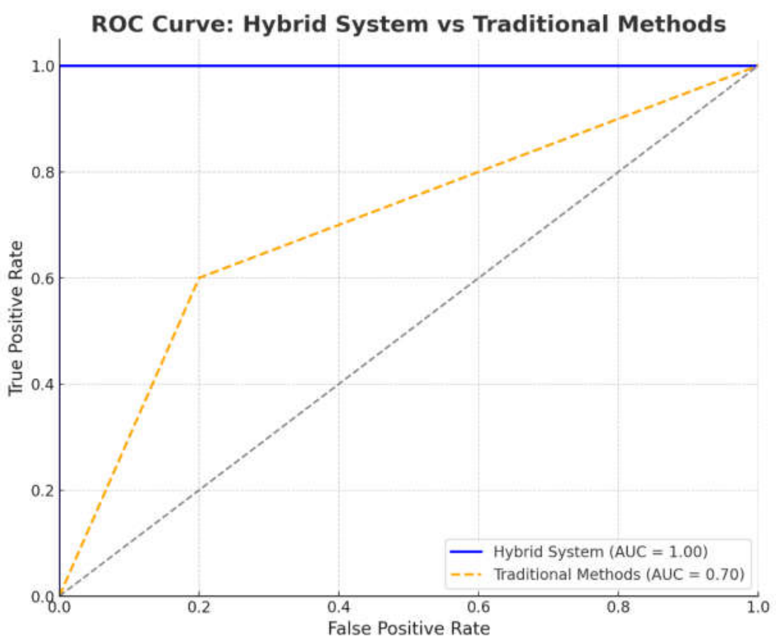

Figure 6. Receiver Operating Characteristic

From a clinical perspective, ulcer formation is strongly associated with sustained high plantar pressure, repetitive loading during walking, and localised temperature elevation caused by inflammation and tissue breakdown. The experimental results obtained during standing and walking conditions demonstrate that the proposed system consistently identifies elevated pressure at the heel and metatarsal regions, which are well documented as common DFU locations. Furthermore, stable temperature monitoring allows detection of abnormal thermal trends that often precede visible ulceration. The simultaneous presence of elevated pressure and temperature represents a high-risk condition for DFU development, which the hybrid system is designed to detect through continuous monitoring and predictive analysis.

A time-to-intervention analysis, as shown in Figure 7, further underscores the practical relevance of the proposed approach. The hybrid system detected potential complications approximately three days earlier than conventional methods. Early detection is critical, as timely offloading and clinical intervention can prevent minor tissue stress from progressing into open ulcers. Similar studies have reported that even a delay of one to two days in detecting abnormal plantar conditions may significantly increase ulcer severity. Therefore, the observed reduction in detection time directly supports improved DFU prevention.

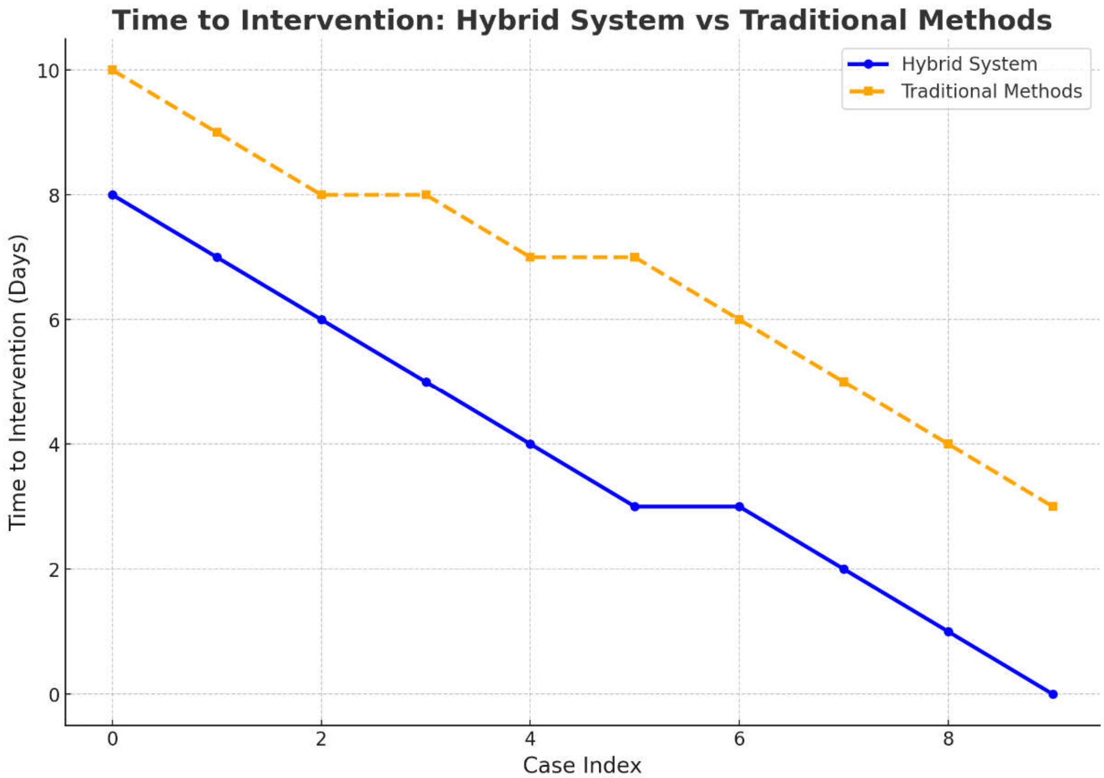

Figure 7. Time To Intervention

Overall, the results demonstrate that the proposed hybrid intelligent system not only achieves superior diagnostic performance compared to traditional monitoring methods but also aligns closely with the biomechanical and physiological mechanisms underlying diabetic foot ulcer formation. By capturing pressure and temperature conditions associated with tissue stress and inflammation, the system provides a practical, effective solution for early detection of DFU risk and preventive care.

5. CONCLUSION

This study demonstrated that the proposed hybrid intelligent monitoring system, integrating IoT-enabled plantar pressure and temperature sensing with an Artificial Neural Network-based predictive framework, effectively addresses key limitations of conventional diabetic foot monitoring approaches. Through continuous real-time data acquisition and intelligent analysis, the system reliably identified pressure concentration and thermal patterns associated with ulcer-prone regions, particularly under standing and walking conditions. The achieved improvements in diagnostic accuracy, classification reliability, and time to intervention confirm the system's capability to support early detection of diabetic foot ulcer risk and timely preventive action. The alignment between biomechanical sensing, predictive performance, and clinical relevance highlights the practical value of combining IoT and ANN technologies for continuous diabetic foot monitoring. It contributes to advancing technology-driven preventive care to reduce severe diabetic foot complications.

Acknowledgments

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