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DEVELOPMENT OF A FOOT MONITORING DEVICE FOR TYPE-2 DIABETIC PATIENTS: A COMPREHENSIVE ANSYS-DRIVEN STUDY

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Abstract

Diabetic Foot Ulcers (DFU) are a significant complication in diabetic patients, often leading to lower extremity amputation and reduced quality of life. Although various monitoring devices measure plantar pressure, the precise placement of sensors remains unvalidated, and issues such as unstable Bluetooth communication and complex data transfer hinder their reliability. This study proposes an IoT-based smart device for monitoring foot pressure and temperature to address these challenges and prevent DFU in Type 2 diabetic patients. Finite Element Analysis (FEA) using Ansys was employed to identify optimal sensor locations based on plantar pressure distribution, while SolidWorks facilitated foot modelling and insole design. The results identified peak plantar pressures at the heel, midfoot, and first and fifth metatarsals, with values of 1,769 kPa, 1,200 kPa, and 910 kPa, respectively. Following the successful fabrication of the device, synchronisation and stability tests confirmed reliable real-time monitoring of both force and temperature under balanced standing and walking conditions. The proposed device addresses the limitations of previous systems by offering precise dual-parameter monitoring, which enables the early detection and prevention of diabetic foot ulcers (DFU). This innovative system holds significant potential for proactive diabetic foot management and the prevention of ulcers.

Keywords: Diabetic foot ulcer, Finite element analysis, Internet of things, Plantar pressure distribution, Pressure and temperature monitoring device.

1. Introduction

Diabetes is a chronic metabolic disorder resulting from a deficiency in insulin secretion or an inadequate biocatalytic response to the body's insulin production [1]. One of the common complications among diabetes patients is Diabetic Foot Ulcer (DFU), which is associated with an increased risk of hospitalisation, lower limb amputation, decreased quality of life, and death [2].

A research study reported that excessive stress on plantar tissue over time is one of the leading causes of DFU among patients with diabetic peripheral neuropathy [3]. Increased foot temperature is also a common symptom and a potential precipitating factor of a foot ulcer [4]. Hence, it is vital to develop a foot pressure and temperature monitoring system to track the plantar pressure and temperature of diabetic patients and prevent the occurrence of foot ulcers.

Over the years, advances in research methods to reduce and prevent foot ulceration among diabetic patients have led to the development of new and innovative foot insoles and shoe designs [5]. Such accomplishments are achieved through innovative pressure and temperature sensing techniques to detect the occurrence of foot ulcers [6].

The combined sensing technologies and monitoring systems enable the device to take readings remotely through a Wireless Fidelity (Wi-Fi) connection. Moreover, the smart monitoring system is integrated with the state-of-the-art Internet of Things (IoT) technology to provide efficient data communication within the system.

This study aims to develop a smart foot monitoring device that utilizes IoT technology to accurately measure plantar pressure and temperature, thereby addressing key challenges in managing diabetic foot complications. By carefully optimizing sensor placement through Finite Element Analysis (FEA) and rigorously testing the device through simulations and experiments, this research aims to provide a dependable tool for the early detection and prevention of Diabetic Foot Ulcers (DFU).

The goal of this study is to design and develop a smart foot monitoring device utilizing Internet of Things (IoT) technology that can accurately measure plantar pressure and temperature. The study involved optimizing the sensor positions using Finite Element Analysis (FEA), and system simulations and experiments were performed to verify the device.

The research work aimed to propose a valuable system for the early diagnosis and prevention of Diabetic Foot Ulcer (DFU). The rest of the paper is organized as follows: Section 1 introduces the background and motivation for the study. Section 2 reviews related work on diabetic foot monitoring approaches and identifies gaps in existing research. Section 3 presents the methodology for designing the system, which includes FEA-based sensor placement optimization, hardware and software integration, and system development.

Section 4 discusses the simulation and experimental results, their analysis, and the validation of the system. Section 5 describes the future work, including the integration of machine learning algorithms for predictive analysis. Section 6 concludes the paper by summarizing the study's findings and contributions, as well as the proposed monitoring device.

2. Related Work

A diabetic foot ulcer represents a full-thickness wound located below the ankle, predominantly observed in individuals with diabetes. This condition is a severe complication that often necessitates limb amputation and leads to reduced mobility and diminished quality of life [7]. Major causative factors include peripheral neuropathy, which induces nerve damage, and ischemia in the lower extremities, which results from insufficient blood flow [8]. Additionally, increased plantar tissue stiffness in individuals with diabetes causes elevated pressure on the foot, particularly in areas prone to ulceration, such as the dorsal toes, heel, and metatarsal regions [9]. Elevated foot temperatures are commonly linked to neuropathic damage, serving as an early indicator of inflammation and potential ulcer development [10].

Finite Element Analysis is a computational modelling method employed to simulate physical phenomena. This approach reduces reliance on physical prototypes, providing cost-effective solutions for design optimisation [11]. In prior research, Akrami reconstructed three-dimensional foot models from MRI data, enabling biomechanical assessments of stress and pressure distributions [12]. Similarly, Feldman et al. [13] applied FEA to examine internal stresses related to obesity, illustrating its applicability to various foot health scenarios. Advanced software tools, such as SolidWorks and Ansys, have facilitated accurate modelling and analysis of plantar pressure distributions under static and dynamic conditions [13, 14].

Numerous monitoring devices have been developed to address diabetic foot health, with a focus on detecting plantar pressure and temperature. Wibowo designed a cost-effective system to monitor foot pressure, though the sensor placement was not rigorously validated [15]. Vigneshwaran introduced a device capable of precise pressure readings under both static and dynamic conditions; however, it faced challenges with data transfer complexities [16]. Baihaqi's dual-parameter device measured pressure and temperature but exhibited instability in Bluetooth communication, limiting its usability [17]. Recent advancements in this field include the study by Nordin et al., which developed an intelligent IoT-enabled algorithm integrating pressure and temperature sensors for diabetic foot monitoring [18, 19]. This system significantly improved data accuracy and processing speed, addressing challenges with real-time feedback and communication stability [20].

IoT-based systems have emerged as transformative solutions to address the limitations of traditional approaches. These systems facilitate real-time data communication by leveraging IoT technology, enhancing efficiency and reliability. When combined with Finite Element Analysis (FEA)-driven simulations, sensor placement accuracy improves significantly. This synergy of IoT and FEA forms the foundation of the present research, which aims to develop a comprehensive monitoring device. This device is designed to overcome challenges of accuracy, stability, and practicality, as identified in previous studies and summarised in Table 1.

Although the summary in Table 1 provides a comprehensive overview of the related work, several unresolved issues persist that previous studies have not addressed. First, earlier research, such as that conducted by Wibowo et al. [15] and Bin Ghazali et al. [17], lacked validation of sensor placement. This oversight resulted in inaccurate sensor readings due to the improper positioning of the sensors. Second, most prior studies focused exclusively on either pressure or temperature measurements, failing to integrate both into a single system. This integration is crucial for enabling early and accurate detection of ulcer occurrences. Third, some systems that utilized Bluetooth for data transmission, such as those developed by Bin Ghazali et al. [17], experienced instability in real-time data transmission during prolonged use, which compromised the reliability of the monitoring. Lastly, the simulation-only implementation by Akrami et al. [12] offers no practical implications for wearable systems.

Table 1. Comparative analysis of studies on foot monitoring systems.

Study	Methodology	Finding	Limitation	Research Gap
Akrami et al. [12]	FEA for biomechanical analysis	Accurate modelling of stress distributions	Simulation-only approach; no device integration	Lack of validation for practical device applications
Wibowo et al. [15]	Simple sensor-based design	Measured pressure at various foot regions	No validated sensor placement	Limited to static pressure measurements
Vigneshwaran et al. [16]	Multi-sensor approach for dynamic analysis	Provided precise pressure data	Complex data transfer processes	Lacked scalability for practical use
Bin Ghazali et al. [17]	Combined pressure and temperature sensing	Real-time measurement capability	Unstable Bluetooth communication	Requires more robust data transfer methods
Izzat Nordin et al. [19]	IoT-enabled algorithm with multi-sensor array	Enhanced real-time feedback and data stability	High computational demand	Optimisation of algorithms for scalability

Recent research conducted after 2022 has further underscored the need for an accurate, real-time, and multi-parameter integrated solution. The latest works by Bevilacqua et al. and Izzat Nordin et al. [18, 19] proposed an intelligent IoT-based diabetic foot monitoring system that successfully integrated both pressure and temperature sensors. This integration resulted in their prototype achieving relatively higher accuracy and quicker response times compared to previously developed systems. However, their research still faced two significant challenges: high computational complexity and the absence of an FEA-based approach for optimizing sensor placement. Therefore, recent studies indicate that developing an all-in-one solution that incorporates multi-parameter sensing, biomechanical validation of sensor placement, and functional, reliable wireless data communication is the most effective approach.

In response, this work unites the three missing elements identified in recent studies: the application of Finite Element Analysis (FEA) for optimizing sensor placement, multi-parameter sensing of both pressure and temperature, and IoT-based wireless data transmission (see Fig. 1). This innovative combination of elements addresses the unresolved issues of accuracy, reliability, and usability in previously developed systems, contributing to advancements in the state of the art.

Figure 1 shows the relevant contributions of this research to overcome some of the gaps discussed in the above section. Unlike the system proposed in [15, 17], this research utilizes Finite Element Analysis (FEA) to determine a more optimal sensor placement, following the successful validation of the sensor positions. This research has also used an IoT-based real-time monitoring framework in contrast to earlier works. While research in [12] was conducted using only simulations, Vigneshwaran and Murali [16] had the problem of complex data transfer. This research has demonstrated the feasibility of dual-parameter sensing of pressure and temperature in a validated system architecture. The recent advancements proposed by Bevilacqua et al. and Izzat Nordin et al. [18, 19] are significantly advanced in this research in terms of the practicality, accuracy, and stability of the device to address some of the current challenges in DFU monitoring.

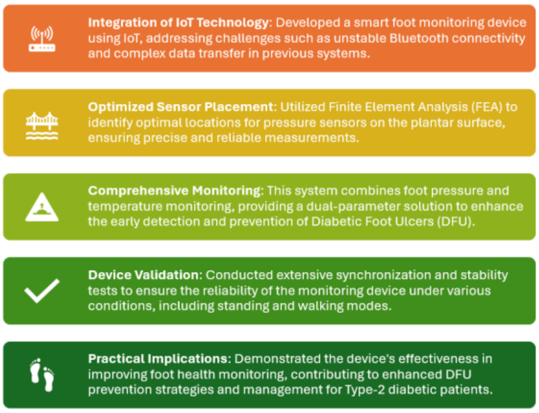

Fig. 1. Key contributions of this research paper.

3. Methods

This section outlines the methodology employed to achieve the study's objectives. It provides a detailed, step-by-step outline of the processes, integrating hardware, software, simulation, and implementation of the foot monitoring device.

3.1. Hardware and software selection

The monitoring device consists of an Arduino Uno with a Wi-Fi shield, which sends data to a smartphone. Four force sensing resistors (FSR) 402 sensors were chosen to measure plantar pressure, and an LM35 sensor was used to detect temperature. FSR 402 pressure sensors were selected as the sensing technology over other technologies (capacitive or piezoelectric sensors) in the context of plantar sensing, as FSRs provide a thin and flexible form factor that can be easily integrated into a simple voltage-divider circuit with minimal cost, yielding stable readings for repetitive foot pressure measurements. FSRs do not require the complex interfacing electronics that are necessary for capacitive sensors and capture both static and dynamic plantar pressures, unlike piezoelectric sensors, which can only respond to dynamic loads. Designing a pressure sensing device using FSRs is also cost-effective for multipoint pressure measurements, as seen in Wibowo’s low-cost foot pressure sensing system [15].

The LM35 temperature sensor was chosen over a thermistor-based temperature sensor because it features a linear analog output and comes with built-in calibration, which provides ease of interfacing and consistent readings without the need for additional complex calibration algorithms [17]. The selected sensors are also easy to use for continuous monitoring and were deemed suitable for use in a wearable insole context to acquire plantar pressure and temperature data simultaneously [18, 19].

Foot models were created in SolidWorks, and ANSYS was used to simulate plantar pressure and determine the optimal placement of sensors. The positions of FSR sensors were determined from FEA identification of the zones of high pressure within the insole, specifically the heel, midfoot, and metatarsal heads. A temperature sensor was placed in the midfoot to capture thermal patterns in this area. The device was programmed using the Arduino IDE, and the Blynk app was utilized to display the data in real-time, providing a synchronized implementation of the hardware-software system.

3.2. Finite element analysis of human foot model

Figure 2 illustrates the finite element analysis (FEA) process, showcasing the 3D foot model's geometry and the tetrahedral mesh used for tissues and bones, comprising 121,239 elements and 202,495 nodes. The simulation replicated plantar pressure distribution in a neutral standing position. It was based on a detailed foot model featuring 28 bony segments, cartilage, soft tissue layers, and ground support for realistic conditions. A vertical load of 350 N, representing a 70 kg individual, was applied to the model, and equivalent stress distributions on the plantar surface were analysed to identify high-stress regions.

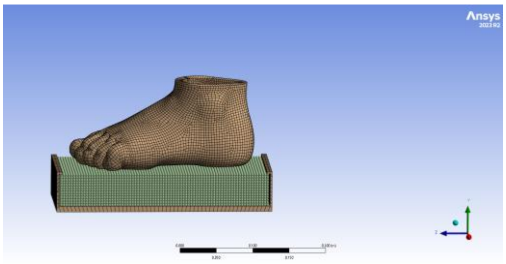

Fig. 2. 3D foot model's geometry.

Material properties were carefully defined to ensure accurate simulation. Bones, cartilage, and plantar fascia were modelled as homogeneous, isotropic, and linear elastic materials. Soft tissues were represented using a hyper-elastic model to capture nonlinear deformation. Contacts between bones and tissues were specified as either bonded or frictionless, and the interaction with the ground was modelled as frictional, with a coefficient of 0.6. Material characteristics are summarised in Table 2, while the coefficients for the hyper-elastic tissue model are detailed in Table 3.

Table 2. Material properties of the human foot and ground support of the FE model.

Components	Young's Modulus, E (MPa)	Poisson's Ratio
Bones	7300	0.3
Plantar Fascia	350	0.4
Ligament	260	0.4
Cartilage	10	0.4
Ground Plate	2000000	0.3

Table 3. Coefficients of the hyper-elastic material model used for tissues in the FE model.

Tissue	Normal	F2
C10 (MPa)	0.08556	0.17113
C01 (MPa)	-0.05841	-0.11683
C20 (MPa)	0.03900	1.07800
C11 (MPa)	-0.02319	-0.04638
C02 (MPa)	0.00851	0.01702
D1 (MPa-1)	3.65273	1.82636
D2 (MPa-1)	0	0

3.3. Development of the monitoring device

The flow chart of the described operation of the suggested monitoring system is shown in Fig. 3. First, the hardware is initiated, and the system undergoes a self-check. Plantar pressure and temperature data are collected using FSR 402 sensors for pressure and LM35 sensors for temperature, respectively. The FSR 402 sensors are arranged at five strategic sites on the foot, including the heel, midfoot, and the first and fifth metatarsals, as determined by optimization using FEA. The collected data are converted from analog to digital form by the Arduino Uno, processed in real-time, and filtered to enhance signal stability.

The processed data is then wirelessly transmitted using ESP8266 and displayed on the Blynk mobile application for real-time monitoring, alerts, and long-term storage. This sequential workflow ensures accurate, stable, and user-friendly foot health tracking in clinical and personal settings. Table 4 presents the pseudocode illustrating the system's working principle of the real-time monitoring system. This pseudocode outlines the sequential operations of the system, starting from sensor data acquisition, preprocessing, and transmission to the microcontroller or Raspberry Pi, followed by real-time data analysis and alert generation. The structured steps in this table provide a clear overview of how the system continuously monitors pressure and temperature readings, ensuring that any abnormal conditions are detected and logged for further evaluation.

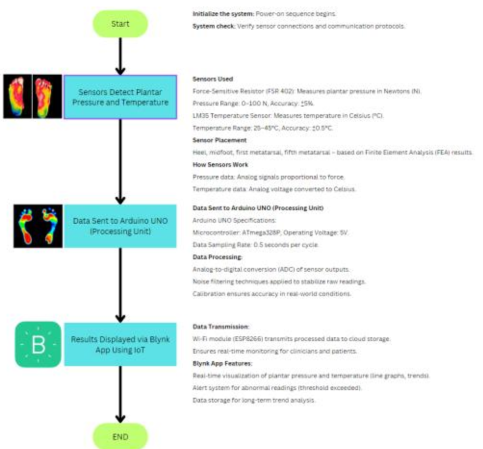

Fig. 3. Flowchart of the system's operation.

Table 4. Pseudo-code.

Pseudo-Code:
Initialize sensors and the microcontroller.
Acquire input data from FSR 402 and LM35 sensors.
Process sensor data to calculate pressure and temperature values.
Transmit data via Wi-Fi to the Blynk app.
Display real-time readings on a smartphone interface.
Perform performance tests to evaluate synchronisation and stability.

The circuit design connected sensors to the Arduino using a voltage divider circuit to ensure accurate data acquisition, as depicted in Fig. 4, and the hardware setup, as shown in Fig. 5. The placement of sensors was guided by FEA findings, with pressure sensors positioned at regions experiencing the highest stress and the temperature sensor placed at the midfoot to monitor thermal patterns. Fig. 6 illustrates the insole design and sensor layout, which were tailored to maximise ergonomic functionality.

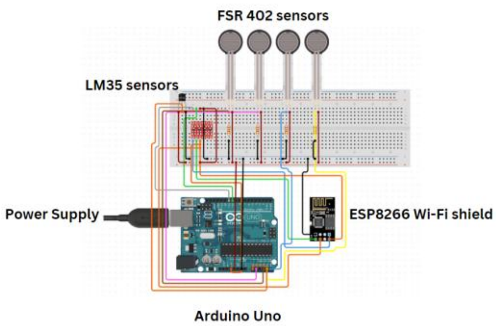

Fig. 4. The circuit connection of the component with Arduino UNO.

Fig. 5. Hardware setup for the foot pressure and temperature monitoring device.

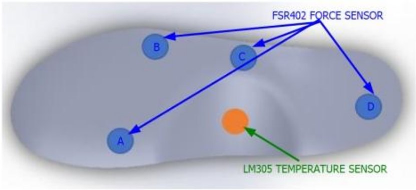

Fig. 6. Insole design of the foot pressure and temperature placement using SolidWorks.

Sensor data was collected and processed with a custom algorithm written in C++ and executed in the Arduino IDE. The processed real-time data was transmitted to the Blynk smartphone app for easy integration with IoT and minimal latency. Tests for system performance included the device's ability to provide real-time, stable data over long periods of operation. This was achieved by having a 70 kg subject test the system in conditions of balanced standing and walking, and collecting data on the recorded pressure and temperature values. The data was then analysed to verify accuracy and reliability. The new system offers a solution to challenges in diabetic foot monitoring by integrating sophisticated simulation methods with practical hardware design, thus enabling real-time data capture and interpretation.

The proposed design was qualitatively compared to other diabetic foot monitoring devices in the literature to verify that known shortcomings of those designs were addressed. For example, unlike Wibowo's proposed pressure-sensing platform [15], which did not verify the sensor positions using FEA, the proposed device utilizes FEA results to validate sensor locations. The FEA-verified placement allows for better stability and precision of pressure data by focusing on anatomically relevant areas.

This overcomes the placement uncertainty in Wibowo's work. In addition, although the research by Bin Ghazali et al. [17] has shown the potential of an insole device with dual-parameter monitoring (plantar pressure and temperature), their monitoring system experienced unstable Bluetooth data transmission. In the proposed system, this has been addressed by adopting an IoT design architecture with Wi-Fi communications, which are more reliable and continuous with the smartphone app. The two sensors (pressure and temperature) are also integrated to have tightly time-synchronised operations for concurrent monitoring of mechanical pressure and foot temperature changes. This can provide valuable insights and early detection of stress and inflammation in the tissues.

While Bevilacqua et al. and Izzat Nordin et al. [18, 19] have also presented a smart IoT-based system with high data accuracy and real-time feedback, their approach is limited by high computational load and complexity. In this work, a more efficient data processing approach is employed to achieve reliable real-time operation without overloading the hardware components. By excluding overly complex operations from the onboard microcontroller, the device is made scalable and power-efficient while still providing accurate dual-parameter data. These improvements in sensor placement verification, multi-parameter integration, and wireless data management directly address the issues of prior studies. The proposed foot monitoring system is a more stable and reliable device that builds on earlier work in this field and is applicable in real-world scenarios to prevent diabetic foot ulcers.

4. Results and Discussion

Developing a smart monitoring device that integrates real-time plantar pressure and temperature monitoring provides essential insights into the mechanical and thermal contributors to Diabetic Foot Ulcer (DFU) formation. This section presents the study's results, analysing key findings from Finite Element Analysis (FEA), experimental testing, and system validation. The outcomes are further discussed to highlight their significance in DFU prevention and clinical implications.

4.1. Plantar pressure distribution and sensor placement

The finite element analysis (FEA) results, as detailed in Section 3.2, revealed that plantar pressure was predominantly concentrated in the heel, midfoot, and metatarsal regions during balanced standing conditions. Specifically, the equivalent von Mises stress values reached approximately 1,769 kPa at the heel, 1,200 kPa at the midfoot, and 910 kPa at the metatarsal heads, clearly visualized by the red stress zones in the simulation output (Fig. 7). These findings were derived from a 3D foot model subjected to a vertical load of 350 N, simulating realistic physiological conditions. The results corroborate those of previous literature (Fig. 8), which highlights these regions as high-risk areas for pressure accumulation due to prolonged mechanical loading [20]. The FEA outcomes served as the basis for optimising sensor placement in the insole design, ensuring coverage of the most critical anatomical zones.

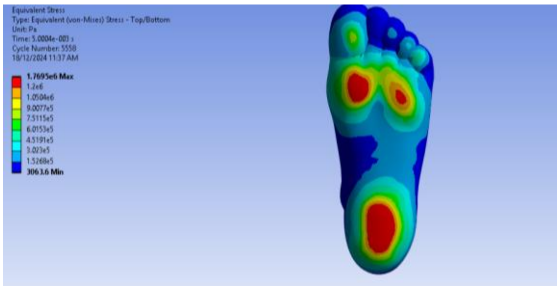

Fig. 7. Results for equivalent von Mises stress values from this study.

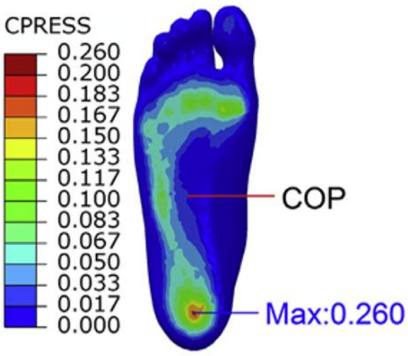

Fig. 8. Results for equivalent von Mises stress values from previous studies [20].

The experimental study was used to validate the system developed, which also established the validity of the sensor position selected in the FEA study. The mean values of pressure distribution while standing showed maximum force at the heel of 73.52 N, followed by the midfoot at 44.43 N and metatarsal areas at 39.28 N (Table 5). When in motion, the pressure distribution changes following the phase of the gait cycle. The peak pressures measured were at heel strike (84.87 N) and at the first and fifth metatarsals during the heel-off phase (Table 6). This is following the gait cycle, in which both the heel and metatarsals experience high loading during the propulsion and stabilization phases. If these repetitive loads are not mitigated, they can cause tissue damage and ischemia, leading to an increased risk for DFUs.

The FEA-guided sensor placement at these regions ensured the precise identification of high-pressure zones, validating the system's capability to capture critical plantar stress data. Accurate detection of these zones is crucial for implementing preventive interventions, such as pressure redistribution and offloading strategies, to minimize the risk of ulcers.

Table 5. Approximated force and foot temperature during 20 seconds of balanced standing mode.

Time (s)	Approximated force (N)			
	Heel	**Midfoot**	**First metatarsal**	**Fifth metatarsal**
1	69.20	44.53	7.00	34.27
2	80.40	37.27	12.00	37.27
3	77.03	44.53	13.00	37.27
4	53.00	27.60	8.73	37.27
5	80.40	46.40	7.00	40.57
6	66.47	53.00	5.33	44.53
7	63.27	48.57	12.00	39.10
8	73.13	48.57	11.00	32.67
9	80.40	30.03	12.00	39.10
10	57.73	46.40	15.90	40.57
11	69.20	30.03	16.50	32.67
12	80.40	34.27	12.00	40.57
13	80.40	48.57	12.00	44.53
14	66.47	53.00	12.00	37.27
15	80.40	46.40	12.00	42.57
16	73.13	55.53	14.00	40.57
17	77.03	48.57	10.90	42.57
18	77.03	50.40	13.40	42.57
19	80.40	46.40	15.90	40.57
20	84.87	44.53	12.87	39.10
Mean	73.52	44.43	11.78	39.28

Table 6. Approximated force and foot temperature during 20 seconds of walking mode.

Time (s)	Approximated force (N)				
	Heel	**Midfoot**	**First metatarsal**	**Fifth metatarsal**	**Foot Phase**
1	104.97	11.00	69.53	55.30	Push-Off
2	0	0	49.57	48.57	Transition
3	0	3.43	0	0	Swing Phase
4	84.87	1.00	6	14.97	Heel Strike
5	10.70	21.93	63.53	80.40	Push-Off
6	0	0	40.73	44.17	Transition

Table 6 (continue). Approximated force and foot temperature during 20 seconds of walking mode.

Time (s)	Approximated force (N)				Foot Phase
	Heel	Midfoot	First metatarsal	Fifth metatarsal	
7	1.00	0	0	0	Swing Phase
8	94.87	8.00	30.03	31.50	Transition
9	6.00	38.8	50.83	58.23	Push-Off
10	0	0	55.30	1.50	Transition
11	69.53	2.00	0	11.00	Heel Strike
12	7.53	25.13	73.13	52.77	Push-Off
13	0	1.00	21.10	10.70	Transition
14	0	5.00	0	0	Swing Phase
15	89.67	0	0	10.00	Heel Strike
16	48.57	28.97	60.53	52.77	Push-Off
17	0	2.47	50.83	34.13	Transition
18	0	0	9.00	5.00	Swing Phase
19	23.07	0	0	0	Transition
20	80.40	16.47	69.53	44.17	Transition
Mean	31.06	8.26	32.48	27.76	

4.2. Temperature stability and its relationship to DFU

In addition to mechanical pressure, temperature variations are a key indicator of tissue stress and inflammation, which are precursors to DFU. The experimental results showed stable mean temperatures of 30.21 °C during balanced standing and 30.80 °C during walking conditions, as detailed in Fig. 9. These values remain within the normal physiological range reported, where plantar temperatures typically vary around 30.6 °C ± 2.6 °C [21].

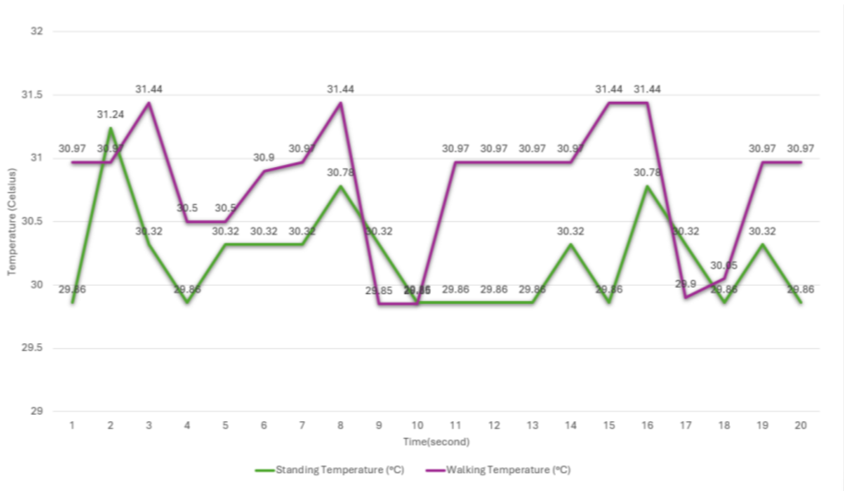

Fig. 9. Temperature variations during standing and walking over time.

Despite no significant deviations observed in this study, the system demonstrated the capability to detect subtle temperature changes. Incorporating a one kΩ resistor effectively minimised sensor instability, reducing temperature deviation to 1.38°C. Stable and accurate temperature readings address limitations in previous monitoring systems, where sensor noise and electromagnetic interference compromised reliability [17]. The relationship between plantar pressure and temperature is crucial in the development of DFU. High mechanical pressure reduces blood perfusion in the affected regions, causing ischemia and subsequent inflammatory responses, which manifest as localized temperature elevations. Combining pressure and temperature monitoring provides a robust, dual-parameter approach to detecting early signs of DFU. Real-time identification of abnormal temperature trends enables timely interventions, preventing tissue breakdown and ulcer formation.

4.3. System validation and performance analysis

The proposed device underwent rigorous validation to ensure functional reliability under real-world conditions. Synchronisation testing confirmed effective data transmission between the sensors and the IoT-enabled Blynk interface. Real-time communication via Wi-Fi demonstrated no delays or errors, overcoming issues of unstable connectivity observed in prior Bluetooth-based systems. With a 0.1-second delay, the algorithm's optimisation ensured the seamless acquisition and display of data from multiple sensors. Stability tests further validated the system's robustness.

Experimental temperature readings showed consistent results in various test cycles, with minimal deviation, ensuring the accurate detection of potential abnormalities. In terms of force measurements, the system performed reliably under varying conditions, including balanced standing and walking modes. The results demonstrated that the device can continuously capture pressure and temperature data, providing clinicians with valuable real-time insights for preventive care.

4.4. Discussion on findings and clinical relevance

The findings of this study confirm the importance of combining plantar pressure and temperature monitoring to address the multifactorial nature of DFU formation. Elevated plantar pressure in the heel, midfoot, and metatarsals aligns with recognised high-risk regions for ulceration due to sustained mechanical stress. Simultaneously, temperature stability ensures that early inflammatory responses, indicated by localised thermal changes, can be accurately detected.

The ability to monitor these parameters in real-time holds significant clinical implications. Pressure measurements enable clinicians to identify high-risk regions, allowing for timely offloading strategies that redistribute mechanical loads and reduce tissue damage. Temperature monitoring complements this by providing an additional metric for detecting inflammation, thereby enhancing the accuracy of DFU risk assessments. Compared to existing studies, the proposed device overcomes key limitations related to sensor instability, inaccurate placements, and data communication delays. The integration of Finite Element Analysis for sensor placement optimisation and IoT-enabled real-time data transmission enhances the reliability and practicality of the system. Previous works by Armstrong et al. [22] and Frykberg and Banks [23] emphasised the need for dual-parameter monitoring to improve diabetic foot ulcer prevention outcomes. The findings of this study align with these recommendations, demonstrating the device's capability to support clinicians in detecting early indicators of ulcer formation.

Although the proposed system offers several benefits, it is also important to note some of its limitations. While the use of low-cost components, such as FSR 402 and LM35 sensors, helps to make the system affordable, there may be challenges in scaling it up for wider clinical use, particularly in low-resource settings, both logistically and financially. The reliance on Wi-Fi connectivity and mobile interface may also limit the system's usability in areas with unstable network access or low digital literacy. These challenges will be addressed in future work, including offline data logging and user-centric design improvements to enhance scalability and real-world applicability, as recommended by Nordin et al. [18, 19].

4.5. Future directions

Integrating Machine Learning (ML) could enhance the system's ability to analyse data and identify initial patterns for the development of diabetic foot ulcers (DFUs). Methods like Support Vector Machines (SVM) or Random Forests have shown great success in similar biomedical fields, particularly in classifying risk level with physiological sensor data. Furthermore, deep learning models, such as Convolutional Neural Networks (CNNs), have been explored in the analysis of foot thermography and plantar pressure distributions for the automated recognition of abnormal patterning in early ulceration. The improvements can be based on clinically validated datasets for accuracy. Clinical trials in a larger population can also be used to improve sensor placement and individualize devices according to a patient’s specific foot anatomy and activity levels.

This includes the ability to create high-resolution 3D foot models from a CT or MRI scan, allowing for more accurate simulation of pressure zones, although this may increase the cost. This is in addition to adding more sensors in key locations such as the toes and metatarsals to improve the precision of the analysis. Cloud-based systems allow for real-time monitoring for early intervention. Figure 10 shows the concepts and the direction of future frameworks. There is an importance in maintaining a balance between innovation and a cost-effective and user-friendly solution to develop a more reliable and practical solution for the early detection and prevention of diabetic foot ulcers.

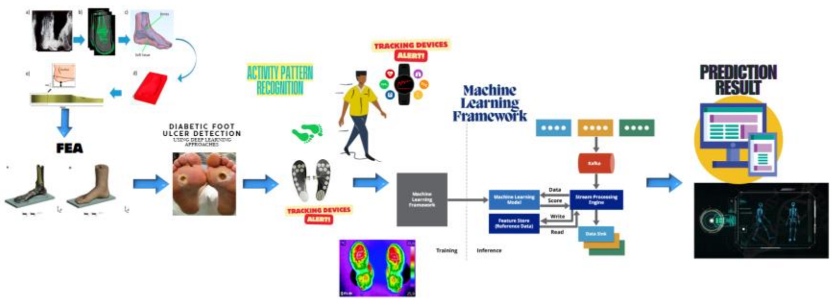

Fig. 10. Future direction framework.

5. Conclusions

This project successfully developed a smart foot monitoring device integrated with IoT to prevent the occurrence of DFU among Type-2 diabetic patients. The plantar pressure distribution analysis using Ansys determined the ideal locations for pressure sensor placement in the insole design: heel, midfoot, and first and fifth metatarsals. Subsequently, an IoT-integrated foot pressure and temperature monitoring device was developed with a Wi-Fi setup for data communication. The device enables users to track foot pressure and temperature through the Blynk app on their smartphones, provided a well-synchronized and stable connection is maintained. Ultimately, the performance analysis, conducted via balanced standing and walking modes, validated the reading and data collection capabilities of the smart monitoring device, revealing higher plantar pressure at the heel and metatarsal regions.

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Greek Symbols

Ω	Unit of electrical resistance, Ohms.

Abbreviations

3D	Three-Dimensional
CNNs	Convolutional Neural Networks
CT	Computerized Tomography
DFU	Diabetic Foot Ulcers
FEA	Finite Element Analysis
FSR	Force Sensing Resistors
IoT	Internet of Things
ML	Machine Learning
MRI	Magnetic Resonance Imaging
SVM	Support Vector Machines
Wi-Fi	Wireless Fidelity

References

1. Balasenthilkumaran, N.V.; Ram S, B.; Gorti, S.; Rajagopal, S.; and Soangra, R. (2022). Design and comparison of machine learning-based computer-aided diagnostic techniques to aid diagnosis of diabetes and detection of ulcer-prone regions in the feet using thermograms. *Research on Biomedical Engineering*, 38(3), 781-795.
2. Wu, Y.-W. et al. (2024). 2024 TSOC/TSPS joint consensus: Strategies for advanced vascular wound management in arterial and venous diseases. *Acta Cardiologica Sinica*, 40(1), 1-44.
3. Lazzarini, P.A.; Crews, R.T.; Van Netten, J.J.; Bus, S.A.; Fernando, M.E.; Chadwick, P.J.; and Najafi, B. (2019). Measuring plantar tissue stress in people with diabetic peripheral neuropathy: A critical concept in diabetic foot management. *Journal of Diabetes Science and Technology*, 13(5), 869-880.

4. Muralidhara, S.; Lucieri, A.; Dengel, A.; and Ahmed, S. (2022). Holistic multi-class classification & grading of diabetic foot ulcerations from plantar thermal images using deep learning. *Health Information Science and Systems*, 10(1), 21.
5. Sousa, L.B.; Almeida, I.; Bernardes, R.A.; Leite, T.R.; Negrao, R.; Apostolo, J.; Salgueiro-Oliveira, A.; and Parreira, P. (2023). A three step protocol for the development of an innovative footwear (shoe and sensor based insole) to prevent diabetic foot ulceration. *Frontiers in Public Health*, 11, 1061383.
6. Naemi, R.; Chockalingam, N.; Lutale, J.K.; and Abbas, Z.G. (2020). Predicting the risk of future diabetic foot ulcer occurrence: A prospective cohort study of patients with diabetes in Tanzania. *BMJ Open Diabetes Research & Care*, 8(1), e001122.
7. Simman, R.; and Abbas, F.-T. (2021). Foot wounds and the reconstructive ladder. *Plastic and Reconstructive Surgery-Global Open*, 9(12), e3989.
8. Zhang, J.; He, S.; Chen, Z.; Li, Y.; Guo, Y.; and He, Y. (2023). The management and antithrombotic strategies of patients with coronary artery disease and high bleeding risk. *Current Cardiology Reports*, 25(7), 669-680.
9. Koltak, C. (2022). The effects of different exercises on tissue mechanics, strength, and neuropathy symptoms in type 2 diabetes patients. Retrieved November 14, 2024, from https://clinicaltrials.gov/show/NCT05422235.
10. Santos, G.F.; Gomes, A.A.; Sacco, I.C.N.; and Ackermann, M. (2017). Predictive simulation of diabetic gait: Individual contribution of ankle stiffness and muscle weakening. *Gait & Posture*, 58, 208-213.
11. Chen, T.L.-W.; Wong, D.W.-C.; Wang, Y.; Lin, J.; and Zhang, M. (2019). Foot arch deformation and plantar fascia loading during running with rearfoot strike and forefoot strike: A dynamic finite element analysis. *Journal of Biomechanics*, 83, 260-272.
12. Akrami, M.; Qian, Z.; Zou, Z.; Howard, D.; Nester, C.J.; and Ren, L. (2018). Subject-specific finite element modelling of the human foot complex during walking: Sensitivity analysis of material properties, boundary and loading conditions. *Biomechanics and Modeling in Mechanobiology*, 17(2), 559-576.
13. Feldman, M.; Sobol, J.; and Gerren, D. (2016). 3664. Advanced lightweight 3D structures (AL3DS) manufacturing design concept. *Proceedings of the* 75th *SAWE International Conference on Mass Properties Engineering*, Denver, Colorado, USA.
14. Liang Wei, C.; Abdul-Kadir, N.A.; Mahmood, N.H.; Embong, A.M.; Harun, F.K.C.; and Wahab, M.A.A. (2023). Early detection of diabetic foot ulcers: Deep learning classification using thermograms (AlexNet Algorithm). *Proceedings of the* 2023 *IEEE International Biomedical Instrumentation and Technology Conference* (*IBITeC*), Yogyakarta, Indonesia, 12-16.
15. Wibowo, D.B.; Suprihanto, A.; Caesarendra, W.; Khoeron, S.; Glowacz, A.; and Irfan, M. (2020). A simple foot plantar pressure measurement platform system using force-sensing resistors. *Applied System Innovation*, 3(3), 33.
16. Vigneshwaran, S.; and Murali, G. (2020). Foot plantar pressure measurement system for static and dynamic conditions. *IOP Conference Series*: *Materials Science and Engineering*, 993(1), 012106.
17. Bin Ghazali, A.B.; Yi Ming, C.; and Abu Seman, M.T. (2021). Design of smart device for foot of diabetic patient in Malaysia. *Proceedings of the* 2021

International Congress of Advanced Technology and Engineering (*ICOTEN*), Taiz, Yemen, 1-6.

18. Bevilacqua, N.J.; Rogers, L.C.; and Armstrong, D.G. (2008). Diabetic foot surgery: Classifying patients to predict complications. *Diabetes/Metabolism Research and Reviews*, 24(S1), S81-S83.
19. Izzat Nordin, M.; Khairi Ishak, M.; Sattar Din, A.; and Tarmizi Abu Seman, M. (2024). Intelligent pressure and temperature sensor algorithm for diabetic patient monitoring: An IoT approach. *Indian Journal of Engineering*, 21(55), 1-13.
20. Wang, Y.; Li, Z.; Wong, D.W.-C.; Cheng, C.-K.; and Zhang, M. (2018). Finite element analysis of biomechanical effects of total ankle arthroplasty on the foot. *Journal of Orthopaedic Translation*, 12, 55-65.
21. Beach, C.; Cooper, G.; Weightman, A.; Hodson-Tole, E.F.; Reeves, N.D.; and Casson, A.J. (2021). Monitoring of dynamic plantar foot temperatures in diabetes with personalised 3D-printed wearables. *Sensors*, 21(5), 1717.
22. Armstrong, D.G.; Tan, T.-W.; Boulton, A.J.M.; and Bus, S.A. (2023). Diabetic foot ulcers: A review. *JAMA*, 330(1), 62-75.
23. Frykberg, R.G.; and Banks, J. (2015). Challenges in the treatment of chronic wounds. *Advances in Wound Care*, 4(9), 560-582.