IoT Solutions to Assist Patients With Diabetic Foot: A Systematic Mapping

Karla Haryanna S. Moura[1], Valéria Lelli[1,*] and Fabiana G. Marinho[2]

[1]Federal University of Ceará, Fortaleza, Brazil
[2]Federal Institute of Education, Science and Technology of Ceará, Fortaleza, Brazil

Abstract
The use of Internet of Things (IoT) applications in the prevention and treatment of diabetic foot has stimulated increasing research interest. Researchers are actively developing strategies to create applications that enable early and personalized interventions for patients with diabetic foot. Additionally, there is a growing focus on leveraging these technologies to enhance patient monitoring effectiveness. This paper provides a systematic mapping of research studies addressing the use of IoT in diabetic foot prevention and treatment. The mapping identified 22 relevant studies proposing various approaches, including smart shoes, smart insoles, and smart socks for remote monitoring. These studies also explored IoT strategies that integrate, cloud computing, prediction algorithms and machine learning to store and analyze collected data. This paper discusses the challenges faced on developing IoT applications for diabetic patients, emphasizing issues related to application architecture, the scope of solutions, the technologies used, and data integration.

Keywords
Diabetic foot, Internet of things, Internet of medical things, Health care

1. Introduction

The Internet of Things (IoT) is recognized as a fundamental technology to significantly expand the reach and usefulness of the Internet. By establishing a global infrastructure of interconnected physical components, IoT integrates a variety of devices, including sensors, actuators, and Radio Frequency Identification (RFID) systems [1]. Through the collection, analysis, and exchange of data in real time, this interconnection of devices enables more agile and accurate decision-making, while also facilitating the creation of highly adaptable and customizable systems. As a consequence, IoT is profoundly revolutionizing our interaction with the physical world, opening doors to countless opportunities for innovation, process optimization and development of new business models [2].

The growing interest in the application of IoT in healthcare is especially significant when considering its impact on remote patient monitoring [3]. Health monitoring technologies have emerged as effective tools for the prevention, early detection and management of chronic conditions [4].These technologies present a diversity of wearable devices and have been developed with the purpose of supporting the independence of the elderly, assisting in post-operative rehabilitation and facilitating the analysis and improvement of individual skills related to health, techniques, or sports [5].

Applications developed with IoT technologies for diabetic foot play a fundamental role in diagnosing and monitoring physical condition, integrating sensors into the human body or clothing with the purpose of monitoring physiological parameters that reflect health status, physical activity and others. Additionally, these systems are capable of measuring a variety of vital sign parameters in real time and forwarding them through a network of wireless sensors to family members, specialists, and caregivers accompanying the patient [6]. This approach not only allows for a rapid and appropriate response when necessary, but also assists in preventing the progression of chronic and progressive diseases that require constant monitoring [7].

ICAIW 2024: Workshops at the 7th International Conference on Applied Informatics 2024, October 24–26, 2024, Viña del Mar, Chile
*Corresponding author.
karlaharyanna@alu.ufc.br (K. H. S. Moura); valerialellids@ufc.br (V. Lelli); fabiana.gomes@ifce.edu.br (F. G. Marinho)
0000-0002-0177-3385 (K. H. S. Moura); 0000-0002-1210-7935 (V. Lelli); 0009-0006-8200-4567 (F. G. Marinho)

In this context, considering the relevance of IoT in healthcare and the problem of continuously monitoring patients with diabetic foot, the main objective of this research is to investigate IoT solutions that offer support to help patients with this condition. To achieve this goal, this study will conduct a systematic mapping to investigate the current state of IoT solutions aimed at enhancing the prevention and effective treatment of diabetic foot. The study will explore the following research questions:

- **(RQ1)** What are the proposed IoT solutions for patients with diabetic foot?
- **(RQ2)** What technologies are most used in the development of IoT applications for patients with diabetic foot?
- **(RQ3)** What is the scope, in terms of functional requirements, of IoT applications for diabetic foot care?
- **(RQ4)** What are the most relevant non-functional requirements of IoT applications for diabetic foot care?
- **(RQ5)** What are the challenges faced in developing IoT applications for diabetic foot care?

Based on the research questions mentioned, 22 studies were selected and underwent quality assessment, data extraction and analysis. This selection was carried out in accordance with Kitchenham's guidelines [8] and incorporating the backward snowballing technique.

The structure of this article is as follows: Section 2 provides theoretical foundation for understanding the research; Section 3 analyzes related studies; Section 4 details the methodology used; Section 5 presents the research findings and offers a discussion of results addressing the research questions; and Section 6 presents the final considerations and future directions.

2. Background

This section presents key concepts related to the application of IoT technology in the monitoring and management of diabetic foot conditions. It highlights the critical role IoT plays in enhancing the early diagnosis, treatment, and continuous monitoring of chronic diabetic foot complications.

2.1. Internet of Things - IoT

IoT is characterized as a network of interconnected devices, sensors, and systems that communicate and share data [9] and represents a scenario in which objects can relay information over a network without the need for human-to-human or human-to-computer interaction [10]. This infrastructure supports the creation of collaborative services and applications, catalyzing transformation across sectors such as education, logistics, healthcare, and smart cities [11].

An IoT infrastructure relies on the integration of sensors and the interoperability of various devices, thus requiring reliable software design for real-time processing and analysis of large volumes of data. Rigorous testing and validation are crucial to ensuring software reliability and performance. Additionally, intuitive user interfaces are essential for enhancing the interaction between users and IoT devices, and consequently promoting the adoption of these technologies [12].

According to Kassab [13], an architecture of a typical IoT solution includes components such as sensors, devices, connectivity, data processing and applications. These elements are detailed below.

- **Sensors** are devices that capture and measure data from either the physical environment or the human body. This includes a wide range of parameters such as temperature, blood pressure, and blood glucose levels, among others. By providing accurate and real-time data, sensors play a crucial role in monitoring health conditions and supporting informed medical decisions.
- **Devices** encompass a variety of equipment including medical devices, wearable technologies, and other connected gadgets that utilize data collected by sensors. These devices process, analyze, and sometimes transmit data to provide insights or alerts regarding health conditions, thereby facilitating timely medical interventions and ongoing health management.

- **Connectivity** refers to the process of transmitting data collected by sensors to cloud-based or local servers using various communication technologies such as Wi-Fi, Bluetooth, or other networking methods. This ensures that the data can be accessed and analyzed remotely, enabling real-time monitoring and effective management of health conditions.
- **Data processing** involves analyzing data obtained from sensors to extract relevant information about the patient's condition. This analysis may include advanced techniques, such as machine learning, to identify patterns, predict potential health events, and generate actionable recommendations for personalized care.
- **Applications** include platforms and tools designed for visualizing and interpreting processed data. These applications offer feedback to both patients and healthcare professionals, enhancing the ability to make informed decisions about health management and treatment plans.

2.2. Diabetic Foot

Diabetic foot refers to a complex condition characterized by infection, ulceration, or tissue damage in individuals with diabetes, often resulting from complications such as peripheral neuropathy and peripheral artery disease. Affecting approximately 18.6 million people globally each year, diabetic foot significantly increases the risk of amputation and mortality [14].

A comprehensive review of the literature identifies four critical parameters for predicting the onset of diabetic foot: temperature [15], pressure [15], humidity [16], and suboptimal oxygenation levels (SpO2) [17]. Each of these parameters is briefly discussed below.

2.2.1. Temperature

According to Kulkarni et al. [15], temperature measurements are considered a crucial parameter for non-invasive remote monitoring of diabetic foot. Research on dermal thermometry has indicated that temperature variations of 4 °F (greater than 2.2 °C) may serve as valuable indicators for monitoring skin health and detecting potential issues [18]. However, the lack of a standardized reference range poses a challenge, as body temperature can vary significantly between individuals and even across different areas of the same person's body.

2.2.2. Pressure

There is extensive literature examining the relationship between increased foot pressure and its correlation with ulcer formation in diabetic patients [15]. Pressure measurements can be categorized into static techniques, which assess pressure while the individual is standing still, and dynamic measurements, which capture pressure during movement. It is well established that areas of abnormally high pressure are prevalent in individuals with a history of ulceration, making these pressure points a critical factor in the recurrence and development of ulcers in diabetic patients [19].

2.2.3. Humidity

Jones et al. [16] highlight that moisture plays a pivotal role in foot health by increasing friction between the skin and surfaces, such as insoles, potentially leading to tissue deformation when skin layers move tangentially relative to each other during movement. Both insufficient and excessive moisture can disrupt the delicate balance necessary for maintaining dermal foot health. Insufficient sweating, a frequent complication of diabetes, impairs the skin's barrier function, rendering it more vulnerable to infections. Furthermore, research has shown a positive correlation between dry skin and the development of diabetic foot.

2.2.4. Suboptimal Oxygenation

Suboptimal oxygenation (SpO2) is a critical factor that impedes the healing of diabetic wounds by restricting blood flow to the affected areas, thereby delaying recovery [20]. Monitoring SpO2 levels can facilitate the early detection of various complications, including hypoxemia, declining organ function, tissues at risk of developing wounds, and even cardiac arrest [21].

2.3. IoT in Diabetic Foot

IoT solutions can help monitor and prevent diabetic foot complications by using sensor-equipped devices to track patients' physical conditions. Figure 1 depicts an IoT application for patient monitoring using sensors that measure pressure, temperature, and humidity.

The collected data is transmitted continuously to a mobile app, which employs data analysis techniques to generate alerts for patients, caregivers, and doctors. These sensors can be embedded in devices like smart shoes, smart insoles, and smart socks. Such applications highlight the importance of empowering diabetic foot patients with intelligent IoT tools for effective self-management.

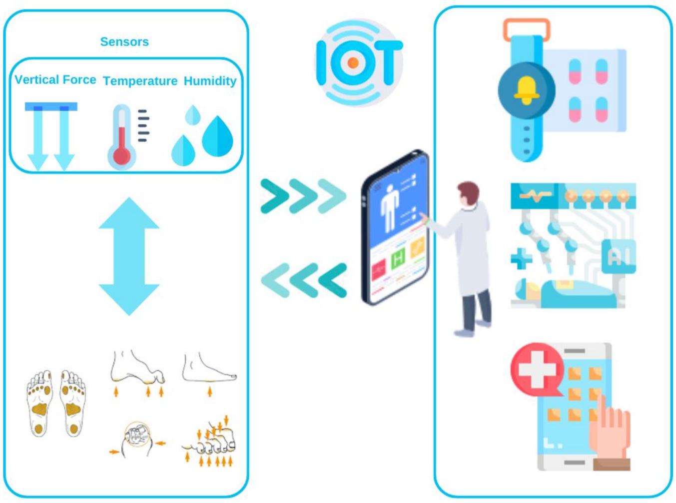

Figure 1: Scenario of an IoT solution for monitoring diabetic foot

3. Related Work

This section presents a comprehensive overview of secondary studies investigating the application of IoT solutions in diabetes management, as well as those focusing specifically on the monitoring of diabetic foot conditions.

The literature includes review studies that analyze solutions focused on improving healthcare for diabetic patients through the integration of remote health monitoring (RHM) and Internet of Medical Things (IoMT) technologies. AlShorman et al. [22] provide a discussion of the current state of digital health processes, including the utilization of sensors, wearable devices, IoT, and big data tools for monitoring diabetic patients more effectively.

The systematic review conducted by Souza et al. [3] provides an overview of the current state of the art regarding data collection methods, system characteristics, and capabilities, and current research challenges and limitations to be addressed. Similarly, Peyroteo et al. [23] provide an overview of complementary technologies and address various challenges associated with the development of an advanced smart healthcare system. This systematic review aims at providing an overview of the state of the art regarding smart wearable systems (SWS) applications to monitor the status of patients suffering from vascular disorders of the lower extremity. In alignment with these objectives, Dwivedi et al. [24] highlight recent advancements in the prevention, diagnosis, and treatment of diabetes.

In the context of diabetic foot, we did not identify any secondary studies focused on IoT solutions. However, Vaishnavi et al. [25], in their survey, highlight the critical aspects of continuous monitoring and prediction, which are vital for the effective management of diabetic foot in the context of IoMT.

Analysis of related works shows that, despite medical advancements, effectively managing diabetic foot remains a significant challenge.

4. Research Method

The systematic mapping performed in this study adhered to the guidelines set forth by Kitchenham [26], while also incorporating the backward snowballing technique. Following these established guidelines, the planning, conduction, and quality assessment of the studies were systematically carried out in alignment with the activities associated with each phase. It is noteworthy that the *Parsifal*[1] tool was used to assist in the entire systematic mapping process.

4.1. Planning

The planning phase entails the development of a comprehensive protocol that clearly defines the research goals, key research questions, search strategy, inclusion and exclusion criteria, and the specific databases to be utilized for sourcing relevant literature. The full protocol is available in the study's linked repository[2].

4.1.1. Goals and Research Questions

This systematic mapping aimed to identify IoT solutions for preventing and treating diabetic foot, guided by the primary research question:

- What is the state of the art in IoT-based solutions for preventing and treating diabetic foot?

Research questions (RQs) were formulated, based on the primary research question, and structured according to the PICOC framework, as outlined below:

- **Population (P)**: IoT solutions;
- **Intervention (I)**: smart health studies to prevent and treat diabetic foot;
- **Comparison (C)**: the comparison dimension was not applicable to the present study;
- **Outcome (O)**: functional and non-functional requirements, architectural characteristics, as well as associated processes and methodologies; and
- **Context (C)**: smart health.

Table 1 presents de RQs to investigate the challenges, trends, and gaps in IoT solutions for diabetic foot care.

4.1.2. Search String

The search string was developed using keywords identified from the goal and research questions, combining logical operators (OR/AND) and customized search strategies for each database. The final search string used in this study is presented in Table 2.

4.1.3. Selection Criteria

Inclusion and exclusion criteria were defined to select studies that significantly contribute to the research objectives. Two inclusion criteria and five exclusion criteria were established, as detailed in Table 3.

[1]https://parsif.al/
[2]https://drive.google.com/drive/folders/161eVvKjN4wJAxeJCVnm5ODrHon3CS35-?usp=sharing

Table 1
Research questions and their rationale

Research Question
RQ1. What are the proposed IoT solutions for patients with diabetic foot? **Rationale:** Identify ways to improve support for the growing need for healthcare IoT applications to enhance diabetic foot management.
RQ2. What technologies are most used in the development of IoT applications for patients with diabetic foot? **Rationale:** Explore emerging technologies and gaps in current diabetic foot monitoring practices.
RQ3. What is the scope, in terms of functional requirements, of IoT applications for diabetic foot care? **Rationale:** Identify key functionalities for IoT apps to support patients effectively.
RQ4. What are the most relevant non-functional requirements of IoT applications for diabetic foot care? **Rationale:** Identify non-functional requirements of IoT applications that impact user, such as satisfaction and safety.
RQ5. What are the challenges faced in developing IoT applications for diabetic foot care? **Rationale:** Explore trends and challenges for new research in Software Engineering.

Table 2
Search String

(“IoT” OR “Internet of things” OR IoMT OR “internet of medical things” OR “e-health” OR ehealth OR mhealth OR IoHT OR “internet of healthcare things” OR “m-health” OR “mobile health” OR “smart healthcare” OR “smart health care”) **AND** (“diabetic foot” OR “diabetes pathology” OR “diabetic pathology” OR “foot disease” OR “pathology of diabetes” OR “pathology of diabetes”)

Table 3
Inclusion and Exclusion Criteria

ID	Description
	Inclusion Criteria (IC)
IC1	Studies that present an IoT solution to treat or prevent diabetic foot
IC2	Studies that were written in English or Portuguese
	Exclusion Criteria (EC)
EC1	Studies that do not explicitly address IoT solutions
EC2	Studies that are not aimed at the diabetic foot
EC3	Studies that are abstracts or conference indexes
EC4	Studies in which the full text is not available
EC5	Studies that are shortened versions of other studies

4.1.4. Databases

To maximize the scope of the mapping, four databases (ACM Digital Library[3], IEEE[4], Scopus[5] and PubMed[6]) were selected based on their extensive, high-quality literature and credibility. Scopus was chosen for its conference coverage, and PubMed for its broad biomedical literature. The search string was applied with no restrictions on the publication period.

4.2. Conduction

During the conduction stage, the search string was applied across four selected databases, yielding 226 studies: 107 from Scopus, 65 from PubMed, 32 from IEEE, and 22 from ACM Digital Library. 70

[3]http://portal.acm.org
[4]https://ieeexplore.ieee.org/
[5]http://www.scopus.com
[6]https://www.ncbi.nlm.nih.gov

duplicates, mainly from PubMed and IEEE, were removed.

The remaining 156 studies were reviewed by title and abstract, leading to the exclusion of 96 studies that were not relevant to the theme. The remaining 60 studies were then fully read to verify their alignment with the established criteria. From these, 13 studies were selected. The stages of study selection are illustrated in Figure 2, depicting the number of studies at each step. Table 4 presents these studies, listing their respective title, year, and reference.

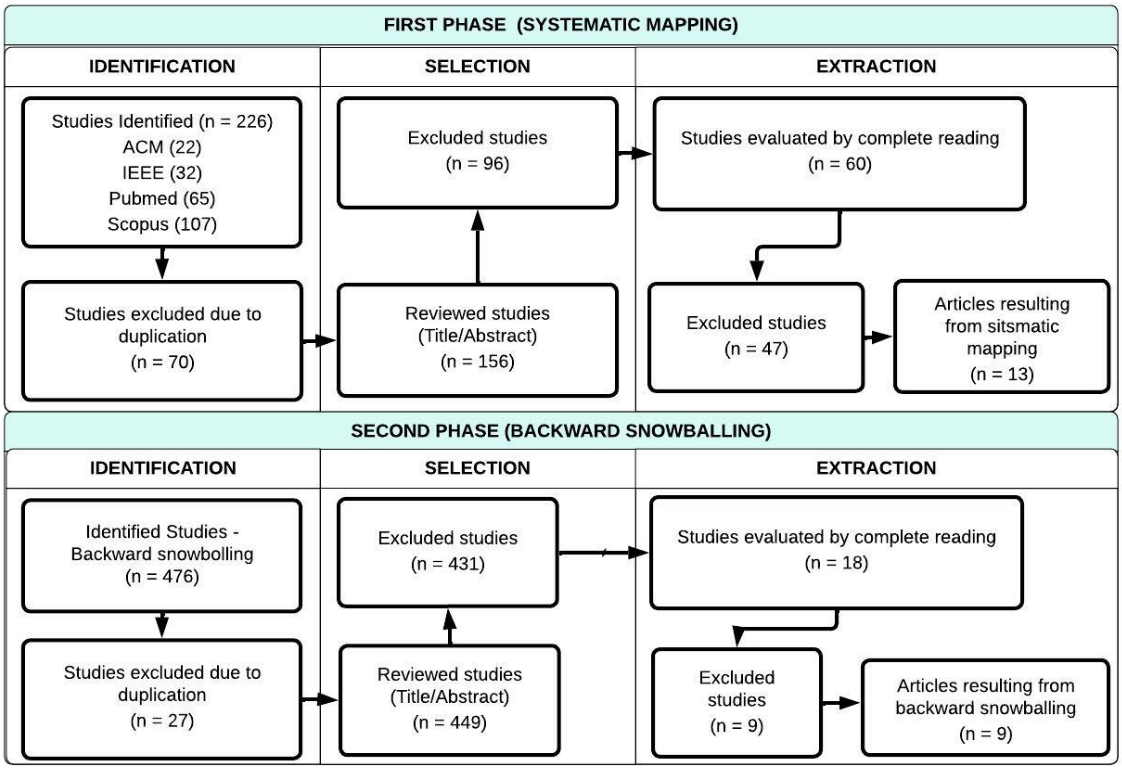

Figure 2: Adapted PRISMA flow diagram from [27]

Backward snowballing was applied to the 13 studies from the initial phase to identify additional relevant research. Of 476 references reviewed, 27 were duplicates from the first phase. After applying the selection criteria, 431 studies were excluded based on titles and abstracts. The remaining 18 studies were fully reviewed, resulting in 9 additional studies.

5. Results and Discussions

This section presents a review of 22 studies identified through systematic mapping and backward snowballing, intended to address the research questions.

The graph depicted in the Figure 3, illustrates the number of studies identified in the systematic mapping of IoT solutions to assist patients with diabetic foot. The publication dates of the selected studies range from 2011 to 2024, showing notable peaks in certain years.

From 2011 to 2018, the numbers remain consistent at 1, followed by a continuous increase starting in 2019, with 2 studies published that year and 3 in 2020. The numbers peak at 4 in 2021, then fluctuate, dropping to 3 in 2022, rising again to 4 in 2023, and falling to 3 in 2024. Overall, the trend shows growth beginning in 2019, with significant peaks in 2021 and 2023, and minor fluctuations afterward. The peak in 2021 indicates a period of notable advancements in the field, likely driven by technological innovations and a growing recognition of the importance of diabetic foot monitoring.

Table 4
Selected Studies in Systematic Mapping

Title	Year	Reference
Planipes: Mobile Foot Pressure Analysis	2011	[28]
IoT Based Monitoring of Foot Pressure Using FSR Sensor	2017	[29]
Health Care Foot Wear for Monitoring the Diabetic Patients	2018	[30]
Dia-Shoe: A Smart Diabetic Shoe to Monitor and Prevent Diabetic Foot Ulcers	2019	[31]
Innovative Intelligent Insole System Reduces Diabetic Foot Ulcer Recurrence at Plantar Sites: a Prospective, Randomised, Proof-Of-Concept Study	2019	[32]
A Medical IoT-Based Remote Monitoring System: Application on Diabetic Foot	2020	[7]
IoT and Cloud Based Healthcare Solution for Diabetic Foot Ulcer	2020	[33]
An Embedded Wearable Device for Monitoring Diabetic Foot Ulcer Parameters	2020	[15]
Design of Smart Device for Foot of Diabetic Patient in Malaysia	2021	[34]
SISTINE: Sensorized Socks for Telemonitoring of Vascular Disease Patients	2021	[35]
Mobile Health–Based Thermometer for Monitoring Wound Healing After Endovascular Therapy in Patients With Chronic Foot Ulcer: Prospective Cohort Study	2021	[36]
A Smart Wearable Device for Monitoring and Self-Management of Diabetic Foot: A Proof of Concept Study	2021	[37]
Smart Sock-Based Machine Learning Models Development for Phlebopathic Patient Screening	2022	[38]
Early Detection of Diabetic Foot Ulcers through Wearable Shoe Design	2022	[39]
A Smart Wearable Oximeter Insole for Monitoring SpO2 Levels of Diabetics Foot Ulcer	2022	[17]
Development of a Flexible Smart Wearable Oximeter Insole for Monitoring SpO2 Levels of Diabetics' Foot Ulcer	2023	[20]
Smart Offloading Boot System for Remote Patient Monitoring: Toward Adherence Reinforcement and Proper Physical Activity Prescription for Diabetic Foot Ulcer Patients	2023	[40]
Implementation of LoRa Wireless Communication in Smart Diabetic Shoes Design	2023	[41]
Prototype Design of Smart Diabetic Shoes with Lora Module Communication	2023	[42]
Home-based Detection and Prediction of Diabetic Foot Ulcers at Early Stage Using Sensor Technology and Supervised Learning	2024	[43]
Design and Manufacturing a Smart Shoe for Diabetic Foot Ulcer Monitoring and Prediction System Using Internet-Of-Things Technology	2024	[44]
Intelligent Pressure and Temperature Sensor Algorithm for Diabetic Patient Monitoring: An IoT Approach	2024	[45]

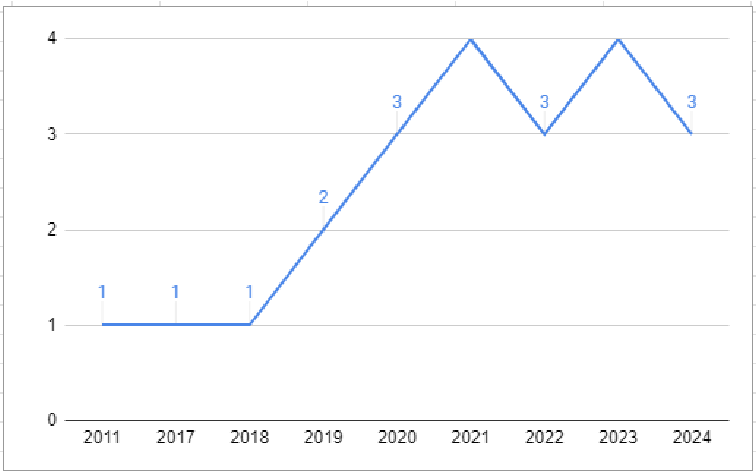

Figure 3: Articles per year

5.1. (RQ1) What are the proposed IoT solutions for patients with diabetic foot?

The most promising IoT solutions for patients with diabetic foot include wearable devices such as insoles, shoes, socks, and boots. These devices are designed to monitor key metrics like vibration, temperature, pressure, humidity, and SpO2, with temperature being the most commonly used parameter.

Table 5 summarizes the components and methodologies used in monitoring diabetic foot health. The analysis highlights the variety of sensor types employed, each requiring distinct approaches for effective monitoring of diabetic foot conditions. For data communication, Bluetooth and Wi-Fi are the most commonly used protocols. However, some solutions also incorporate advanced technologies such as ANT+, Wireless LoRa (integrated with Bluetooth or Wi-Fi), 4G, or 5G to enhance data transmission capabilities.

Table 5
IoT Solutions

Wearable	Hardware	Communication	Software	Study
Smart Insole	Vibration Sensor	Bluetooth	Mobile	[43]
	Pressure | Temperature Sensors	Bluetooth	Blynk App	[45]
	Pressure Sensor	ANT+	Smartwatch	[32]
	Force Sensitive Register	Bluetooth	Mobile	[29]
	SpO2 Sensor	Bluetooth	Mobile	[20]
	Pressure | Temperature Sensors	Bluetooth	Blynk App	[34]
	Temperature | Humidity | Pressure Sensors	Wi-Fi	Mobile	[30]
	Flexiforce | Pressure Sensors	Bluetooth	Mobile	[33]
	Force Sensitive Resistor	Bluetooth	Mobile	[28]
	SpO2 Sensor	Bluetooth	Mobile	[17]
Smart Shoes	Humidity | Temperature Sensors | Force Sensitive Resistor	Wi-Fi	Mobile	[44]
	Pressure | Temperature Sensors	Wireless Lora (integrated with Bluetooth or Wi-Fi)	Web	[42]
	Humidity | Temperature Sensors | Force Sensitive Resistor	Bluetooth	Mobile	[37]
	Temperature | Vibration | Pressure Sensors	Wi-Fi	Mobile	[39]
	Temperature Sensor | Force Sensitive Resistor	Wireless Lora (integrated with Bluetooth or Wi-Fi)	Web	[41]
	Plantar Pressure Scanner | SpO2 | Temperature Sensors	Bluetooth	Mobile	[7]
	Temperature | Humidity Sensors | Tilt Switch Sensor | Calibrated Load Cell Sensor	Wi-Fi	Mobile	[31]
Smart Sock	Force Sensitive Resister | Temperature Sensor | Accelerometer | Gyroscope | Heart-Rate Sensor	Wi-Fi Bluetooth	Mobile	[15]
	Pressure | Inertial Sensors	Bluetooth | 4G	Mobile	[38]
	Flexiforce | Inertial | Stretch Sensors	Bluetooth | 5G	Mobile	[35]
Smart Boot	Accelerometer and Gyroscope Sensor	Bluetooth and 4G	Smartwatch	[40]
Body Temperature	Temperature sensor	Bluetooth	Mobile	[36]

Additionally, Table 5 outlines the software platforms associated with these studies, which include both Mobile, Smartwatch, Blynk and Web-Based applications. Each platform is designed to support specific aspects of remote patient monitoring and management, facilitating real-time data access and interaction. These platforms contribute to more effective patient care and informed decision-making.

5.2. (RQ2) What technologies are most used in the development of IoT applications for patients with diabetic foot?

The 22 studies analyzed concentrate on the architecture and prototype development of systems involving sensors, electronic boards, and microcontrollers. They emphasize the design and construction of IoT frameworks and prototypes that integrate multiple components. Additionally, the examined IoT solutions incorporate a variety of technologies, as summarized in Table 6.

Table 6
Technologies

Technology	Study
LoRa	[42]
LoRaWAN	[41]
Bluetooth Low Energy (BLE)	[40] [20] [17] [39] [38] [35] [37] [36] [34] [15] [33] [7] [32] [31] [30] [29] [28]
Energy Management System (EMS)	[41] [40] [39] [38] [35] [36] [34] [15] [33] [7] [32] [31] [30] [29] [28]
Blynk Application	[44] [45]
Machine Learning | Data Analysis | Prediction	[43] [38] [38] [40] [35] [37] [36] [34] [15] [33] [7] [32] [31] [30] [29] [28]
Web Platform | Smartphone Application	[43] [42] [40] [20] [17] [39] [38] [35] [35] [36] [34] [15] [33] [32] [31] [30] [29] [28]
Dash Board Web	[40] [36] [33] [7]
Cloud Computing	[33] [7] [29]

LoRa and LoRaWAN enable long-range, low-power wireless communication for monitoring data transmission in remote or home-based settings. In addition, the system may also integrate other communication technologies, such as Bluetooth or Wi-Fi, for short-range data transfer and synchronization with smartphones.

Bluetooth Low Energy (BLE) offers low power consumption and efficient transmission of sensor data to mobile devices or remote monitoring platforms. Additionally, Energy Management System (EMS) is designed to optimize battery life and ensure the continuous operation of wearable devices by effectively managing the power supplied to sensors and microcontrollers.

The Blynk Application provides an interface for real-time data visualization and monitoring on smartphones. Additionally, Machine Learning, Data Analysis, and Prediction services are applied in various studies to interpret sensor data, detect patterns, and provide insights into diabetic foot health, enhancing monitoring accuracy.

The Web Platform and Smartphone Application are used to visualize sensor data and alert patients or healthcare providers in case of abnormal readings, enabling continuous real-time monitoring and early prediction of diabetic foot. The Web Dashboard further analyzes sensor data and may incorporate algorithms to provide feedback on disease progression. Cloud computing processes, stores, and analyzes data from wearable devices, emphasizing the interpretation of health metrics to identify risks associated with diabetic foot conditions.

5.3. (RQ3) What is the scope, in terms of functional requirements, of IoT applications for diabetic foot care?

The functional requirements summarized in Table 7 reveal that Physical Parameters Monitoring, Real-Time Communication, and Notifications and Alerts are present across all studies. This consistency indicates that these features are fundamental to all implementations and are crucial for maintaining continuous monitoring of diabetic foot health and facilitating interventions.

Visualization Interface is featured in 15 of the 22 studies, highlighting the importance of providing an intuitive platform for patients and healthcare providers to monitor and interpret data in real time. It

Table 7
Functional Requirements

Functional Requirements	Studies
Physical Parameters Monitoring	Present in all studies
Real-Time Communication	Present in all studies
Notifications and Alerts	Present in all studies
Visualization Interface	[31] [7] [41] [28] [35] [17] [39] [20] [40] [37] [44] [33] [34] [32] [29]
Data Collection and Storage	[31] [7] [41] [35] [28] [17] [39] [20] [40] [37] [36] [43] [38] [15] [32] [30] [29]
Sensor Calibration	[41]
Physical Activity Prescription	[40]
Report Generation	[33]
Historical Data Recording	[34]

emphasizes the role of user-friendly interfaces in ensuring the accessibility of health data.

Data Collection and Storage is another frequently employed requirement, present in 17 studies. This functionality ensures that data gathered from sensors is stored for future analysis, supporting both real-time monitoring and long-term tracking of patient health trends.

Sensor Calibration is featured in a single study. This suggests that, despite the importance of sensor accuracy, it is not always emphasized. Physical Activity Prescription and Report Generation indicate specific functionalities that are supplementary to particular use cases, such as providing guidance on patient activity or generating health reports for further analysis.

Although the Historical Data Recording functionality is crucial for tracking the progression of a patient's condition over time, adding depth to long-term monitoring and aiding in the identification of trends or recurrent issues, it is rarely considered in the studies.

5.4. (RQ4) What are the most relevant non-functional requirements of IoT applications for diabetic foot care?

The non-functional requirements outlined in Table 8 were reviewed to identify the essential characteristics needed for effective IoT systems.

Table 8
Non Functional Requirements

Non Functional Requirements	Studies
Low Cost	[31] [36] [43] [15] [42]
Low Power Consumption	[31] [7] [41] [42] [35] [32] [30] [29]
Accuracy	[31] [35] [28] [17] [39] [20] [40] [37] [36] [43] [38] [15] [42] [45] [32] [29]
Usability | Comfort	[31] [41] [35] [28] [17] [39] [37] [20] [40] [36] [43] [38] [15] [42] [44] [33] [34] [45] [32] [30] [29]
Device Durability	[31] [35] [17] [39] [20] [40] [37] [15] [36] [38] [42] [44] [32] [30]
Data Security | Privacy	[7] [28] [35] [17] [39] [20] [40] [37] [36] [43] [38] [15] [42] [44] [33] [34] [45] [32] [30] [29]
Performance	[28] [35] [17] [39] [20] [40] [37] [43] [38] [15] [42] [44] [33] [34] [45]
Low Latency	[7] [36]
Reliability	[31] [7] [41] [35] [37] [33] [34] [32] [29]
Signal Robustness	[41] [41] [43] [38] [45]

Low Cost emphasizes economic viability in system design, making solutions accessible to a wider audience, while Low Power Consumption highlights the importance of energy efficiency in IoT-based healthcare devices. Accuracy, emphasized in 16 studies, stresses the critical importance of precision in monitoring health parameters such as pressure and temperature for diabetic patients.

Usability and Comfort are cited in nearly all studies and demonstrate the importance of user-friendly designs in wearable devices to enhance patient adherence. Device Durability is essential for long-term use, especially in wearable devices that are exposed to various conditions.

Data Security and Privacy, noted in 20 of the 22 studies, are prioritized to protect patient data and safeguard sensitive medical information against unauthorized access and breaches, ensuring patient privacy and data integrity.

Performance, Low Latency, Reliability, and Signal Robustness underscore the importance of the system's efficiency in executing its functions without delays or failures, ensuring consistent data transmission without interruption, and accentuating the need for robust systems that can reliably handle tasks critical for real-time monitoring.

5.5. (RQ5) What are the challenges faced in developing IoT applications for diabetic foot care?

The studies analyzed in this systematic mapping reveal a range of significant challenges and limitations. A key issue is the high cost associated with IoT technologies, which often rely on specialized sensors with considerable price variability. This cost factor can increase the overall price of devices, making them impractical for large-scale production and inaccessible to a substantial portion of the population.

Several studies mention the limitation of small sample sizes, which significantly undermines the statistical power and reliability of their findings. Furthermore, the studies predominantly relied on data gathered during proof-of-concept stages or short-term trials, restricting the generalizability and applicability of their conclusions.

Another critical challenge is ensuring the usability of IoT devices, which is vital for promoting patient adherence to treatment. Poorly designed user interfaces can significantly hinder user engagement and compromise treatment outcomes. Despite studies mentioning its importance, they report substantial obstacles in achieving participant adherence to sensor usage, citing discomfort with wearing the devices, an increased risk of falls or accidents due to non-standard designs compared to traditional footwear, and mobility limitations when sensors are worn on only one foot.

For IoT solutions to be effective, they must perform reliably across all functions, including data reception, transmission, feedback, and processing. Accuracy is paramount in medical systems, but technical shortcomings such as delayed response times, limited battery life, communication failures between sensors, and inaccuracies in sensor measurements pose significant barriers to effectiveness. These inaccuracies are compounded by factors such as asymmetry resulting from using sensors on only one foot and measurement errors caused by fluctuating environmental conditions like temperature and humidity. Such limitations severely compromise the reliability of the results.

6. Conclusion

This study employed systematic mapping, following Kitchenham's guidelines and incorporating the backward snowballing technique, to investigate the integration IoT technology in managing diabetic foot disease. The research revealed that monitoring key parameters such as temperature, pressure, humidity, vibration, and SpO2 bridges the gap between health and technology. This integration supports early detection of potential issues, enhances treatment efficacy, prevents complications, and ultimately improves the overall quality of life for patients.

From the reviewed studies, several technical limitations were identified, including challenges related to prototype planning, sensor placement, and the structural design of wearable devices. Usability constraints, security concerns, and issues with the effectiveness of data transactions within the network were also frequently observed, particularly concerning the duration and conditions of device use by patients. Based on these findings, a prototype of an IoT system for monitoring and detecting risk symptoms in diabetic foot will be developed. This prototype will address the identified solutions, functional and non-functional requirements, technologies, and challenges highlighted in the mapping.

To fully realize the potential of IoT integration in managing diabetic foot disease, future research must address not only the existing technical limitations but also consider additional factors such as patient acceptance, healthcare professional training, and cost implications. Evaluating these social and technical aspects is essential for optimizing the deployment and efficacy of IoT technologies in practical, real-world settings.

Acknowledgments

The present work was supported by the Federal University of Ceara (UFC), Brazil. We thank CAPES for the assistance with grant support that helped the first author.

References

[1] M. M. Rathore, A. Paul, A. Ahmad, M. Anisetti, G. Jeon, Hadoop-based intelligent care system (hics): Analytical approach for big data in iot, ACM Trans. Internet Technol. 18 (2017). URL: https://doi.org/10.1145/3108936. doi:10.1145/3108936.
[2] M. Chui, et al., The internet of things, McKinsey Quarterly 9 (2010) 1–9.
[3] J. Souza, S. Escadas, I. Baxevani, D. Rodrigues, A. Freitas, Smart wearable systems for the remote monitoring of selected vascular disorders of the lower extremity: A systematic review, International Journal of Environmental Research and Public Health 19 (2022) 15231.
[4] M. M. Baig, H. GholamHosseini, A. A. Moqeem, F. Mirza, M. Lindén, A systematic review of wearable patient monitoring systems - current challenges and opportunities for clinical adoption, Journal of Medical Systems 41 (2017) 115. doi:10.1007/s10916-017-0760-1.
[5] L. Gatzoulis, I. Iakovidis, Wearable and portable ehealth systems, IEEE Engineering in Medicine and Biology Magazine 26 (2007) 51–56.
[6] S. Patel, H. Park, P. Bonato, L. Chan, M. Rodgers, A review of wearable sensors and systems with application in rehabilitation, Journal of NeuroEngineering and Rehabilitation 9 (2012) 21. doi:10.1186/1743-0003-9-21.
[7] L. F. Moncada-Sánchez, R. A. Salido-Ruiz, A. Espinoza-Valdez, A medical iot-based remote monitoring system: application on diabetic foot, in: VIII Latin American Conference on Biomedical Engineering and XLII National Conference on Biomedical Engineering: Proceedings of CLAIB-CNIB 2019, October 2-5, 2019, Cancún, México, Springer, 2020, pp. 1313–1319.
[8] B. A. Kitchenham, S. Charters, Guidelines for performing systematic literature reviews in software engineering, Technical Report 7, EBSE Technical Report, 2007.
[9] M. M. Jassem, M. I. Al-nouman, Design and implementation of IoT-based burglary detection system, Nome do Jornal ou Conferência Volume 9 (2023) Páginas 549–557. doi:http://dx.doi.org/10.26555/jiteki.v9i3.26602.
[10] D. Farahiyah, B. W. Purnama, Design prototype of temperature and humidity control and monitoring on weaver ant cage based on Internet of Things, J. Ilm. Tek. Elektro Komput. dan Inform. 7 (2021) 326–337. URL: https://doi.org/10.26555/jiteki.v7i2.21438. doi:10.26555/jiteki.v7i2.21438.
[11] S. Deshkar, R. Thanseeh, V. G. Menon, A review on iot based m-health systems for diabetes, International Journal of Computer Science and Telecommunications 8 (2017) 13–18.
[12] L. F. Mourão, A. D. B. Marques, T. M. M. Moreira, S. K. P. d. Oliveira, Mobile applications to promote diabetic foot care: Scoping review (2022).
[13] W. Kassab, K. A. Darabkh, A–z survey of internet of things: Architectures, protocols, applications, recent advances, future directions and recommendations, Journal of Network and Computer Applications 163 (2020) 102663.
[14] J. J. van Netten, S. A. Bus, J. Apelqvist, B. A. Lipsky, R. J. Hinchliffe, F. Game, G. Rayman, P. A. Lazzarini, R. O. Forsythe, E. J. Peters, Definitions and criteria for diabetic foot disease, Diabetic Medicine 37 (2020) 158–167. URL: https://doi.org/10.1002/dmrr.3268. doi:10.1002/dmrr.3268, citations: 205.

[15] V. V. Kulkarni, F. Seraj, J. R. Rathikumar, An embedded wearable device for monitoring diabetic foot ulcer parameters, in: Proceedings of the 13th ACM International Conference on PErvasive Technologies Related to Assistive Environments, 2021, pp. 1–7.

[16] P. Jones, R. Bibb, M. Davies, K. Khunti, M. McCarthy, D. Webb, F. Zaccardi, Prediction of diabetic foot ulceration: The value of using microclimate sensor arrays, Journal of diabetes science and technology 14 (2020) 55–64.

[17] M. Panahi, S. Masihi, A. Hanson, J. Rodriguez-Labra, A. Masihi, D. Maddipatla, B. Narakathu, D. Lawson, M. Atashbar, A smart wearable oximeter insole for monitoring spo 2 levels of diabetics' foot ulcer, in: 2022 IEEE International Conference on Flexible and Printable Sensors and Systems (FLEPS), IEEE, 2022, pp. 1–4.

[18] D. G. Armstrong, K. Holtz-Neiderer, C. Wendel, M. J. Mohler, H. R. Kimbriel, L. A. Lavery, Skin temperature monitoring reduces the risk for diabetic foot ulceration in high-risk patients, The American Journal of Medicine 120 (2007) 1042–1046.

[19] T. Duckworth, A. J. Boulton, R. P. Betts, C. I. Franks, J. D. Ward, Plantar pressure measurements and the prevention of ulceration in the diabetic foot, The Journal of Bone and Joint Surgery. British Volume 67 (1985) 79–85.

[20] M. Panahi, S. Masihi, A. Hanson, J. Rodriguez-Labra, A. Masihi, D. Maddipatla, B. Narakathu, D. Lawson, M. Atashbar, Development of a flexible smart wearable oximeter insole for monitoring spo 2 levels of diabetics' foot ulcer, IEEE Journal on Flexible Electronics (2023).

[21] M. Ochoa, et al., Integrated sensing and delivery of oxygen for next-generation smart wound dressings, Microsystems and Nanoengineering 6 (2020) 1–16.

[22] O. AlShorman, B. AlShorman, M. Alkhassaweneh, F. Alkahtani, A review of internet of medical things (iomt) - based remote health monitoring through wearable sensors: A case study for diabetic patients, Indonesian Journal of Electrical Engineering and Computer Science 20 (2020) 414. doi:10.11591/ijeecs.v20.i1.pp414-422.

[23] M. Peyroteo, I. Ferreira, L. Elvas, J. Ferreira, L. Lapão, Remote monitoring systems for patients with chronic diseases in primary health care: Systematic review, JMIR Mhealth Uhealth 9 (2021) e28285. doi:10.2196/28285.

[24] R. Dwivedi, D. Mehrotra, S. Chandra, Potential of internet of medical things (iomt) applications in building a smart healthcare system: A systematic review, Journal of Oral Biology and Craniofacial Research 12 (2022) 302–318. URL: https://www.sciencedirect.com/science/article/pii/S2212426821001408. doi:https://doi.org/10.1016/j.jobcr.2021.11.010.

[25] R. Vaishnavi, P. Jegathesh, M. Jayasheela, K. Mahalakshmi, A survey on impact of internet of medical things against diabetic foot ulcer, EAI Endorsed Transactions on Pervasive Health and Technology 10 (2024). doi:10.4108/eetpht.10.5170.

[26] B. Kitchenham, Procedures for performing systematic reviews, Keele, UK, Keele University 33 (2004) 1–26.

[27] D. Moher, A. Liberati, J. Tetzlaff, D. G. Altman, T. P. Group, Preferred reporting items for systematic reviews and meta-analyses: the prisma statement, Annals of Internal Medicine 151 (2009) 264–269.

[28] S. Pfaffen, P. Sommer, C. Stocker, R. Wattenhofer, S. Welten, Planipes: Mobile foot pressure analysis, in: Proceedings of the First ACM Workshop on Mobile Systems, Applications, and Services for Healthcare, 2011, pp. 1–6.

[29] P. S. Malvade, A. K. Joshi, S. P. Madhe, Iot based monitoring of foot pressure using fsr sensor, in: 2017 International Conference on Communication and Signal Processing (ICCSP), 2017, pp. 0635–0639. doi:10.1109/ICCSP.2017.8286435.

[30] V. Priya, A. Dhanaseeley, Health care foot wear for monitoring the diabetic patients, International Journal of Pure and Applied Mathematics 119 (2018) 969–973.

[31] N. Kularathne, U. Wijayathilaka, N. Kottawaththa, S. Hewakoralage, S. Thelijjagoda, Dia-shoe: A smart diabetic shoe to monitor and prevent diabetic foot ulcers, in: 2019 International Conference on Advancements in Computing (ICAC), 2019, pp. 410–415. doi:10.1109/ICAC49085.2019.9103408.

[32] C. A. Abbott, K. E. Chatwin, P. Foden, A. Fletton, N. Rumble, S. Williamson, K. G. Harding, P. E.

Price, F. Crawford, A. J. Boulton, Innovative intelligent insole system reduces diabetic foot ulcer recurrence at plantar sites: a prospective, randomised, proof-of-concept study, The Lancet Digital Health 1 (2019) e308–e318.

[33] P. Gupta, N. Gaur, R. Tripathi, M. Goyal, A. Mundra, Iot and cloud based healthcare solution for diabetic foot ulcer, in: 2020 Sixth International Conference on Parallel, Distributed and Grid Computing (PDGC), 2020, pp. 197–201. doi:10.1109/PDGC50313.2020.9315824.

[34] A. B. Bin Ghazali, C. Yi Ming, M. T. Abu Seman, Design of smart device for foot of diabetic patient in malaysia, in: 2021 International Congress of Advanced Technology and Engineering (ICOTEN), 2021, pp. 1–6. doi:10.1109/ICOTEN52080.2021.9493450.

[35] L. Lucangeli, E. D'Angelantonio, V. Camomilla, A. Pallotti, Sistine: Sensorized socks for telemonitoring of vascular disease patients, in: 2021 IEEE International Workshop on Metrology for Industry 4.0 & IoT (MetroInd4. 0&IoT), IEEE, 2021, pp. 192–197.

[36] J.-K. Lin, Donna Shu-Han e Lee, Mobile health-based thermometer for monitoring wound healing after endovascular therapy in patients with chronic foot ulcer: Prospective cohort study, JMIR mHealth e uHealth 9 (2021) e26468.

[37] K. Moulaei, M. Malek, A. Sheikhtaheri, A smart wearable device for monitoring and self-management of diabetic foot: A proof of concept study, International Journal of Medical Informatics 146 (2021) 104343.

[38] E. D'Angelantonio, L. Lucangeli, V. Camomilla, A. Pallotti, Smart sock-based machine learning models development for phlebopathic patient screening, in: 2022 IEEE International Workshop on Metrology for Industry 4.0 & IoT (MetroInd4. 0&IoT), IEEE, 2022, pp. 137–142.

[39] V. Vijean, S. A. Mohammed, R. Ahmad, W. A. A. W. Ahmad, R. Santiagoo, A. G. Ahmad, R. Palaniappan, Early detection of diabetic foot ulcers through wearable shoe design, in: 2022 4th International Conference on Artificial Intelligence and Speech Technology (AIST), IEEE, 2022, pp. 1–5.

[40] C. Park, R. Mishra, D. Vigano, M. Macagno, S. Rossotti, K. D'Huyvetter, J. Garcia, D. G. Armstrong, B. Najafi, Smart offloading boot system for remote patient monitoring: toward adherence reinforcement and proper physical activity prescription for diabetic foot ulcer patients, Journal of Diabetes Science and Technology 17 (2023) 42–51.

[41] B. Purwono, L. Asmat, Implementation of lora wireless communication in smart diabetic shoes design, International Journal of Robotics and Control Systems 3 (2023) 899–910. doi:10.31763/ijrcs.v3i4.1152.

[42] P. Purwono, A. Burhan, S. K. Wibisono, I. S. Mangkunegara, P. Dewi, A. Ma'Arif, I. Suwarno, et al., Prototype design of smart diabetic shoes with lora module communication, in: 2023 International Conference on Computer Science, Information Technology and Engineering (ICCoSITE), IEEE, 2023, pp. 863–868.

[43] K. B. Sai, R. Raghu, S. S. V. Nukala, J. Jayaraman, V. Jayaraman, Home-based detection and prediction of diabetic foot ulcers at early stage using sensor technology and supervised learning, Journal of Harbin Institute of Technology (New Series) (2024) 26 – 37. URL: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85187699094&doi=10.11916%2fj.issn.1005-9113.2023019&partnerID=40&md5=ecb93587356403d2e45c7e820fd98da3. doi:10.11916/j.issn.1005-9113.2023019, cited by: 0.

[44] R. F. Ghazi, J. S. Chiad, F. M. Abdulghani, Design and manufacturing a smart shoe for diabetic foot ulcer monitoring and prediction system using internet-of-things technology, Journal of the Brazilian Society of Mechanical Sciences and Engineering 46 (2024) 1–13.

[45] M. I. Nordin, M. K. Ishak, A. Sattar, M. T. A. S. Din, Intelligent pressure and temperature sensor algorithm for diabetic patient monitoring: An iot approach, Indian Journal of Engineering 21 (2024) e2ije1676.