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A Technical Review of Foot Temperature Measurement Systems

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People suffering from diabetes are at risk of developing foot ulcerations, which, if left untreated, could also lead to amputation. Monitoring of the foot temperature can help in the prevention of these foot complications, and various studies have shown that elevated temperatures may be indicative of ulceration. Over the years there have been various devices that were designed for foot temperature monitoring, both for clinical and home use. The technologies used vary from infrared (IR) thermometry, liquid crystal thermography (LCT), IR thermography and a vast range of analogue and digital temperature sensors that were incorporated in different measurement platforms. All these systems are able to collect thermal data from the foot, some being able to acquire data only when the foot is stationary

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and others being able to acquire from the foot in motion, which can give a more in-depth insight to any emerging problems. The aim of this review is to evaluate the available literature related to the technologies used in these systems, outlining the benefits of each and what further developments may be required to make the foot temperature analysis more effective.

Elevated skin temperature has been associated with pressure ulcer development in several studies [1, 2, 3, 4]. Any condition that increases skin temperature is suggested to increase the susceptibility to tissue breakdown [5]. Monitoring of the skin foot temperature has been shown to be an effective approach in determining the health status of the foot [6]. In recent years, this has triggered interest among various researchers to investigate different ways on how best to measure skin foot temperature in a non-invasive approach while the foot is static as well as when in motion, using various micro-sensors and wireless sensors. Various skin temperature monitoring systems that have been suggested, are used by researchers themselves solely as research tools [7, 8, 9], whereas others have been made commercially available as clinical tools and consumer products [10, 11, 12]. The aim of this review is to analyse these systems, highlighting their strengths and shortcomings while identifying any gaps in the present technology. An in-depth assessment of the design and technology used in foot temperature monitoring systems is conducted, with a particular

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interest in the engineering aspect of the devices. While some other reviews have been carried out, these have either been limited to very specific geographical regions [13], or focused primarily on the clinical relevance of the systems and only provided a general overview of the technical characteristics of the system [14, 15]. The desirable characteristics of ideal foot temperature measurement systems are also discussed.

Review Methodology

For this review, a search was conducted for articles published up to 2020 in the following four databases: Google Scholar, PubMed, Science Direct and Scopus, using the following keywords: "in-shoe temperature measurement" and "foot temperature measurement" with the addition of other terms including: "diabetic", "system", "portable" and "wearable". All the retrieved articles were reviewed and literature that focused on foot temperature monitoring systems was considered further and included in this review. Out of the 22 papers identified through the initial search, two articles were omitted because the investigation did not focus on monitoring the health status of the foot or because the technology used could not be utilised for monitoring the temperature of the foot. For example in [16], a foot model was reproduced with 3D-printed bones and sensors placed in between the bones; a method which cannot be used with living subjects. From the

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remaining 20 papers, a total of 15 unique systems were identified and reviewed in this article.

Foot Temperature Measurement Methods

Over the years, a range of foot temperature recording modalities have been investigated. In this review these will be broadly categorised as static or dynamic measurement modalities. Static systems are those systems where temperature data can only be recorded at a single point in time while the foot is stationary. These include systems such as single-spot infrared (IR) thermometry and liquid crystal thermography (LCT). On the other hand, dynamic systems enable continuous temperature recording while the foot is in motion, and these are generally composed of temperature sensors embedded in socks, insoles or shoes. Even though IR cameras can be used to record continuous video data, the technology cannot be used while the subject is in motion. For this reason, thermal imagery has been categorised as a static modality for the purpose of this review.

Static Measurement Systems

A static measurement system can vary from a single point measurement modality such as an IR thermometer to one producing a dense temperature map of the surface being analysed as in the case of LCT plates. In the following subsections, the principles of operation and salient characteristics for the different systems are presented. A list

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summarising the main characteristics of the different static measurement systems is presented in Table 1.

Infrared Thermometry

Radiation is one of the means of transfer of heat energy, and any object with a temperature greater than 5 degrees Kelvin will emit some degree of infrared radiation [17]. In an IR thermometer a lens is used to focus the radiated IR waves from a specific area onto a detector. This detector, also known as a thermopile, converts this heat energy into electricity, which can then be measured and translated into a quantifiable unit of heat [18], as illustrated in Figure 1. One such device is the Xilas Medical (San Antonio, Texas, USA) TempTouch® Dermal Thermometer. It has been used in various studies [10, 19] to determine its effectiveness in detecting possible diabetic foot ulceration (DFU) when used as a home-monitoring tool. The TempTouch® houses an IR sensor to measure the temperature of the skin, displaying the reading on a single-line monochrome liquid crystal display (LCD) screen. Thermal cameras can be used to capture images based on the IR emission of objects. Similar to IR thermometers, thermal imagers focus the IR energy onto a detector that creates a complete thermal image rather than acquiring a single temperature point.

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Such a system provides patients with an affordable means of analysing the temperature of their feet in the comfort of their own home. However, a prominent limitation of this IR thermometer is the fact that readings can only be taken one at a time, with several separate readings required to get temperature data from different parts of the sole of the foot. Furthermore, with the system being static, it is not possible to monitor the temperature variation in continuous-time.

Liquid Crystal Thermography

A different kind of technology that does not require separate multiple readings to get a full thermal snapshot of the foot is liquid crystal thermography (LCT). Systems using this thermographic technology are generally composed of plates filled with thermochromic liquid crystals. This material changes colour in response to temperature, producing components of red, green and blue to represent the current temperature of the crystals. In the case of LCT foot monitoring systems, users are instructed to place their feet on the plates for one minute to give the thermochromic crystals time to reach the same temperatures of the feet's plantar surface. A thermal image is obtained on the plates, which would fade away in a few minutes once the liquid crystals start to acclimatize to the surrounding temperatures. Two variants of these systems are the Spectrasole Pro 1000 (Linköping, Sweden) and the Tempstat™ (Visual Footcare Technologies, LLC, South Salem, New York). The Spectrasole Pro 1000 [20] system is

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made up of two separate liquid crystal plates, whereas the Tempstat™ [21] has both plates incorporated in a single unit similar to a bathroom scales, with a convex mirror in between to assist the user in visually assessing the plantar aspect of the foot. A limitation of these systems is that they do not provide absolute temperature measurements that can be stored digitally, but only a thermal image that fades in a few minutes.

Since temperature evaluation is based on subjective colour interpretation by the user or clinician, there is a possible margin of error based on various factors ranging from the perception of colours from one person to another, as well as ambient light conditions. Although in studies evaluating the LCT technology [20, 21] it was demonstrated that temperature hot spots and ulcerations were correctly highlighted by both systems, it was not possible to get accurate temperature readings from the thermographic images. Therefore, an IR thermometer was still required to measure hot spots that could have possibly required attention after utilizing the LCT systems.

Temperature Sensor Array Systems

With the aim of having precise digital readings while still using the concept of sensory weighing scales similar to the Tempstat™, there have been various electronic foot temperature measuring devices developed in this form factor. These systems have arrays of sensors mounted below a plane onto which users can place their feet and get feedback on the thermal properties of the sole of the feet. Both Koven Technology (Canada) and

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Manichand Healthcare (Taiwan) have designed smart weighing scales able to acquire temperature readings from the plantar aspect of the foot [11]. The Koven SMART foot device incorporated two stainless steel sheets with 63 thermistor sensors on each sheet. The analogue sensor readings are converted using a 24-bit analog-to-digital convertor (ADC) and sent to the microcontroller for processing; checking for any temperature differences between contralateral spots on the foot and highlighting these hot spots on the device LCD. It was determined that the performance of the system is highly sensitive to foot placement. Specifically, the lack of contact between the skin surface and the sensor can lead to the false detection of hot-spots. In cases of foot deformities, where there is a considerable change in foot morphology, this issue is of greater concern because there may be a larger region of the skin surface which is not in contact with the sensors. Furthermore, since the plantar distribution is more likely to differ between the two feet, proper identification of hot spots using the system can be even more challenging.

The issue of sensor distribution is avoided altogether in the Remote Temperature Monitoring System Podimetrics Mat (Podimetrics, Inc., Somerville, MA) shown in Figure 2(a). This system was utilised in a clinical trial using patients with a history of DFUs [22]. The system aims to highlight any asymmetry in the temperature distribution along the soles of both feet by making use of an array of 2,000 thermistor sensors. Unlike the previous system, where the sensor quantity and distribution constrains foot placement and

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size, the Podimetrics Mat is able to analyse temperatures throughout the device's area (approximately 30 cm by 43 cm). Besides the distribution of the sensors, a further improvement is the material used below the sensors; a soft foam which ensures good contact between the foot soles and the sensors, avoiding non-contact issues as previously mentioned for other systems. Readings are initiated by stepping onto the device and standing stationary for approximately 20 seconds, after which the temperature data is wirelessly sent to the manufacturers' database for analysis. The data is then accessible by the healthcare professional, and any required intervention is communicated to the patient. Throughout the study, it was found that 97% of non-traumatic DFUs were properly detected round about 5 weeks before any visual signs were presented to the patient or clinician [22], based on a 2.2°C threshold used in previous studies [19, 23].

The systems reviewed in this section are all intended to provide patients with a tool to monitor temperatures along the sole of the foot in a reliable manner, without the need of frequent visits to a clinic to acquire such reliable measurements. When considering the digital systems, there was a constant increase in the number of sensors used, with the Podimetrics Mat being the most high-resolution system with the added benefit of communicating the results to the clinician instantly. The high- resolution temperature maps presented in the study using the Podimetrics Mat are replicated in Figure 2(b).

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Infrared Thermography

Thermography is widely used in various medical applications, ranging from: fever screening, thermoregulation analysis, breast cancer screening and diagnosis of vascular disorders in the diabetic foot [24]. Similar to the IR thermometer, thermal cameras also work on the principle of detecting the thermal radiation emitted by an object, using a lens to focus the IR energy onto a detector. The major improvement from IR thermometers is that the detector in the IR camera does not have a single sensing point, but contains a dense grid of sensory pixels that convert the heat energy into an electronic thermal image [25]. These devices have been reported to be able to collect reliable thermal data in medical applications, given that the standard procedures for thermal imaging are adhered to [26]. There have been various studies using thermal imagery to investigate the relation between plantar foot temperature and the diabetic foot [27, 28, 29].

There are various benefits in using a non-contact method of temperature measurement in such studies, since it doesn't pose any risk to the patient, no matter the state of health of their feet, and the equipment does not require decontamination between patients. Unfortunately, even though thermal cameras are becoming more common and their cost is going down, they are still quite expensive when compared to other technologies. Additionally, the lack of ease of operation of an IR camera makes it less suitable to be used by the patients as a home monitoring device for day-to-day checks.

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The devices reviewed up to now are limited to analysing the barefoot skin temperature at rest, and no information can be collected during ambulation which would be vital when trying to localise areas along the sole of the foot prone to tissue damage. With the aim of being able to collect data during ambulation, various studies in the literature have developed and evaluated the use of in-shoe temperature monitoring systems. These devices range from single sensors placed in contact with the skin to sensory insoles analysing the temperature at various points along the sole of the foot.

Dynamic Measurement Systems

Dynamic measurement systems can be categorised into three main groups, namely:

1. Direct contact sensor systems, where the individual temperature sensors are placed in direct contact with the skin of the foot;
2. Sensory insoles, where a number of sensors are typically integrated in a semi-rigid material worn in the shoe as an insole;
3. Sensory socks, where temperature sensors are integrated in the fabric of a sock.

Direct contact systems were mostly developed and utilised within controlled laboratory conditions for research purposes. On the other hand, due to their convenience of use, a

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number of sensory insole and sensory sock systems are already commercially available for home use. The technical specifications of the systems described in this section are summarised and listed in Table 2, including the types of microcontrollers used, and information about the sensor type and precision are outlined.

Direct Contact Sensor Systems

Two advantages of placing sensors in direct contact with the skin include the precise sensor placement at the area of interest and the continuous contact between the sensors and the skin, even during ambulation. In Kang et al. [30], a thermocouple-based temperature logger set up with a T-type thermocouple was used. The thermocouple was placed on either the dorsal area of the foot or in between the big and second toe. Additionally, the temperature logger also has an internal temperature sensor that was used to monitor the ambient temperature, in order to better understand the effect of the surrounding ambient conditions on the temperature within the shoe. The system was used to obtain one temperature reading per minute, targeting recording periods of between 24 and 36 hours; well within the memory capabilities of the system. During the study, some technical issues with the system were reported, with the main issue being breakages of thermocouples due to excessive torsion and pressure when placed within the shoe.

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Wiring is a very important aspect to consider when designing such in-shoe systems. Wires need to be as thin as possible so as not to cause irritation or damage to the skin, but at the same time they must be robust enough to withstand the tough conditions of the environment within the shoe. With the aim of avoiding the use of any wiring within the shoe, more compact single sensors solutions were proposed [31] [32]. Specifically, the internal temperature sensors of a microcontroller chip were used, enabling the entire system to be packaged within the size of a button and placing it within the shoe. In a collaborative study between Digilog Inc. (Perg, Austria) and the Centre of Biomedical Technology at Danube University (Krems, Austria) [31], an ultra-low power microcontroller encapsulated in an epoxy resin was used and placed on the talus bone. Being a single sensor system, the amount of data that could be captured is limited, and the chosen sensor placement can only provide temperature data from that particular location of the foot, meaning that concurrent temperature data from other areas of interest is unavailable. The placement of the sensor close to the shoe collar also meant that the recorded temperature values are more likely to be affected by ambient temperature. Since no ambient data is collected with this system, there may be situations where it is difficult to deduce if variations in temperature are a cause for concern or simply a fluctuation in the ambient temperature.

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In the other study involving a single-sensor system [32], these issues were avoided by placing the sensor within the shoe, on the web space between the big toe and the second digit, and by using a secondary sensor to monitor ambient conditions. The iButton from Maxim Integrated Inc. (California, USA) used by Rutkove et al. [32] consists of a readily encapsulated microcontroller chip that uses an internal sensor to measure the temperature of the surface it is in contact with. The temperature of the surroundings, was being monitored by an ambient probe placed on a keyring attached to the user's clothing. The system was set to take readings every 2 minutes, with a target recording time of 48 hours per subject. In addition to temperature probes, this study used an activity monitor (Actiwatch 16, Mini Mitter Company Inc., Oregon, USA) attached to the user's ankle, whereby using an accelerometer, the type and degree of physical activity (i.e. sitting, walking, running, or sleeping) could also be recorded. The inclusion of such measurements is key in order to be able to understand better the temperature trends recorded from such devices. Variation in temperature trends are expected to be different when walking and running, and not being aware of a change in activity could lead to an incorrect diagnosis. However, monitoring a single temperature point on the foot can be very limiting, and the only way around the issue is to increase the number of sensors used.

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Various studies have considered systems with multiple temperature sensors placed at specific anatomical landmark points along the sole of the foot, typically including the big toe, the metatarsal heads (MTHs), the medial longitudinal arch and the heel. In a study by Mizzi [33], two areas in the foot were investigated; the medial longitudinal arch (navicular bone) and on the dorsal aspect between the hallux and second toe. Focusing solely on temperature and relative humidity (RH), Mizzi [33] used a combination of sensors to monitor the micro-climate within the shoe during ambulation. Two sets of sensors (temperature sensor and RH sensor) were used, taped directly to the foot to minimize movement when placed on the skin as shown in Figure 3.

A number of other multi-sensor systems have also been reported in the literature. A study by Shimazaki and Murata [34] using a multi-sensor system investigated various parameters including skin foot temperature (plantar and dorsal) using J-type thermocouples, plantar pressure and motion. Moreover, ambient temperature, metabolic rate and body weight were also recorded, in order to establish a relationship between the pressures exerted at various walking speeds and foot temperatures. Coates et al. [9] reported a similar multi-sensory system, designed to record temperature, humidity, pressure, rate of acceleration and rotation, galvanic skin response, and skin inflammation by means of a bioimpedance sensor. Having multiple types of sensors in a single system

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provides a wide range of data from the foot, but when considering its capacity to analyse foot temperature, it is somewhat limited to three temperature sensors. The negative temperature coefficient (NTC) flexible thermistors were placed at the same positions as the pressure sensors; at the big toe, the first MTH and the calcaneus. The data was sampled by an Arduino Nano microprocessor and transmitted to the Raspberry Pi microcontroller via Bluetooth for processing.

Sensory Insoles

The alternative to having the sensors directly attached to the foot is to have a complete sensory surface placed under the foot. Morley et al.'s study [35] was one of the first to adapt sensory insoles to temperature analysis. Their system, illustrated in Figure 4(a), consisted of an insole with four combined temperature and pressure sensors as well as a humidity sensor. Other similar systems have been designed, including that by Reddy et al. [9], where four temperature sensors were embedded into a 5 mm hard foam insole. The micro-controller used in this setup had a built-in accelerometer which was useful for collecting information on the type of activity being carried out by the user during temperature recording.

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Ideally, the sensory insoles should have sensors as close as possible to the skin's surface in order to ensure that the recorded temperature fluctuations are due to elevations in skin temperature and not the surrounding environment. However, at the same time the sensors and any associated wiring should not be of discomfort to the user. In an evaluation study of the sensory insole system developed by Reddy et al. [7], it was determined that the encapsulation of the sensors between the two layers of plastazote forming the insole could lead to deviations in the foot temperatures measured with respect to the actual skin temperature values.

Furthermore, insufficient contact between the foot and the sensor areas on the insole, as well as the horizontal and vertical movements of the foot in the shoe, also led to inconsistencies in the collected temperature readings.

Such issues were reported by Sandoval-Palomares et al. in [8], where a similar insole system was used to monitor the micro-climate within the shoe. In this case, foot movement was causing a cooling effect on the temperature transducers embedded in the insole, increasing the ventilation and leading to temperature dips.

The above issues highlight how inconsistent contact of the foot with the insoles can limit the suitability of sensory insoles for the purpose of continuous and reliable foot temperature sensing. The use of direct contact sensors attached to the foot or the

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integration of sensors in a sock can help overcome this limitation by providing better contact and placement of the sensors with the foot even during ambulation.

Sensory Socks

One such smart sock prototype is that designed and developed by Novinoor LLC [38], called SmartSox. It is embedded with fibre Bragg gratings (FBG) sensors, which consist of single core fibres that are laterally exposed to intense ultra violet light patterns in order to alter the refractive index (grating) of parts of the fibre core [39]. With this process, the fibre core reflects light at a particular wavelength defined by the period of the gratings, but dependent also on the strain and temperature of the core. The response to changes in strain and temperature makes the FBGs useful as sensors to be able to measure these parameters, as well as calculate plantar pressure readings.

In this system, each FBG sensor was connected to an optical filter and IR detector, with a micro-controller processing the raw data and storing the angular strain and temperature fluctuations of the foot. Testing of the system was done in various stages; starting out with in vitro testing of the system characteristics, then in vivo testing on subjects with Type 2 diabetes with a high risk of DFU, and finally testing on a more generic population of diabetic subjects with a range of foot deformities.

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One significant limitation of the setup is that the fibre optic cables were too fragile and easily damaged when pulled, stepped upon, or twisted during walking. Eventually, the prototype was improved, incorporating a thread latch lock for a more robust connection to the sock and eventually omitting the need for a cable altogether by having the system transfer data wirelessly to a computer. Alterations were also required for the actual sock design, as the fibres were getting damaged with excessive weight and uneven distribution of weight along the plantar surface for subjects with severe foot deformities. The addition of a thin layer of soft padding on the bottom side of the sock helped to preserve the integrity of the fibre cores while at the same time increasing the comfort of the socks themselves. This improved prototype was then used for testing under less controlled conditions.

The Siren Diabetic Socks [40] (Siren Care Inc, San Francisco, CA) is another sensory sock system with six temperature sensors. Micro-sensors are woven directly into the fabric of these socks and connected to a small processing unit integrated in the sock located above the ankle (Figure 5). The unit consisted of a microcontroller and Bluetooth communication chip, along with the battery powering the sock. Temperature readings from the sensors are taken at 10-second intervals, with the data stored in the processing unit and sent to a smart-phone paired with each pair of socks. The software application offered with the system has the option to set up alerts to detect potential ulcerations. A pilot study

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involving 35 diabetic patients was conducted to assess the comfort of the socks as well as the integrity of the collected data [12]. Separate testing on the sensors was also conducted, showing that the socks could yield precise temperature readings within a 10 second window. The temperature sensors were shown to provide temperature readings with a precision of 0.01°C and users reported no noticeable differences in terms of comfort with respect to ordinary socks. Additionally, even though the socks are washable, they need to be replaced every six months due to possible wear to the fabric that could compromise the fit of the sock [40]. In this way, the user never needs to replace the batteries since the button cell batteries that are fitted with the processor tag should last the whole 6-month period [41].

Discussion

Skin temperature monitoring can help detect variations in temperature associated with peripheral arterial disease and dermal inflammatory changes, thereby helping reduce the risk of foot complications in people living with diabetes mellitus [41]. While several tools have been developed to measure plantar foot temperatures using static single measurements, such as the TempTouch® Dermal Thermometer [10], which is an IR-thermometer for self-inspection of the feet, others developed wearable systems that are able to continuously monitor skin foot temperature, such as the SmartSox [37]. Such

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systems gave the possibility for continuous dynamic temperature monitoring, aimed at acquiring information in relation to the health status of the foot from within the shoe even when the user is in motion. As shown in Table 3, the number of temperature sensors used varies across the range of wearable systems reviewed, but never exceeds eight sensors. The benefits of acquiring a denser representation of temperature data from the foot has been investigated in diabetes-related foot complications with the use of thermal cameras [41]. The dense temperature data thermal cameras can provide, can allow clinicians to obtain a clearer picture of peripheral circulatory perfusion or other pathological vascular changes their patients might experience over time. These changes, especially at an early stage, are unlikely to be detectable with systems having a single or just a few sensors. Setups with a limited number of sensors are generally used for a simple comparative analysis of skin temperature changes with respect to the corresponding contralateral site of the foot.

Although, dense temperature images obtained by thermography have the potential to detect early stage peripheral arterial disease through the use of lower limb temperature measurement [24], this technology is restricted to static foot temperature measurements outside the shoe. On the other end of the spectrum, in-shoe measurement temperature systems can provide in-shoe temperature readings but lack the density of thermal images and are limited to a few locations on the foot. This limits the information that can be

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obtained in relation to temperature dynamics and variations across the entire foot during ambulation, that would be useful for detecting relevant changes in spatial patterns in diabetic patients [42]. Therefore, in-shoe temperature measurement systems with a dense array of temperature sensors can combine the benefits of both approaches, providing a better representation of in-shoe foot temperature dynamics during ambulation and everyday activities. Dynamic in-shoe temperature monitoring would provide timely detection of areas in the foot which are at risk of tissue breakdown, and this can, in turn, lead to improved preventive and treatment plans. Specifically, dense in-shoe temperature maps from the foot during normal daily activities and over extended periods can, for instance, allow for the detection of foot regions prone to ulceration, and the assessment of the suitability of footwear and footwear material in individuals living with diabetes. The use of a dense temperature array can also facilitate issues related to sensor placement and/or re-configurability for different foot sizes and shapes, often reported as a major challenge with single-sensor systems. Systems with a large number of sensors go beyond the need to place sensors at standard landmark points along the sole of the foot, offering instead a temperature map that is sufficiently dense and that can be used to compensate for foot movement within the shoe.

This concept was clearly demonstrated with the Podimetrics Mat [22], where a large enough number of sensors was used to provide coverage over the entire area of the mat

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used for static measurements. The sensor coverage of this systems allows for the acquisition of dense temperature data from the plantar section of the foot irrespective of the specific foot placement. Clearly, when adapting such a concept to an in-shoe based system, restrictions linked to space and comfort limit the number of sensors and associated wiring that may be used. Furthermore, the larger the number of sensors used, the bigger is the accompanying circuitry required to process the signals from the sensors.

One other issue that emerged from a number of reviewed studies is the loss of contact between the sensors and the plantar aspect of the foot that can lead to inconsistencies in the recorded temperatures and which may lead to erroneous diagnosis if unnoticed. This was particularly the case in systems where the foot is placed on top of a plane of sensors, as in insole-based systems, where parts of the foot can move away from the sensors during ambulation. The best approach to avoid such situations is to have the sensors directly attached to the foot, such as the ones employed in the study by Mizzi et al. [32]. Although, such systems are ideal for research and clinical purposes, it is less feasible to be used for at-home-monitoring. The alternative is to have the sensors embedded in a sock, as in the case of the Smartsox [37] and Siren [12] systems. In this way, the sensors are kept in close proximity to the skin, with a system that is easy to put on, making it more user friendly and ideal for home use by the patients. With such a thin and flexible platform for the sensors, the choice of cable and sensors is even more critical and various factors need to be taken

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into consideration; the most important being the preservation of the health of the foot. As vital as it is to build a robust system to be able to monitor the foot's temperature reliably, the sensors and wiring must be as thin and discreet as possible. This helps to avoid any irritation or damage to the foot's skin due to high pressure points originating from the cables and/or sensors. This issue was also highlighted by Martin-Vaquero et al. [13], where the authors had to reduce the number of sensors originally planned in order to strike a balance between an ideal design and what is actually feasible for actual implementation of such a design.

Conclusions

This review paper presented systems reported in the literature that have been utilized to monitor foot temperatures, including details on the technological and usability needs for these static and dynamic measurement systems. Static measurement systems were found to be commonly used to identify areas of increased skin temperature in the foot, associated with inflammation, or with neuropathic foot ulceration in people living with diabetes. On the other hand, in addition to this, dynamic systems are able to acquire continuous skin temperature during ambulation, thereby providing for enhanced patient monitoring, and also allowing for timely detection of areas in the foot at risk of tissue breakdown.

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While this paper presented a number of factors, crucial in designing an improved system for home monitoring of foot temperature, it also highlighted other aspects that need to be taken into consideration in order to make such systems easy to wear and carry around, without making the user feel uncomfortable or self-conscious when using such systems. These include the use of a lightweight and small processing unit, connected to the sensory platform, with minimal wiring. With all these characteristics, and the ease of use of accompanying software on mobile platforms, such systems should provide a means of continuous foot temperature monitoring for the people who need it, which in turn will help to reduce the occurrence of foot complication, including ulcerations in people living with diabetes.

Acknowledgements: This work forms part of the DRIFT (Dense Recording of In-shoe Foot Temperatures) project, financed by the Malta Council for Science & Technology through FUSION: The R&I Technology Development Programme 2018.

Financial Disclosure: None reported.

Conflict of Interest: None reported.

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System Name	Sensing Technology	Number of Sensors	Resolution	Precision	Dimensions
Temptouch	Thermopile IR Sensor	1	0.1°C	0.5°C	40.5cm
Spectrasole	LCT	n/a	n/a	n/a	⁻¹
Tempstat	LCT	n/a	n/a	n/a	⁻¹
Koven SMART Foot	Digital Sensor	126	⁻¹	⁻¹	⁻¹
Thermoscale	Digital Sensor	⁻¹	⁻¹	⁻¹	32cm x 35cm
Podimetrics Mat	Digital Sensor	2000	⁻¹	0.1°C	30cm x 40cm

¹ No information was provided in the literature, and no further information could be found.

Table 1: Static Temperature Measuring Systems - Technical Specifications

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Study	System Name/ μ -Controller	Battery Life	Temperature Sensors	Precision	Other Parameters
Shimazaki et al. (2015) [34]	⁻¹	⁻¹	J-type Thermocouple	$\pm 2.2^{\circ}\text{C}$	Pressure, inertial measurement unit (IMU)
Coates et al. (2016) [9]	Arduino Nano, Raspberry Pi	2.5 hours	Thermistor (ATC-Semitec)	1%	Humidity, Pressure, IMU, Bio-impedance
Mizzi (2016) [33]	PC	⁻¹	Thermistor (Biopac TSD202A)	0.2°C	Humidity
Morley et al. (2001) [35]	Motorola 68HC912V32, Atmel AT45DB161 16mb RAM	4.5 hours	Digital Sensors (Paramed 0255-205)	⁻¹	Humidity
Reddy et al. (2016) [7]	NI myRio	10 hours	Digital Sensors (Analog Devices TMP35)	2.0°C	⁻²
Sandoval-Palomares et al. (2016) [8]	PIC18F452, Atmel AT24C256 memory	8 hours	Digital Sensors (SHT 15)	$\pm 0.3^{\circ}\text{C}$	Humidity

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Naiafi (2016) [38]	⁻¹	⁻¹	FBG sensors	⁻¹	⁻²
Martin-Vaquero et al (2018) [13]	Arduino Mega2560	⁻¹	Thermistors (PT 100)	⁻¹	⁻²
Revzelman et al. (2018) [18]	⁻¹	6 months	⁻¹	0.01 ⁰ C	⁻²

¹No information was provided in the literature, and no further information could be found.

²No further parameters were measured by the system.

Table 2: Multi-Sensor In-shoe Temperature Measuring Systems - Technical Specifications

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System	Sensor Type	Sensors/Foot	Sensor Placement	Temp Range	Precision	Sampling Rate	Storage	Duration
Morley et al.(2001) [35]	RDT	2	Insole	-20°C to 80°C	- ¹	1 reading/min	270 readings [16Mb]	4.5 hours
Kang et al.(2003) [30]	Thermocouple	1	Direct	-200°C to 1190°C	±0.5°C	1 reading/min	16,383 readings	24-36 hours
Foltyn'ski et al. (2012) [31]	Digital Sensor	1	Direct	-40°C to 85°C	- ¹	1 reading/min ²	57,000 readings	2-3 years
Rutkove et al.(2007) [32]	Digital Sensor	1	Direct	15°C to 46°C	±1°C	1 reading/2 min	2048 readings [2Kb]	3.5 years
Shimazaki & Murata et al (2015) [34]	Thermocouple	8	Direct	-210°C to 1200°C	±2.2°C	1 reading/min	- ¹	50 minutes ⁴
Reddy et al.(2016) [7]	Digital Sensor	4	Insole	-40°C to 125°C	±2°C	100Hz	USB Storage [Unlimited]	10 hours
Sandoval-Palomares et al (2016) [8]	Digital Sensor	5	Insole	-40°C to 123.8°C	±0.3°C	1 reading/min	500 readings	8 hours
Coates et al.(2016) [9]	Thermistor	3	Direct	-50°C to 125°C	±0.4°C	20Hz	- ¹	2.5 hours
Mizzi (2016) [13]	Thermistor	2	Direct	max 60°C	±0.2°C	1kHz ⁵	PC Memory [Unlimited]	50 minutes ⁶

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Najafi et al.(2017) [38] (SmartSox)	FBG	6	Sock	0 to 60°C	⁻¹	500Hz	⁻¹	⁻¹
Reyzelman et al. (2018) [12] (Siren Diabetic Socks)	Digital Sensor	6	Sock	20°C to 40°C	±0.01 ⁰ C	⁻¹	⁻¹	6 months

¹ No information was provided in the literature, and no further information could be found.

² The frequency was reduced to 1 reading/5 mins for healthy participants.

³ Stated generic J- thermocouple specifications.

⁴ Stated length of recordings, no information was given on portability of system.

⁵ The data was down-sampled to 1reading/min.

⁶ Stated length of recordings, unit did not operate on batteries.

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Figure 1: The principle of operation of an IR thermometer.

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Figure 2: Remote Temperature Monitoring System Podimetrics Mat: (a) The sensory mat on which the user stands to get his/her foot temperatures measured; (b) Foot temperature maps extracted from the data collected by the system (images provided by Podimetrics, Inc.)

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Figure 3: RH and Temperature sensor locations on the foot for Mizzi's study (images provided by author of [33]).

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Figure 4: Insole based multi-sensor temperature monitoring systems: (a) processing unit and insole housing four sensors used in Morley et al.'s study (reproduced with permission from [36]); (b) system components used in Reddy et al.'s study and participant wearing the system (reproduced with permission from [37]); (c) subject wearing the measurement system during Sandoval-Palomares et al.'s study (reproduced with permission from [8]).

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Figure 5: Siren Diabetic Socks: (a) image of socks showing (circled) processing unit location; (b) image of the bottom of the sock showing sensor locations (reproduced with permission from [12]).