Towards Digital Twins Driven Breast Cancer Detection

Safa Meraghni[1,2], Khaled Benaggoune[1,3], Zeina Al Masry[1], Labib Sadek Terrissa[2], Christine Devalland[4], and Noureddine Zerhouni[1]

[1] FEMTO-ST institute,ENSMM, Besançon, France {safa.meraghni, khaled.benaggoune, zeina.almasry,noureddine.zerhouni}@femto-st.fr
[2] LINFI Laboratory, University of Biskra, Algeria
meraghni.safa@gmail.com, terrissalabib@gmail.com
[3] LAP, Batna 2 University, Batna, Algeria
k.benaggoune@univ-batna2.dz
[4] Service D'anatomie Et Cytologie Pathologiques, Hôpital Nord Franche-Comté, Trevenans, France christine.devalland@hnfc.fr

Abstract. Digital twins have transformed the industrial world by changing the development phase of a product or the use of equipment. With the digital twin, the object's evolution data allows us to anticipate and optimize its performance. Healthcare is in the midst of a digital transition towards personalized, predictive, preventive, and participatory medicine. The digital twin is one of the key tools of this change. In this work, DT is proposed for the diagnosis of breast cancer based on breast skin temperature. Research has focused on thermography as a non-invasive scanning solution for breast cancer diagnosis. However, body temperature is influenced by many factors, such as breast anatomy, physiological functions, blood pressure, etc. The proposed DT updates the bio-heat model's temperature using the data collected by temperature sensors and complementary data from smart devices. Consequently, the proposed DT is personalized using the collected data to reflect the person's behavior with whom it is connected.

Keywords: Digital Twin, breast cancer detection, thermography

1 Introduction

Breast cancer has become one of the most terrible experiences in women's health nowadays. It is the first cause of mortality and the most commonly diagnosed form of cancer among women [1]. Diagnosis is the first and principal step in the treatment of any disease, and so far for cancer. However, despite the amount of research provided to this growing disease, the survival rate is still dependent on detecting the tumor in the earlier stages. Screening is a strategy adopted to identify women at the initial stages of this breast disease. However, all kinds of tests, including mammography, recognized as the gold standard for cancer detection, have limitations. A patient has to undergo, many times, burdensome procedures associated with these techniques, such as radiation side-effects, long duration of the diagnostic procedure, high diagnosis cost [2]. Therefore, research is required to develop a simple and less expensive diagnostic procedure without any side effect. The present work concentrates on the possible application of one such procedure.

Due to the limits of mammography and with the aim of increasing the life expectancy of patients, thermography is used to detect early breast cancer [3].Because of changes in temperature have been identified by thermal imaging for a breast lesion. In addition, the advantages of thermography compared to mammography are a radiation-free technology and a better sensitivity to detect lesions in dense breasts [4].

Nevertheless, this new technique's application is in the early stages and faces many challenges, especially the generalization of the solution on different patients with heterogeneous anatomies. In medicine, the effectiveness of the medication is not always ensured for all cases. Personalized medicine is the principle of turning health care adapted to the patient-specific physiology; it consists of adapting treatments according to patients' characteristics and their diseases. It involves anticipating, through a diagnostic test on patients. Personalized medicine aims to better monitor each patient by collecting, measuring, and analyzing their health data to adapt their care cycle to their needs. This innovative approach is based on the digital revolution. The concept of digital twins (DTs) is at the origin of this principle. It originated in the engineering industry but has found a place in medicine.

The concept of digital twin (DT) was proposed in 2011 [5]. DTs act as a bridge between the physical and digital worlds by using sensors to collect real-time data on physical objects. Collected data is used to create a digital duplicate of the monitored object [6]. This digital duplicate, combined with other technologies such as cloud computing, artificial intelligence, and machine learning, will understand, analyze, manipulate data, and make decisions.

Currently, the digital twin is mainly used in product design and service management, manufacturing, product life forecasting, and real-time monitoring of industrial equipment. Based on the successful applications of DT in the industrial field, it is believed that DT can also play a significant role in the medical field [7]. DTs can accelerate the adoption of connected devices such as smart sensors, smartphones, and smartwatches in the smart healthcare ecosystem to improve data collection capacities and promote artificial intelligence applications for predictive healthcare. DTs help to gather these technologies to provide personalized, proactive, and preventive care in real-time.

This work, and to the authors knowledge, presents the first initiative in the field that overlaps DTs with thermal data for breast cancer detection. The Detection based on thermal data is not always accurate; therefore, this overlap is proposed to integrate different data sources from smart devices in the eco-healthcare system. The DT processes and analyzes patient data in real-time and provide an adapted decisions.

The main contributions of this paper are as follows:

- DT is proposed for early breast cancer detection, using collected data from smart devices
- Thermal data is combined with other information to provide an accurate detection.
- Personalized bio-heat model is integrated with digital twins.

The rest of this paper is organized as follows: Section 2 discusses the research background and some critical challenges. Section 3 provides the details of our proposed approach, its general architecture, and design. In section 4, the numerical simulation of the bioheat model is explained. Our results are then depicted in section 5, and we discuss and conclude in section 6.

2 Research background

In this section the research related to DT and breast cancer detection are discussed.

2.1 Digital twin in healthcare

In the hospital world, digital twins are increasingly being used, sometimes called "medical twins". The potential application areas of digital twins in the healthcare sector are numerous, from diagnosis to therapeutics. [8]. DT is increasingly being studied for preventive healthcare to raise awareness of people's health through bio-feedback functions and help them take the right actions using personalized recommendations. Angulo et al. [7] have proposed a DT to monitor the behavior of lung cancer in patients to personalize healthcare about the behavior of this disease on patients. Bagaria et al. [9] have proposed a DT for heart rate and galvanic response monitoring to prevent heart diseases. Based on data collected from different smart devices as accelerometer, GPS, and smartwatch, an AI model estimates the real twin's physical activity level and recommends different activities to ensure a healthy physical condition.

In health treatments, The digital twins can test new experimenting decisions in a simulated "real" environment to see how the treatment results [10]. DT enables simulation with real-world scenarios, which can reduce medical risks and costs and improve diagnosis, treatment, and disease prediction quality.

2.2 Breast detection using thermography

Over the last few decades, the need for effective and cheap diagnostic techniques to screen and diagnose breast cancer has led to the development of various new technologies. Accordingly, studies show that there is a link between breast skin temperature and breast cancer since cancerous tissue temperature is commonly higher than healthy encircling tissues [11]. Thus, thermography has been considered as a promising screening method for breast cancer detection by generating images that reveal the heat distribution on the skin surface[12]. The first attempt to use thermography for detecting breast cancer was by Lawson [13]. He observed an increase from 21°C to 31°C in the local temperature of the skin surface over the place where the tumor is located when compared to healthy breast tissue. In [14], the authors concluded that thermography shows to be a useful technique for breast cancer detection in young women with a higher breast density level.

In fact, numerous studies showed the effect of tumor state on the thermal image [15] [16]. In [17], the authors investigated the ability to estimate tumor sizes by analyzing the thermal images. In [18], an estimation methodology is performed to define the breast tumor parameters using the surface temperature profile that may be captured by infrared thermography (see Figure 1). In [19], the author estimates the size and position of a spherical tumor in a human breast utilizing the temperatures taken on the surface of the breast.

Thermography is non-invasive and painless without any exposure to dangerous ionizing radiation. This imaging technique shows to be a potential adjunction tool. Nevertheless, procedures need to be done in the hospital or thermography center by trained medical personnel, and it is still impractical to use it as a personal healthcare device.

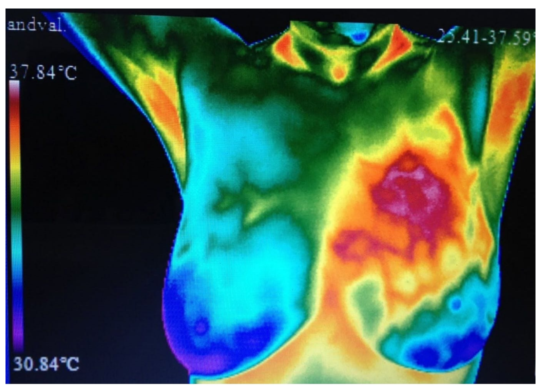

Fig. 1. Breast thermography using infrared camera [20]

2.3 Factors influencing skin temperature

The skin's properties and conditions can be influenced by numerous factors such as the location, skin type, ethnicity, gender, or even lifestyle and body mass index. The blood flow of the skin is highly vital for thermal balance represented by skin temperature. However, this blood flow can be influenced by various parameters, from humans to another.

Female hormones such as estradiol and progesterone have essential effects on regulating body temperature and blood pressure [21]. Estradiol generally favors vasodilatation, heat dissipation, and lower body temperature. In contrast, progesterone promotes less vasodilatation, heat retention, and raising body temperature. During the mid-luteal phase of the menstrual cycle or with the exogenous hormones of oral contraceptives when estradiol and progesterone are simultaneously high, the temperature threshold for sweating and skin cutaneous vasodilation is changed to more elevated temperatures [21]. Besides, changes in thermoregulation during the menstrual cycle and the hot flashes of menopause are influenced by hormones on the neural control of skin blood flow and sweating.

During pregnancy, blood pressure levels can decrease, increase, or remain the same from one woman to another. This depends on several parameters, such as sympathetic nerve activity, various combinations of blood volume interactions, vascular stiffness, and additional variables [22]

Thermoregulatory reactions to the rise and fall of body temperature are affected by healthy aging and various age-related diseases such as diabetes and hypertension [23]. Therefore, healthy aging will induce lower heat dissipation responses due to reflex neural, local vascular, and sweat gland mechanisms changes.

Abnormal body temperature is a natural indicator of disease. Thermal imaging cameras have been used to obtain correlations between thermal physiology and skin temperature to diagnose breast cancer, diabetic neuropathy, and peripheral vascular disorders. However, the human body's different physiologies make this diagnosis difficult to be universal due to the variation in the healthy temperature threshold from one human to another. Therefore, customized thermographic detection technology is required to adapt the detection threshold to each person. This solution is part of personalized medicine with continuous monitoring of the person using new information technologies.

2.4 Focus of the paper

Many works have proposed potential solutions for monitoring body temperature using sensors. These new solutions have opened up a new horizon for diagnostics using portable devices to monitor abnormal temperature changes. Also, intelligent devices used to monitor human performance, and health conditions can collect valuable information from individual patients. This paper proposes a DT for breast cancer using temperature sensor information collected by portable intelligent devices. The DT is first based on a simulated heat transfer model in the human body, based on the anatomy and thermal characteristics of different human breast tissues. Once the DT is connected to its physical user, data will be collected from all temperature sensors to detect abnormalities. As breast anatomy and the tissues' thermal characteristics may vary from one woman to another, the proposed twins will be updated with the information collected by the temperature sensors and other intelligent devices for blood pressure, age, diseases, etc. The use of complementary data helps the model to adapt quickly to the patient properties and provide an accurate detection.

3 Proposed Methodology

This section describes our proposed methodology based on the interconnection between the human and its digital twin via several technologies and services. This connection ensures real-time monitoring and control. Our solution plays the role of middleware [24] layer to fill the gap between heterogeneous services and abstract the technical details inside the digital twin and its relevant functionalities. Figure 2 shows the layered architecture of our proposition which consists of four layers described as follow:

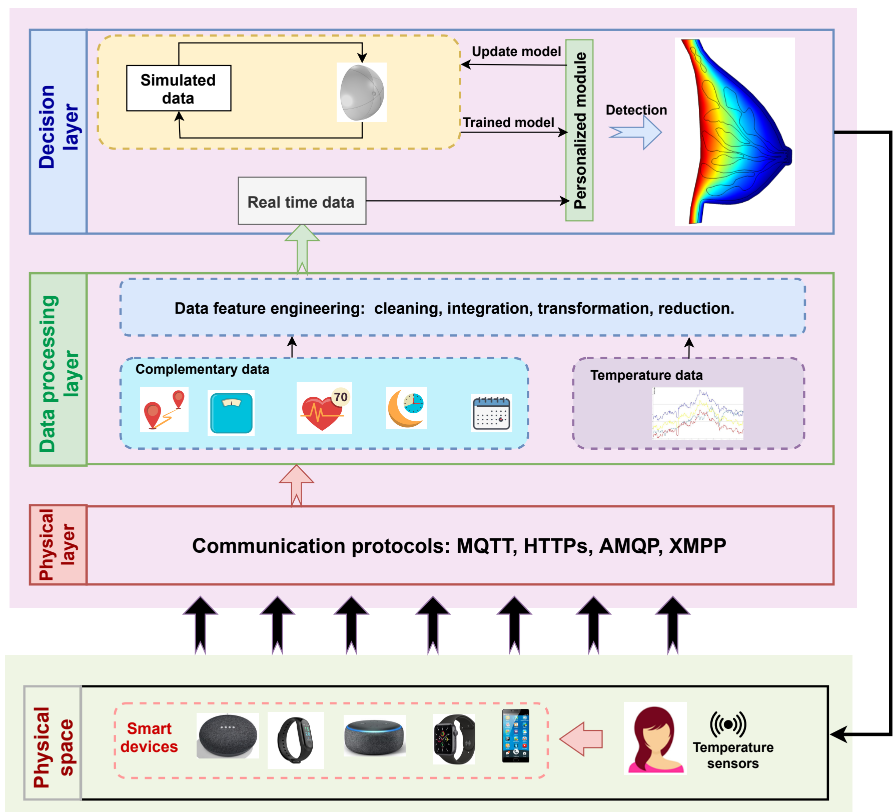

Fig. 2. DT for breast cancer detection: Physical space is connected with the virtual space to perform detection in real-time. The bio-heat model is used for tumor detection based on temperature data and other information such as blood pressure, external temperature, etc.

3.1 Physical space

The Internet of Things (IoT), a new Internet revolution, is rapidly gaining area as a priority multidisciplinary research theme in the healthcare sector. With the advent of multiple portable devices and smartphones, the various IoT-based devices are changing and evolving the typical old healthcare system towards a smarter, more personalized system. This is why the current health care system is also referred to as the Personalized Health Care System. Accordingly, technologies such as smartphones, smartwatches, and smart tissues, and others are used in the physical space to collect relevant data about the patient's health state.

3.2 Physical layer

In this layer, a set of interconnection functionalities must be provided to ensure data collection from various small devices connected to the human body. The communication technologies generally used in this type of application refer to the M2M stack [25], which allows the use of lightweight protocols and technologies with less influence on human health. Using the green M2M, a multitude of protocols are established in this work, such as HTTPs, HTTP, CoAP, AMQP, XMPP, MQTT, MQTT-sn, etc. We have also included other tools to support the interconnection of legacy or non-Internet devices (Zigbee, BLE, etc.) to our platform through gateways and proxies.

3.3 Data processing layer

For early detection of breast cancer, data is essential. Raw data collected from different connected devices are heterogeneous, and several actions are required to transform these data into usable information, ready to be used in algorithms and statistical analysis. Although the data is collected and sorted, there may be significant gaps or erroneous data. The cleaning phase eliminates duplicate, and irrelevant values, applies imputation methods and converts it to the acceptable format.

3.4 Decision layer

Once the data has been processed into a useful format, a trained model will use it to detect tumors in the breast. There are two phases in this decision-making layer: (i) the offline phase: the model is trained on simulated temperature data. More details on the offline phase are presented in section 4. (ii) the online phase: which uses the trained model and real-time data for tumor detection. A personalized module is proposed to match new data with historical data. Also, the predicted decisions made previously with the actual states from the physical space are linked to the model's update and converge to the actual and specific patient parameters.

4 Numerical simulations of dynamic thermography

Multiple mechanisms are involved in living tissue's heat transfer, such as metabolism, heat conduction, and heat convection by blood perfusion. The blood flow in the biological systems provides thermal stability and homogenous temperature distribution of the whole body. Hence, any change in the temperature distribution of the body can be intrinsically connected to an abnormality of the body process, which can be the first sign of tumoral tissue. Therefore, tumors are clumps of cells that multiply in an uncontrolled manner, and New blood vessels known as angiogenesis are formed to transport nutrients to these cells. Therefore, the blood perfusion rate and metabolic heat generation rate of the tumor are higher than healthy tissues. The increased heat generation at the tumor is diffused to the encircling tissue and can be seen as a temperature spike at the surface of the breast [26]. The first step in this work consists of simulating the bioheat of the heat transfer in healthy human breast and breast with abnormality using the Pennes bioheat equation, one of the most used transfer heat model in a biological tissue.

The Pennes bioheat equation Eq. (1) was proposed by Pennes in 1948 [27] to describes the effect of the metabolism and blood perfusion on the energy balance within the tissue. Therefore, the Bio-heat transfer processes in human tissues are affected by the rate of blood perfusion through the vascular network. The Pennes equation is easy to implement because it does not need information about the vasculature within tissues. What makes it widely used [19]. The dynamic bioheat transfer process presented by Pennes is described in Eq. (1) as follows:

$$\rho c \left(\frac{\partial T}{\partial t} \right) = (k \bigtriangledown T) + \rho_b \omega_b c_b \left(T_a - T \right) + q_m \tag{1}$$

where k, ρ, c, q_m correspond to thermal conductivity, density, specific heat of tissue and metabolic heat generation rate, respectively. ρ_b, c_b, ω_b stand for blood density, blood specific heat and he blood perfusion rate, respectively. T_a and T are respectively the arterial blood temperature and the tissue temperature. The values of these properties are listed in table 1.

A simplified breast model is studied to facilitate the heat transfer understanding in the breast. Therefore, the human breast is modeled as a 3D hemispherical domain with 6.5cm of radius (Figure 3), and the entire breast is assumed to be fat. A 1 cm diameter spherical tumor has been embedded in the breast model to study the effect of the presence of a tumour on heat distribution.

Table 1. *The properties of breast tissue* [28]

Tissue	Density (kg/m)	Specific Heat C(kg/m)	Perfusion rate C(kg/m)	Metabolic heat generation Q	Thermal conductivity C(kg/m)
Fat	930	2674	0.00008	400	0.21
Tumor	1050	3852	0.0063	5000	0.48

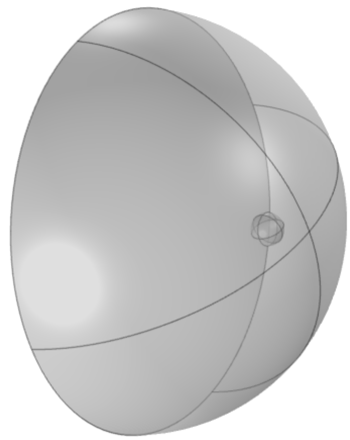

Fig. 3. Human breast model modeled as a 3D hemispherical domain, with a spherical tumour of 1cm of diameter

In order to enhance and maximize the thermal contrast between tumor and healthy tissue, a cooling thermo-stimulation is applied to the skin. Thus, many works supposed that the boundary condition on the breast skin surface is at 0°C or 10°C; however, this temperature can not be used in real cases. The 17°C is the minimum temperature that the skin can expose to. Therefore, in our study, we suppose the temperature of the air around the skin is 17°C. The bottom of the model is assumed to be at 37 °C, which is constant core body temperature.

5 Results and discussion

Figure 4 shows the impact of blood flow on temperature regulation. The breast temperature is 33Â°C and the outside temperature is 17Â°C. The blood perfusion rate (ω_b) has been modified to study the impact of blood perfusion on the perceived temperature on the skin. The higher the perfusion rate, the faster the temperature stabilization, and the lower the skin temperature.

The temperature difference between the three configurations is between 3Â°C and 8Â°C. This difference indicates that no-thermal factors can affect the skin's temperature as the blood. The heat propagation in the human body is influenced by many factors, not just its temperature and outside temperature. The anatomy of the human body nevertheless influences it.

The external temperature has been varied to study the impact of the place and season on a healthy breast's skin temperature. Figure5 shows the temperature of a healthy breast at different outdoor temperatures. The skin temperature has been adjusted differently according to the outdoor temperature for each studied body anatomy.

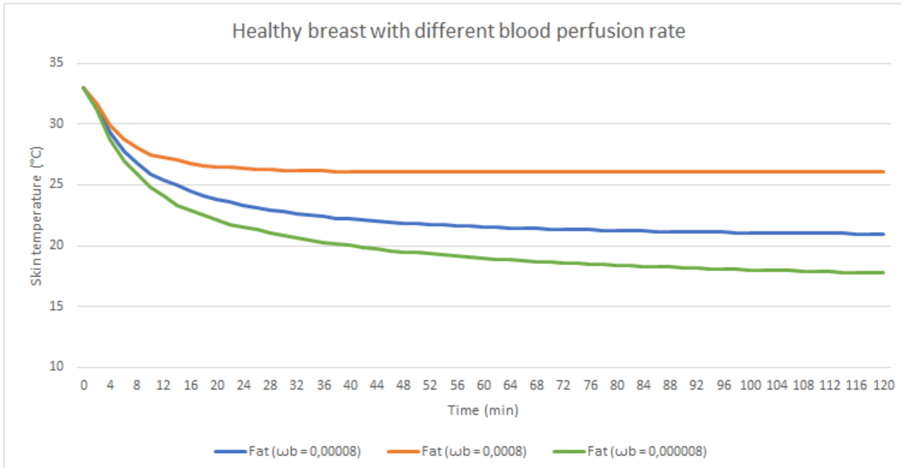

Fig. 4. Healthy breast with different blood perfusion rate

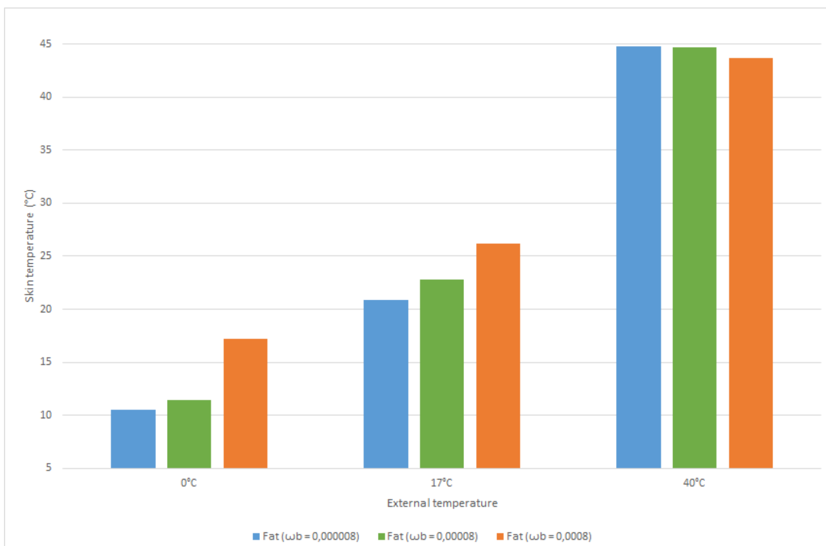

Fig. 5. Healthy breast in different external temperature. Results show the impact of external temperature on the generated temperature in the breast.

This study shows the importance of having complementary data about the location, the weather, and the time to update the temperature model correctly and accurately interpret the temperature difference results according to all the data collected from different smart devices.

The skin temperature distribution is symmetrical. Thus, for breast diagnostics by thermography, the temperature distribution of both breasts is compared

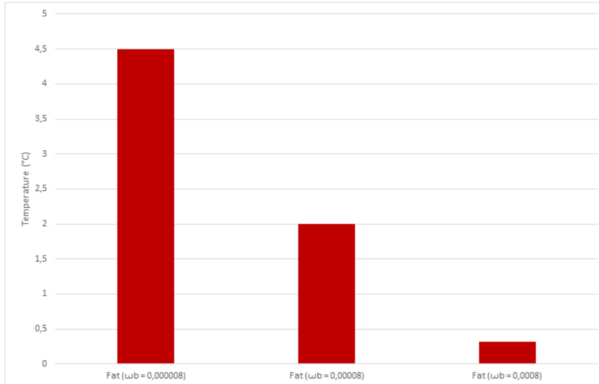

Fig. 6. Skin temperature difference between health breast and breast with tumor for three different levels of fat in the breast. Results show that the threshold value to detect tumor is relative to the human body's anatomy and environmental factors.

to confirm whether an abnormality has altered one breast's skin temperature. Therefore, a tumor is detected if the temperature difference is above a threshold. In this study, a tumor 1 cm in diameter is introduced into the breast. For each anatomy, the skin temperature is measured before and after tumor introduction. Then, the temperature difference is calculated to study the detection threshold.

Figure 6 shows a difference of 4.49Â°C, 1.99Â°C, and 0.31Â°C between healthy and tumor breast. These results confirm that the threshold is relative to the human body's anatomy and environmental factors; therefore, the threshold value cannot be generalized for tumor detection.

6 Conclusion

The proposed DT is intended to provide a personalized tool for diagnosing breast cancer using temperature data. The proposed DT is developed in an offline phase based on the bio-heat model. In the online phase, the DT is connected to the user, and then the behavior of the DT is updated based on temperature data. However, results show that the temperature data cannot be sufficient to conclude an abnormality. Many other factors can influence the body temperature as outdoor temperature, blood pressure, anatomy, and body mass index. To overcome these differences, the proposed DT is updated using the temperature data and the other data collected from the smart connected devices, allowing the DT to be accurate to mirror the body temperature behaviour.

DT is a significant advance in the medical field as it will allow the transition to personalized medicine. However, DT's development still faces some challenges, such as data heterogeneity, security and confidentiality, certification, and regulation. Future work will focus on the integration of the proposed DT, taking into account these challenges. Moreover, as the proposed method has been validated on simulated data, the next step will be to use the proposed DT with real data from patients.

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