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Review

Human-centered IoT-based health monitoring in the Healthcare 5.0 era: literature descriptive analysis and future research guidelines

Samad Rashid[1] · **Arash Nemati**[1]

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Abstract
Continuous monitoring of individuals' health, particularly those with chronic diseases, out of healthcare centers could result in lower patient traffic in healthcare centers, much more real-time health control, and faster emergency services. Hence, using the internet of things (IoTs) as an enabler of Industry 4.0 facilitating remote health monitoring has gained more attention in recent years. Although plenty of research has been focused on IoT-based health monitoring, they neglected emerging concepts like human-centered health data analytics as a significant requirement in the Healthcare 5.0 era. This paper contributes to the status of human-centered IoT-based health monitoring by conducting a descriptive analysis of the corresponding literature according to biometrics monitored, applied software, hardware, sensors, and communication models, highlighting the lack of consideration of long-term, human-centered health monitoring in the existing IoT-based health monitoring literature. Results showed that the focus of the literature has mostly been on information transit technology development and not human-centered data analytics. In addition, a gap analysis of the current literature recommendations emphasized multi-biometrics monitoring and cybersecurity, not human-centered health data analysis. Finally, several guidelines are provided for human-centered IoT-based health monitoring in future research.

Article Highlights

- Descriptive analysis of literature on IoT-based health monitoring.
- Highlighting the lack of attention to the human-centered IoT-based health monitoring.
- Proposing guidelines for human-centered IoT-based health monitoring.

Keywords Internet of medical things · Remote health monitoring · Healthcare 4.0 · Healthcare 5.0 · Human-centered health data analytics

✉ Arash Nemati, r.nemati@nit.ac.ir; Samad Rashid, samad_rashid@stu.nit.ac.ir | [1]Healthcare Systems Engineering, Department of Industrial Engineering, Faculty of Materials and Industrial Engineering, Babol Noshirvani University of Technology, Babol City Postal Code: 47148-71167, Mazandaran Province, Iran.

1 Introduction

Industry 4.0 (I4.0) is conventionally defined as using intelligent tools, including the internet of things (IoT), cloud computing, blockchain, big data analytics, autonomous robots, simulation, additive manufacturing, virtual reality/augmented reality, cybersecurity, and system integration [1–3]. The fourth industrial revolution was built on the capabilities of cyber-physical systems networks, connected sensors, and autonomous robots that enable equipment to function without human participation. Consequently, the healthcare system has benefited from the pillars of I4.0, Healthcare 4.0 (H4.0), to reach high intelligence in care services, such as remote patient monitoring, repetitive tasks automation, and robot applications in critical surgeries [4–9]. H4.0 utilizes lots, connected sensors, and autonomous robots to collect vast amounts of data, enabling remote patient monitoring, repetitive task automation, and minimally invasive surgeries [5, 6]. It is predicted that by 2030, nearly 50 billion IoT products and devices will be used worldwide, and the global market for IoT health monitoring devices is expected to reach $204.2 billion by 2027 [10–14]. Continuous monitoring of biometrics, such as heart rate, respiratory rate, temperature, and blood pressure, provides valuable help for the public, particularly for patients, elder people, and individuals with chronic diseases. However, this target seemed out of reach before the H4.o era because of limited care resources, huge demand, large amounts of collected data, wasting time, and cost restrictions. In the H4.0 era, continuous health monitoring for all people is reachable using intelligent technologies like the internet of medical things (IoMTs), big data analytics, cloud computing, and blockchain [15–32]. Although IoT-based health monitoring has received significant notice on the hardware and software development for data collection and transfer, less attention has been paid to collected big data analytics, particularly in terms of long-term health monitoring. On the other hand, human-centered design and analysis is a key newly added feature to H4.0, besides digitalization, resiliency, and sustainability, resulting in viable Healthcare 5.0 (H5.0) [9, 33–42]. However, the existing literature on IoT-based health monitoring literature never concentrates on human-centered data analysis, particularly in the long-term as well. Hence, the following questions remained unanswered in the context of human-centered IoT-based health monitoring.

- To what extent the human-centered health monitoring has been the target of IoT-based health monitoring literature,
- What has been the most popular concentration of IoT-based health monitoring literature,
- Which data analytics techniques could be considered for human-centered IoT-based health monitoring in the future?

This paper answers the above-mentioned questions by investigating the concentration of the literature on IoT-based health monitoring to highlight the research gap on human-centered IoT-based health monitoring in the H5.0 era. Hence, a literature descriptive analysis is proposed according to the noticed biometrics, and employed technologies in IoTs applied for health monitoring. In addition, a prescriptive analysis is proposed to recommend guidelines for human-centered data analytics in IoT-based health monitoring. In conclusion, the contributions of this paper are as follows:

- Conducting a descriptive analysis on the concentration of IoT-based health monitoring literature,
- Highlighting the gap in data analytics for human-centered IoT-based health monitoring,
- Proposing several guidelines for human-centered data analysis in IoT-based health monitoring.

The remaining sections of the paper are as follows. Section 2 proposes the background knowledge on IoMT used in health monitoring and the corresponding conventional health features noticed. Section 3 provides a literature descriptive analysis, and Sect. 4 presents the guidelines for future related works. Finally, the conclusions are provided in Sect. 5.

2 Background

This section reviews the basic concepts of IoT-based health monitoring, including remote health monitoring, IoMT, and health features.

2.1 Remote health monitoring

Health assessment in healthcare centers in several periods, such as week, month, or year, only provides a discrete pattern of health measures with no information during the time intervals between sequential health checking. Continuous health monitoring and the need to check patients' health from undeveloped remote areas urge using emerging technologies, such as cloud computing, IoT, and blockchain, to provide a remote health monitoring option without specific healthcare facilities and staff. Thanks to H4.0, intermittent hospital-centered health monitoring is transforming into real-time continuous home-centered care using IoMTs [27, 43, 44]. Health monitoring with the aim of IoT uses wireless sensors to collect information on people's health, such as heart rate, blood pressure, blood sugar levels, and body temperature. This information is continuously measured and sent online to doctors or other healthcare professionals. The main advantage of IoT-based health monitoring is that doctors can monitor people's health constantly and accurately. This can lead to early diagnosis of diseases and provide more effective treatments [45, 46].

2.2 Internet of medical things

The remote health monitoring system consists of several items, such as sensors and electronic circuits for biometrics' real-time data collection, processing unit, network software and devices for data transmission, and screen for results visualization [47–51]. Health monitoring systems using the IoT include integrating various devices and sensors to collect and transmit health-related data in real time. These systems aim to continuously monitor people's health parameters, enabling timely intervention and personalized health care, as illustrated in Fig. 1 [52]. The functional perspective of an IoMT involves data collection, transmission, storage, processing, results representation, and feedback provision. Healthcare IoT systems incorporate sensors into various medical devices, such as wearables, implanted medical devices, and healthcare equipment. These sensors continuously monitor and collect real-time patient health data, including vital signs, physiological parameters, and clinical measurements. The data collected must be high in quality, accuracy, and completeness. They also need to be secured to protect against unauthorized access.

The collected health data should be effectively transmitted to a central repository for further processing and analysis using network technologies such as Wi-Fi, Zigbee, Sigfox, LoRa, Bluetooth, and cellular networks. This allows the data to be accessible from anywhere with an internet connection, enabling individuals to monitor their health remotely and

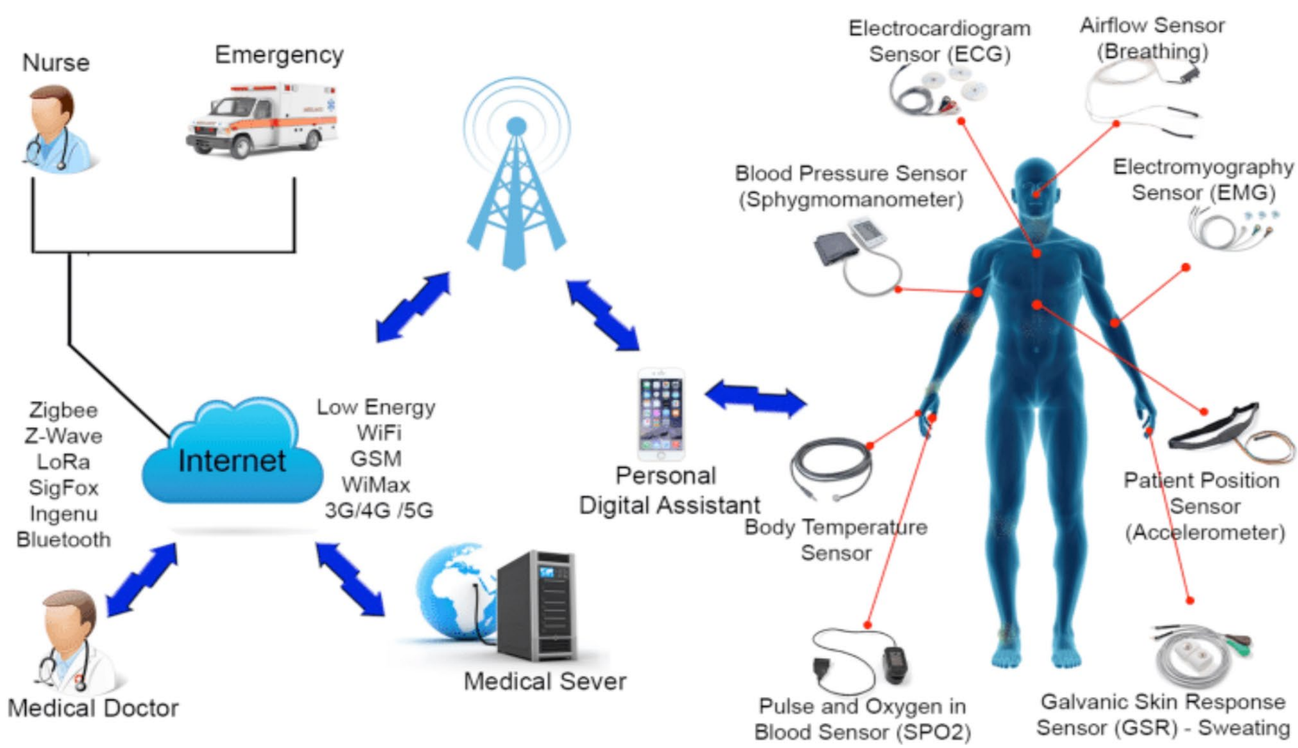

Fig. 1 Remote health management system architecture [53]

healthcare providers to remotely manage patient care. The health data received is stored in a secure, scalable database such as cloud computing on the medical server. This database should be able to manage big data and provide efficient access for analysis and decision-making. Once the data has been transmitted, it undergoes sophisticated processing and analysis. Advanced algorithms and machine learning techniques are employed to identify patterns, trends, and anomalies. This analysis contributes to a person's overall health status, identifying potential health risks, and tracking progress over time. The extracted information is analyzed to identify the potential variations or abnormalities in health status. This analysis can be performed by healthcare professionals or smart systems. If any changes or abnormalities are detected, the appropriate interventional actions are taken. This may include contacting the patient, requesting a doctor's visit, or issuing treatment instructions [11, 22, 27, 54–58].

2.3 Health measures

Vital signs, such as heart pulse, blood pressure, respiratory rate, saturation of peripheral oxygen (SpO_2), and temperature, are the most significant and popular indices for health assessment by patients, athletes, or even ordinary people passionate about knowing about their health continually. In recent years, lots of research has focused on collecting data on vital signs and reporting the resulting figures and patterns using digital tools, such as wearable tools or mobile health [59–62]. However, other metrics like the state of the bed, glucose level, muscle spasms, heart attack, falls, and epilepsy are helpful in health monitoring [45, 63–67].

3 IoT-based health monitoring literature descriptive analysis

This section proposes the results of the literature descriptive analysis according to several criteria, including biometrics (BP, HR, BT, SpO_2), and breathing rate (BR), state of the bed (SB), glucose level (GL), muscles spasm (MS), heart attack (HA), falls, and epileptic), communication modules (Bluetooth, ZigBee, RFID, BLE, LoRa, GNSS HAT, GUI, Ubidots IoT, ThingSpeak, GSM/GPRS/GSR/GPS, SigFox, and Wi-Fi), software (MATLAB, PYTHON, MQTT, Blynk, MicaZ node, TinyOS, JavaScript, VITAL APP, HTTP, MySQL, and HTML), hardware (Arduino UNO, Raspberry Pi 3, LCD Display, D/A Converters, Nodemcu, ATMEGA16 (AVR), Zencore microcontroller, and Jumper wires), and sensors (ECG SENSOR, EMG v3 Sensor, HB Sensor, BT Sensor, SpO2 Sensor, PR Sensor, BP Sensor, Pulse Oximeter, IC Sensor, PPG sensor, and Accelerometer). Table 1 shows the list of literature concentrated on each criterion and the corresponding items.

Table 1 Literature concentrated on various criteria and items

Biometrics	BP [29, 68–96], HR [20, 27, 46, 53, 55, 63, 68, 69, 71, 74, 80–82, 84–89, 97–126] [29, 90, 91, 94, 95, 127–144], BT [20, 27, 46, 53, 55, 63, 68, 69, 71, 72, 74, 78–80, 84–93, 97, 98, 101, 103–105, 108, 110, 112–117, 119, 124–126, 128–132, 136, 139–153], SpO2 [27, 29, 46, 68, 71, 83–87, 92, 96, 103, 104, 106, 108–110, 112, 114, 118, 129, 132, 133, 139–142, 144, 145, 149, 150, 153, 154], BR [53, 72, 87, 88, 90, 95, 105, 109, 111, 119, 127, 148–150, 152, 154–156], State of the Bed [111], Glucose Level [81, 82, 84], Muscles spasm [63], Heart Attack [99], Falls [63], and Epileptic [63]
Communication modules	Bluetooth [46, 82, 116, 119, 129, 133, 135, 137, 154, 157], ZigBee [81, 107, 125, 142, 154], RFID [91, 151, 154], BLE [120, 157, 158], LoRa [84, 125, 145], GNSS HAT [110], GUI [97, 110, 148, 157], Ubidots IoT [84, 112], ThingSpeak [85, 87, 108, 117, 120, 123, 124, 130, 131, 142, 144], GSM/GPRS/GSR/GPS [53, 55, 72, 81, 83, 85, 86, 90, 97, 101, 103, 110, 114, 115, 117, 121, 124, 125, 128, 130, 131, 140, 142, 158], SigFox [145], and Wi-Fi [27, 29, 53, 55, 69, 71, 74, 84, 85, 87, 91, 92, 97, 98, 103, 106, 108, 111–117, 121, 124, 126, 128, 130, 132, 138, 143, 144, 148, 149, 154, 155, 158]
Software	MATLAB [63, 87, 120], PYTHON [110, 119, 144], MQTT [27, 98, 106, 122, 134, 158], Blynk [114, 118, 135, 148], MicaZ node [154], TinyOS [154], JavaScript [81, 120, 122, 158], VITAL APP [80], HTTP [97, 98, 112], MySQL [110, 158], and HTML [81, 97, 128, 158]
Hardware	Arduino UNO [29, 46, 53, 55, 69, 71, 81, 89, 91, 97, 101, 103, 104, 108, 112, 114, 115, 117, 118, 121, 125, 128, 130–135, 142, 144, 145, 148, 153], Raspberry Pi 3 [53, 69, 71, 72, 74, 86, 90, 92, 97, 98, 101, 110, 113, 119, 123, 128, 134, 149, 153, 158], LCD Display [20, 29, 46, 53, 86, 91, 97, 98, 103, 115, 117, 121, 124, 142, 148], D/A Converters [63], Nodemcu [27, 29, 55, 63, 84, 86, 112–114, 118, 130, 132, 141, 155], ATMEGA16 (AVR) [97], Zencore microcontroller [80, 104, 109, 110, 140, 152], and Jumper wires [46, 118]
Sensors	ECG SENSOR [27, 29, 53, 63, 71, 85, 91, 97, 98, 103, 105, 114, 115, 117, 118, 120, 126, 132, 137, 143, 145, 151, 153], EMG v3 Sensor [113], HB Sensor [29, 55, 69, 72, 82, 84, 86, 92, 97, 98, 115, 116, 119, 123, 124, 126, 128, 130, 132, 134, 140, 152, 158], BT Sensor [20, 29, 46, 53, 55, 68, 69, 71, 72, 84–87, 91, 92, 97, 98, 103–105, 108, 112–118, 120, 124, 126, 128–135, 140, 143, 145, 148, 149, 151, 152, 158], SpO2 Sensor [46, 82, 87, 103, 114, 118, 133, 145], PR Sensor [20, 53, 71, 80, 89, 98, 101, 103, 105, 113, 117, 130, 131, 133–135, 143], BP Sensor [29, 68, 69, 71, 80, 82, 84–86, 91, 119, 151], Pulse Oximeter [27, 29, 68, 85, 86, 92, 108, 112, 119, 123, 149, 154], IC Sensor [120], PPG sensor [120, 132, 135, 143], and Accelerometer [63, 72, 91, 125, 140, 157]

According to Table 1, the IoT-based health monitoring literature mostly focused on monitoring vital signs, including BP, HR, BT, SpO_2, and breathing rate (BR), and Wi-Fi is the most commonly used communication tool followed by the GPS. Also, MQTT received more attention than all software used for IoMT development, Arduino UNO, Raspberry Pi 3, and LCD Display are basic hardware in IoTs' creation, and the body temperature sensor is the most mentioned in the literature on IoT-based health monitoring. Figure 2 depicts the results of literature frequency analysis in each criterion, verifying the above-mentioned literature concentration analysis.

Although IoT-based health monitoring is a growing emerging topic concentrated on sensors, software, hardware, and connection development, none of the studied literature focused on human-centered data analytics of collected biometrics. Table 2 illustrates the recommendations of the IoT-based health monitoring literature for future research.

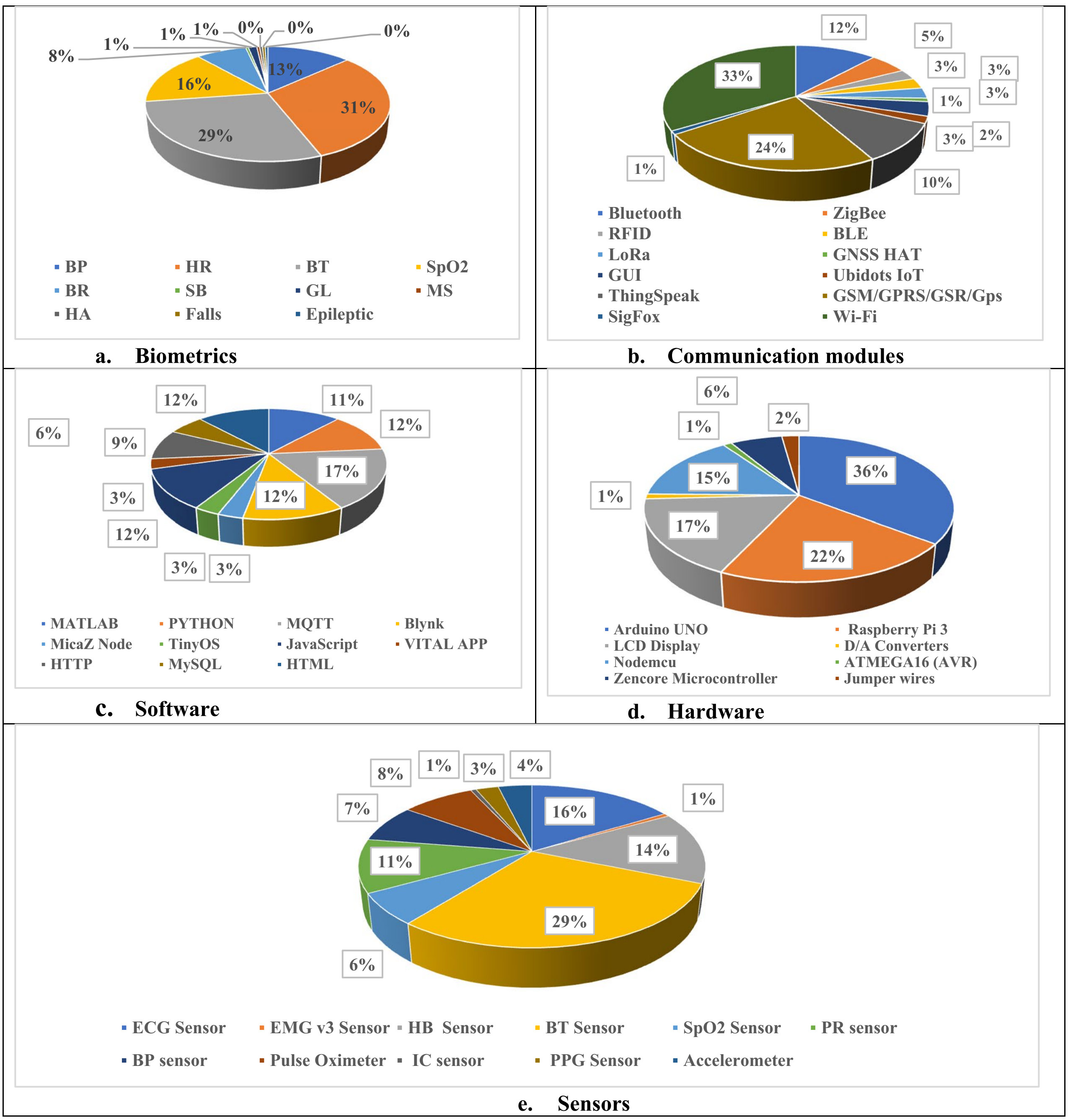

Fig. 2 The share of items in each criterion

Table 2 The IoT-based health monitoring literature's recommendations analysis

	Multi-signs	Using ML/DL	Cloud computing	Battery life	Cybersecurity	Message length	Health data analysis integration	Multi-sensors	Audio instructions	Multi-communication tools	Visual contacts	Human-centered data analysis
Rahaman et al. (2019)		✓						✓				
Brezulianu et al. (2019)								✓				
Swaroop et al. (2019)										✓		
Basu et al. (2020)	✓											
Kadhim et al. (2020)								✓				
Khamitkar et al. (2020)	✓		✓						✓			
Choi et al. (2020)		✓										
Kadhim et al. (2020)	✓											
Lou et al. (2020)		✓			✓			✓				
Hadis et al. (2020)								✓				
Bora et al. (2021)	✓										✓	
Park et al. (2021)		✓										
Yakubu et al. (2021)	✓											
Sundaravadivel et al. (2021)			✓									
Alekya et al. (2021)					✓							
Savaridass et al. (2021)		✓										
Khan et al. (2022)	✓	✓							✓			
Bhardwaj et al. (2022)		✓			✓							
d'Angelis et al. (2022)		✓			✓							
Arakawa et al. (2022)				✓								
Abdulmalek et al. (2022)							✓					
Phan et al. (2022)												

Table 2 (continued)

	Multi-signs	Using ML/DL	Cloud computing	Battery life	Cybersecurity	Message length	Health data analysis integration	Multi-sensors	Audio instructions	Multi-communication tools	Visual contacts	Human-centered data analysis
Hassan et al. (2022)								✓				
Abo-Zahhad. (2023)	✓	✓										
Mohammed and Hasan. (2023)	✓											
Sangeethalakshmi et al. (2023)		✓										
Srinivasan et al. (2023)		✓									✓	
Alshammari et al. (2023)				✓								
Govarthan et al. (2023)					✓	✓		✓				
Boikanyo et al. (2023)					✓							
Chi et al. (2023)		✓	✓		✓					✓		✓
Yenurkar et al. (2024)			✓					✓		✓		✓
Wu et al. (2024)		✓	✓		✓					✓		✓
Soulaimani et al. (2024)			✓		✓					✓		
Vamshikrishna et al. (2024)		✓	✓							✓	✓	

According to Table 2, the majority of recommendations are about using machine learning and deep learning tools to provide more diverse and accurate information on health based on the collected data by IoTs, followed by inspiration on creating multi-purpose IoTs. Also, the recently published literature has emphasized more on the cybersecurity of IoTs. However, none of the literature mentioned human-centered health data analytics in the future IoMTs development.

4 Future research guidelines

As illustrated in the previous sections, human-centered data analysis has not been a matter of interest in the literature of IoT-based health monitoring. According to human-centered, the design of IoT's attributes, such as hardware, sensors, and communications modules, must be personalized according to end-users' physical and mental specifications, disabilities, literality, needs, and emotions. The literature reviewed in Sects. 2 and 3 showed that the focus was IoTs' hardware, software, and communication tools development, and less attention was paid to health data analysis using machine learning and deep learning forecasters and classifiers.

On the other hand, the collected data by sensors are mostly time series like blood pressure or are of signal form such as ECG. Hence, using conventional computer vision tools for graphical data analysis could provide several classifiers for diagnostic or alarm purposes. In addition, IoTs collect random samples of biometrics over time. Therefore, statistical descriptive analysis and statistical process control tools, such as control charts, and process capability analysis, might be useful tools for health monitoring via biometrics' statistical control over time [159–161]. Particularly, profile monitoring might be the best-suited tool for health graphical data monitoring [162, 163].

Profile process capability Indices, representing the degree of capability of the process to operate without fail in the long run like a day, could be employed to assess an individual's body capability in terms of biometrics' profiles [164–169]. Also, process capability indices monitoring using control charts could monitor the health in a longer time window, like a month or year. Nemati and Mehrdoost (2023) proposed a model-free approach for monitoring and capability assessment of blood pressure circulation, considering two profiles for systolic and diastolic blood pressures. They used a dissimilarity index, conventional in graph matching from computer vision context, called D_{max}, the maximum distance between the target profile and observed profiles of each biometrics. D_{max} was applied in the bi-profile monitoring and capability assessment of blood pressure. ECG signals' statistical analysis needs multi-profile monitoring methods because it involves several waves, segments, and intervals of different patterns, tolerances, and anomaly interpretation [170–176]. Also, simultaneous monitoring of vital signs could be categorized as a multi-profile monitoring problem. Furthermore, using D_{max} in the biometrics' multi-profile monitoring problems can lower computational complexity and mitigate the lack of accurate regression models for profile approximation in the traditional multi-profile assessment [166, 177]. The natural tolerances of biometrics of individuals might be different according to age, gender, physical specification, occupation, chronic disease, etc., Hence it is necessary to consider the personalized tolerances of biometrics, such as HR, BP, BT, and ECG, in the analysis of collected data by IoTs. Programming optimization under predefined conditions like considering a significant process capability analysis could be an option for human-centered tolerancing. Furthermore, forecasters and classifiers provided by machine learning and deep learning tools could use the personalized historical data and tolerances for human-centered real-time biometrics monitoring and proposing proper alarms [178–181]. To sum up, the following topics could be mentioned for research on human-centered IoT-based health monitoring in the H5.0 era:

- Proposing a human-centered target profile upon each biometrics using the corresponding historical time series data,
- Establishing human-centered tolerances for each biometrics profile using programming models and pre-expected capability conditions,
- Applying multi-profile methods, particularly model-free techniques, for human-centered simultaneous biometrics monitoring,
- Using profile process capability indices in the human-centered short-term body capability assessment upon each biometrics,
- Employing multivariate profile process capability indices for human-centered short-term body capability assessment for multiple biometrics,
- Applying profile process capability control charts for human-centered long-term body capability assessment,
- Creating human-centered forecasters and classifiers of biometrics using machine learning and deep learning algorithms.

5 Conclusions and recommendations

This paper focused on the human-centered IoT-based health monitoring problem by highlighting the lack of attention paid to human-centered data analytics in designing and applying IoMTs. Hence, a descriptive analysis was conducted on the IoT-based health monitoring literature focusing on the type of biometrics monitored, sensors, communication modules, software, and hardware. The results showed a high concentration on vital signs monitoring, Arduino UNO as software, and Wi-Fi as a communication module. However, none considered human-centered data analytics in the IoMTs development. In addition, the literature's recommendations were analyzed to highlight that the vision of researchers who concentrated on the IoT-based health monitoring problem is mostly focused on other subjects, such as multi-biometrics monitoring, and cybersecurity, else using human-centered IoMT, developed IoTs based on personalized health data analytics.

Several research opportunities for human-centered IoT-based health monitoring were provided, such as providing personalized biometrics profiles tolerancing using programming models, using process capability indices for human-centered short and long-term biometrics profile assessment, employing multivariate profile monitoring methods for human-centered multi-biometrics assessment, and human-centered forecasters and classifiers. Also, focusing on the proposed human-centered data analytics framework for any IoMTs could be a related future work topic.

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Data availability No datasets were generated or analysed during the current study.

Data and code availability The Authors would submit the related data set and codes whenever a request is received.

Declarations

Ethics approval and consent to participate The Authors declare that no real clinical data is applied in this paper and the required information is generated via simulation.

Declaration of generative AI and AI-assisted technologies in the writing process None.

Competing interests The authors have no relevant financial or non-financial interests to disclose.

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