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A Survey on Smart Wearable Devices for Healthcare Applications

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Abstract
This paper introduces a survey on recent smart wearable devices used in different fields, especially healthcare applications. A discussion is presented in terms of power supply, wireless technologies, applications, and wearability of these devices. Regarding the power supply, a photovoltaic is the best harvesting energy source, while the best energy storage is a Li-ion battery. Regarding wireless technologies, Bluetooth low energy (BLE) is the best for personal usage, while Wi-Fi has preferred for Internet of Things (IoT) applications. Regarding the applications, medical and non-medical applications can be used. Regarding wearability, smart wearable devices can be positioned on a human hand or arm. Also, wearable sensors can be patched on human skin, besides, they can be placed on clothes, such as a smart suit which is preferred for heavy duties.

Keywords Smart wearable devices · Sustainability · Energy harvesting · Internet-of-Things (IoT) · Bluetooth · Photovoltaic · Thermoelectric · Low energy

1 Introduction

Smart medical wearable devices are very important to monitor the vital signs of people, thus taking care of their health [1]. Wireless technologies, such as Bluetooth and Internet-of-things (IoT) enhanced these wearable devices, so the wireless technologies became able to use with a mobile phone or can be used to monitor patients online. The traditional medical wearable devices are bulky, so the ability to wear them makes them more mobile and adaptive to be used. Renewable energy resources are currently rising to generate clean and safe energy. Figure 1 shows a framework of smart wearable devices connected through a Wi-Fi network with an IoT cloud service [2]. This paper presents a survey about several smart

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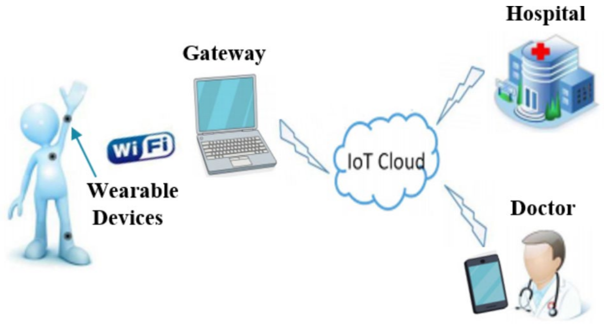

Fig. 1 A framework of Smart wearable devices with an IoT cloud service [2]

wearable devices, which are used in different fields, mostly in the medical field to monitor healthcare.

The rest of the paper is organized as follows: Sect. 2 presents a survey in terms of energy harvesting, storage, and management. Section 3 introduces wireless technologies. Section 4 demonstrates the applications of wearable devices. Section 5 illustrates the wearability and mobility of devices. Section 6 discusses the paper and presents the best recommendations and suggestions for future works. The paper is concluded in Sect. 7.

2 Related Work

2.1 Energy Harvesting

The methods of energy harvesting varied, but they all agree on supplying power in little amounts to supply low-power wearable devices. The sources used or to be used are photovoltaic energy, thermoelectric energy, and piezoelectric energy. In the literature, several smart wearable devices were reviewed [2–9], these devices used photovoltaic power as a main source, or as a part of a hybrid harvesting system. Photovoltaic power was the most used due to its ease as a source to generate electric power, high power density, and availability worldwide. However, it had some constraints, such as a decrease of generated power with weather fluctuations, for instance, cloudy weather and the necessity to use wide areas to increase power generation, etc. The photovoltaic cells used in [2, 3] were flexible to suit the body contour.

Some wearable devices use thermoelectric generation. The generated thermoelectric power was very low. In [9], thermoelectric generation can be used to increase power production, if the generated photovoltaic power decreased for any reason. In [10], thermoelectric was used alone to supply micro-power devices, where a hand watch was supplied by a thermoelectric source, which may be better than automatic hand watches which may damage due to collisions. Mostly the electric power generated by this method comes from the heat energy emitted by the human body, in wearable devices, such as watches and medical sensors. Due to the possible constraints that may reduce generated power and increase the productivity of the energy, hybrid generation had been developed. It comprised more than one source to generate power [8, 9], a hybrid energy harvesting was used, which utilized a photovoltaic generator with a thermoelectric generator. Photovoltaic cells generated power through sunlight and any other lights, while the thermoelectric generator provided power via the difference between the human body and ambient temperatures. In [6], a piezoelectric generated power was used by installation in a shoe sole or as embedded fibers in textiles, but it's not used due to high output voltages, low output currents, high optimum load resistances, and the possible deterioration of the textiles due to increased air humidity.

2.2 Energy Management

The harvested energy must be managed well. This power management is important to improve generated power and utilize the generated power well. In [2, 3], a TP4056 charge charging controller was used to regulate the charging voltage of a photovoltaic cell. In [4], a BQ25570 energy harvester integrated circuit was utilized to increase energy conversion efficiency by the automatic setting of its internal input impedance to achieve maximum power transfer. In [8], the BQ27441 fuel Gauge chip did a similar function. In [5], a circuit was based on a maximum power point tracking (MPPT) algorithm. This algorithm was used also in [6], but the LT3119 IC was used to step down the generated voltage to a suitable level to recharge the battery. It had battery protection to turn off the power when the battery voltage decreased. In [9], energy management was used comprising the DC-DC converter chips, which used LTC3108 IC. In [10], LTC3105 IC was used and programmed with different voltages, and so to extract the maximum power point.

2.3 Energy Storage

The selection of energy storage isn't of less importance than energy harvesting. It depended on some factors, i.e., energy density, lifetime, and size. In [2–4, 6], the Li-ion battery was used. In [5, 9, 10], super-capacitors were used. Also, there were other types of energy storage, such as NiCd and NiMH. The Li-ion was most used due to its very high energy density, low self-discharge, and long lifetime although its charging circuit was complicated, which can be solved by power management systems. The super-capacitors were good, as a lifetime, but they were bulky and their capacity was very low. The NiCd batteries delivered their full capacity, but they discharged quickly. The NiMH batteries were less power density than Li-ion ones, but the lifetime of NiMH batteries was low. These two latter types of batteries were abandoned due to their disadvantages.

The continuous measurement of medical wearable devices has a disadvantage; it wastes power on unnecessary measurements. So, to save energy, an active-sleep mode appeared to save energy by measuring and sleeping regularly and continuously over a definite period of time. The active-sleep mode can reduce wasted power and harvesting helped to make the devices sustainable by decreasing power consumption versus power production. However, to judge sustainability, looking at charging and discharging time isn't enough. A ratio between discharging to charging time can be taken, which can be used as a figure of merit to judge the sustainability of devices. If this ratio is less than 1, the device isn't sustainable. If more than 1, the device is sustainable. If equals exactly 1, the device is said to be "critically sustainable" where all produced power is consumed directly. This factor can be improved by decreasing power consumption or increasing power production.

3 Wireless Technologies

At first, medical devices were standalone, they measured and stored data in their memories only. However, with the rise of wireless technologies, such as Bluetooth and Wi-Fi in addition to data-logging through SD cards which became integrated with different devices to give them the ability to communicate through Bluetooth with smartphones and Wi-Fi to communicate with online servers through the internet, which is known by Internet of Things (IoT) technology; to save records of vital data of patients to track their health history, or even diagnosing them remotely, which may be useful in case of emergency. This may benefit in reducing the consumed power by an LCD if added. In [11], the wearable IoT-cloud-based health monitoring system (WISE) enabled people to register on an online server and their smart wearable devices which support this technology, which may be beneficial to follow the health status of the people instantly.

Bluetooth technology became integrated with the medical sensors, which made them easy to be communicated with through smart mobile phones to monitor them. Wireless technology consumes too much power. So, Bluetooth Low Energy (BLE) technology was used in the medical sensors, to save power consumed in wireless communication. With the rise the IoT technology, connectivity to the internet through Wi-Fi became integrated into medical sensing devices. This helped to link the sensor nodes directly with online servers to store data about patients and follow their vital data remotely without the need to manually measure. Artificial intelligence, i.e., deep learning, data mining, and machine learning, helps in the diagnosis of patients by gaining features from vital data.

4 Applications of Wearable Devices

The applications of the previous works [2–9] included medical and non-medical applications, used in personal usages and in hospitals to collect data from patients and utilized for remote diagnosing via the internet of things (IoT) technology. One of the non-medical applications is micro-power devices, such as watches or lights [10]. Due to the low power density of heat energy solar, solar power was preferred, which was used as photovoltaic cells integrated with smart clothing [6].

Medical applications were the most used. The need for new technologies to monitor vital data increases daily; to save the lives of people and monitor their health easily and quickly. New techniques to measure the vital signs appeared, instead of their corresponding old ones. The heart rate was the most important vital sign, so almost all medical sensor nodes support it. Traditional sensors measured the heart rate alone, then the photoplethysmography (PPG) sensors appeared which can measure blood oxygen saturation level (SpO_2) besides the heart rate.

Previously, blood pressure was measured using a mercury sphygmomanometer, also used handcuffs, such as the traditional devices, until a new technique appeared to measure blood pressure based on electrocardiography (ECG) and photoplethysmography (PPG) [12], where pulse arrival time and heart rate were used to calculate the blood pressure, utilizing two sensors: one sensor to collect an ECG signal and the other sensor to measure PPG signals. This system was placed on the chest. Other medical sensors may include a body temperature sensor to measure body temperature besides these data and accelerometers to measure acceleration. Also, one of the applications was detecting stress [8] where artificial intelligence was utilized in a wearable device. On the other hand, a non-medical application, such as a solar energy harvester for a wireless sensor system toward environmental monitoring [13].

5 Wearability

Since the past century, traditional wearable devices weren't wearable, which made their mobility difficult somewhat. The need to light mobile devices appeared, so many works were implemented to mobilize the wearable devices and reduce their size. Nowadays, a lot of devices became wearable in different ways. They can be worn on the hand, wrist, or arm, as a patch, or even in form of smart clothes. This technology was introduced in medical devices, which made the medical devices compact, multifunctional, and easy to use. The traditional thermometer, sphygmomanometer, and ECG recording machines were bulky, but the recent medical sensing devices had several functions of these devices wholly, besides their ability to be worn on the body. The wearable devices worn on the hand had some sensors on the fingers, which was good for mobilization, but this may impede the use of the patient's hand which contains the device, and placing of harvesting system may be difficult. To solve this problem, the devices became wearable on the upper arm, which makes the hand free to use, but its use may not be suitable with clothes that have long sleeves. The wearability on the wrist appeared, which solved all these previous problems, but this may not be suitable with some sensors, such as the ECG sensor.

Smart clothing appeared to compete with hand-wearable devices. It may be used for medical applications, or for other uses that may require it such as mountain climbing. The smart patch was good for special usages, such as in hospitals, but it doesn't prefer for everyday use. The wearable devices contain fixed sensors, so a new solution appeared that made the medical sensing devices more customizable, which is the body-area network (BAN) [11]. It comprised a device to which the sensors can be connected. It supported both connections to smartphones and Wi-Fi to connect to networks.

6 Discussion, Suggestions, and Recommendations

Many new technologies have appeared, which have different advantages and disadvantages, are discussed. According to these pros and cons, every technology will has a definite purpose, which is its best use.

6.1 Energy Harvesting, Storage, and Management

The harvesting ways differ between photovoltaic, thermoelectric, and piezoelectric. Photovoltaic is the most preferred for relatively high-consumption micro-power applications. It's suitable everywhere, in hot or cold areas, and for all uses. Thermoelectric energy generates very low power, so it is best in use for ultra-low consumption wearable devices, such as hand watches. Thermoelectric energy is the best in hot areas, where the temperature difference between body and ambient temperatures may be high.

Regarding piezoelectric energy, if used as fibers in a textile, it's best in hot areas where the weather is less humid, but it doesn't recommend in cold areas. The piezoelectric generates high voltages, but low currents, so it's not recommended at all. When possible, the hybridization of energy harvesters is recommended to increase production, where photovoltaic and thermoelectric are the best choice in a hybrid harvester (if wearable).

Regarding energy storage, the best to be used in all applications is Li-ion batteries. Their energy density is high which enables them to store more energy in smaller sizes than other types. Their charging circuit is complicated, but this can be solved by energy management, so the advantages of the Li-ion battery overweigh its disadvantages. The super-capacitors have a so low capacity, so their best use is in the low consumption devices which consume power as low as the order of microwatts. The benefits of the Li-ion batteries versus the disadvantages of the NiCd and NiMH make the use of these two latter types obsolete.

The energy management ways are also different. There're circuits that regulate the generated voltage, maximum power point tracking (MPPT) circuits, chips that automatically set their internal impedance to achieve maximum power transfer (impedance track), and DC-DC converter chips. The best selection is energy management by combining MPPT and impedance track together. The impedance track sets its impedance to achieve maximum power transfer from the circuit, and the MPPT sets the generated voltage to be the maximum power point of the harvester. The transformation by a DC-DC boost converter still suffers from the fluctuation of the generated voltage, and the voltage may drop below the maximum voltage output of a regulator, which doesn't achieve the maximum power transfer at all.

The active-sleep mode is very useful for saving power wasted when a measurement isn't needed, but sometimes an instant measurement is needed in an emergency situation. This problem can be solved by adding a button on the device, mobile application, or online service website to override the active-sleep work cycle and restart it again from the instant of pressing the button.

6.2 IoT and Wireless Technologies

Most of the wireless technologies used include two technologies: Bluetooth and Wi-Fi. The wireless technology is so energy-consuming, so it's preferred to use as low-energy modules as possible. Bluetooth is preferred for personal-use devices where the data can be shown through a mobile phone app and Wi-Fi with IoT technology is best to be used in places and for purposes that require dealing with mass numbers of people, such as hospitals, where the devices are registered on an online server. It's good to utilize artificial intelligence in the online server or mobile phone application, which benefits diagnosing patients.

Regarding IoT applications, there's use can be suggested to be introduced, which may benefit epidemics. An online server can be created by the health authorities worldwide (i.e., ministries of health) which people can register through it and register on their accounts their own smart medical devices. The health authorities monitor the people through this server. In case of emergency situations, the health authorities are reported automatically to take suitable action. This may benefit in epidemics, such as the COVID-19 pandemic, where the health authorities advise some patients to be home-quarantined. This helps the health authorities to monitor patients in home quarantine.

6.3 Wearability

The wearable devices are different according to their way of wearing on the body. The wearability on the upper arm is best when the user needs to use both hands and best to be used in hospitals. The wearability of the hand may impede the use of the hand that the device is worn on. However, if used, it's best to be designed to be worn on the left hand. The wearability on the wrist is suitable for personal non-medical use devices at most, such as sport uses. The wearability of medical clothes differs according to the purpose, where the smart T-shirt is most suitable for hospitals, and the smart suit is most possible for heavy-duty uses i.e., mountainous areas (climbing or saving), firefighting, camping, remote areas, etc. The smart patch is more suitable for hospital uses. Table 1 shows a comparison between some recent smart wearable devices.

6.4 Other Suggestions and Recommendations

The use of phone apps or online servers in IoT uses eliminates the need for a liquid crystal display (LCD), which saves power expected to be consumed by the LCD. This is best

Table 1 Comparison between some recent smart wearable devices

Reference	[3]	[2]	[9]
Sensors	Temperature sensor and heart pulse sensor	Temperature sensor and pulse oximeter sensor	Temperature sensor, pulse oximeter sensor, accelerometer sensor
Vital Data	Temperature and heart rate	Temperature, heart rate and blood oxygen level	Temperature, heart rate, blood oxygen level and acceleration
Energy Storage	Li-ion battery 4.2 V 4800 mAh	Li-ion battery 4.2 V 3800 mAh	Super-capacitors 5.4 V 50 F
Energy Harvester	One photovoltaic cell with TP4056 charging controller	Two photovoltaic cells in series with TP4056 charging controller	Photovoltaic cell parallel with thermoelectric generator module and DC-DC boost converter
Power Consumption (mW)	4.97	20.23	2.13
Theoretical Lifetime (days)	137	33.26	1.91
Charging Time (days)	14.6	11.73	0.04
Times of Activity per Hour	4	60	3
Wake-up-sleep period (minutes)	15	1	20
Active Time per Period (seconds)	15	5	10
Sleep Time per Period (seconds)	885	55	1190
Sustainability Factor	9.38	2.84	47.75
Wireless Technology	BLE 100 m	Wi-Fi 400 m	BLE 100 m
Wearability	Wrist with sensors on fingers	Upper arm	Wrist with temperature and pulse oximeter sensors on fingers
Data Monitoring	Android phone application	Online server	Android phone application

preferred for people's uses and may be suitable for personal uses. However, the low-experienced people with technology must be taken into account, so they can use devices with LCD, but the utilized LCD must consume power as lower as possible. The medical devices at most have the sensors fixed. This is customary, but it's suggested to use customizable devices, which have removable sensors. This is evident in the body area network (BAN).

7 Conclusion

This paper presents a survey on some types of smart wearable devices, in the context of energy harvesting and energy management and storage, applications, wireless technologies, and wearability on different parts of the human body. The rechargeable batteries differ, whereas the Li-ion battery remains the best and most used. Harvesting by photovoltaic cells is the best and generates power a lot more than other means, such as thermoelectric. The wearability, IoT, and wireless technology are different according to personal and mass in hospitals and monitoring home-quarantined patients in epidemics. In future work, a push button can be provided to interrupt and reset the active-sleep cycle of wearable devices, especially if an instant reading needs to be recorded and using an online server created by the health authorities to register the smart medical devices through it to monitor home-quarantined patients in epidemics. Also, customizable medical sensing devices that are known as body area networks (BAN) could be suggested for implementation.

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Declarations

Conflict of Interest The authors declare that there is no conflict of interest regarding the publication of this paper.

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