# Wearable Energy Harvesters

Subjects: Medical Informatics

Contributor: Ahsan Ali, Muaz Ashfaq, Aleen Qureshi, Umar Muzammil, Hamna Shaukat, Shaukat Ali, Wael A. Altabey, Mohammad Noori, Sallam A. Kouritem

A rapidly expanding global population and a sizeable portion of it that is aging are the main causes of the significant increase in healthcare costs. Healthcare in terms of monitoring systems is undergoing radical changes, making it possible to gauge or monitor the health conditions of people constantly, while also removing some minor possibilities of going to the hospital. The development of automated devices that are either attached to organs or the skin, continually monitoring human activity, has been made feasible by advancements in sensor technologies, embedded systems, wireless communication technologies, nanotechnologies, and miniaturization being ultra-thin, lightweight, highly flexible, and stretchable. Wearable sensors track physiological signs together with other symptoms such as respiration, pulse, and gait pattern, etc., to spot unusual or unexpected events.

Keywords: wearable sensors ; energy harvesting ; electrical sensing mediums

## 1. Introduction

In recent years, wearable healthcare devices have brought an exponential change in human life. The different versatile sensors follow the thermoelectric, piezoelectric, and electrostatic principles, which are combined using materials that are flexible and easy to handle by users [1][2][3][4][5]. This idea and concept have picked up pace rapidly and many products are introduced into the commercial market related to wearable healthcare monitoring (WHM), some of which are health bands, Apple Watches, Fitbit, Withing, Oura Ring, ECG Patch Monitors, and so on [6][7]. These all are wearable healthcare products available in the market and are based on different mediums and sensors, i.e., pressure sensors, temperature sensors, and optical sensors, etc. Researchers describe these electrical sensing mediums, which include three main piezoelectric-, electrostatics-, and thermoelectric-based wearable sensors for healthcare monitoring. Although all these products are somewhat of a breakthrough in the health monitoring field, they are still, however, constrained due to some other requirements, such as integration or attachment with human skin, the measurement of minute physiological parameters, or a lack of power generation for their prolonged charging. A key factor in their lacking is the charging of these products, which is somewhat traditional, like the plug and charge process [8]. To overcome these problems or hurdles, multi-functional, stretchable, flexible, self-charging health-monitoring devices are a much-needed necessity [9]. In these health-monitoring devices, their main body comprises multiple types of sensors, which will serve several purposes, such as the power generation of the product and the detection or monitoring of the physiological movements and signals in the human body, such as the temperature of the body, blood glucose, heart rate, fever, heart rhythms, blood oxygen, sleep patterns, cold checks, and acceleration, etc. [10][11]. To achieve these features or purposes, researchers must see the different sensors fabricated through multiple mechanisms, such as single or hybrid mechanisms [12], and these sensors are divided according to their specific area of expertise [13][14]. For accurate human health monitoring, these sensors should be able to attach to the human skin as effortlessly as possible and the sensing range of these monitoring sensors should be wide, that is, for detecting subtle reactions such as heart rate, pulse, and respiration to vigorous experiences, which include running, bending, and stretching, etc. [15][16][17][18]. Another crucial factor in health-monitoring tools is their sensitivity, which can be further enhanced through better structuring and fabrication [19][20]. The charging or power generation of wearable sensors is also another milestone to go, because, in traditional health-monitoring devices, these products need an external power source for the power generation for its health-monitoring parameters to work, which has multiple effects on the environment, as well as the overall structure of the product [21]. Thus, another reason for using multiple sensors (piezoelectric, thermoelectric, and electrostatic sensors) is to solve these environmental and structure-related problems, and also to achieve the compactness of this health-monitoring device [22][23][24][25]. Electrostatic sensors are versatile and cost-effective tools that have been used for monitoring various processes and clinical environments over the past 30 years [26]. They operate on the principle of static electricity generated by friction between two objects or the triboelectric effect [27]. Electrostatic sensors use an electrode and an insulator to detect the motion of an object. They provide solutions to measurement issues and offer a cost-effective alternative to other types of sensors [28][29][30][31]. These sensors can detect the triboelectric effect, which prompts a surge or electric current that can be used to generate power [32]. In addition to gas turbine engines, electrostatic sensors are used in healthcare for sensing different body movements, including wearable sensors for monitoring blood pressure and blood oxygen levels [33][34][35][36]. Electrostatic sensors are commonly referred to as battery sensors or inductive sensors, which were originally used to track human activity [37][38][39].

In the field of wearable healthcare, wearable electrical sensing mediums such as piezoelectric-, electrostatic-, and thermoelectric-based wearable sensors are regarded as smart and versatile technology. These sensors have a variety of qualities that contribute to their adaptability. First of all, these sensors have the ability to measure several signals or characteristics simultaneously. For instance, strain or mechanical pressure can be detected using piezoelectric sensors, which are able to transform these into electrical signals. They are able to measure a variety of bodily motions, such as muscle contractions, joint motions, and even heartbeat, because of this ability. On the other hand, electrostatic sensors are able to detect changes in charge distribution or electric potential, allowing them to capture tiny movements such as eye blinks and gaze directions. Thermal patterns in the body can be studied and monitored with thermoelectric sensors, which can detect temperature gradients or variations. These sensors' ability to measure numerous signals broadens the range of the healthcare applications in which they can be used. Second, wearable electrical sensing mediums are appropriate for people of all ages, sizes, and health problems. Sensors are designed to be versatile, flexible, and conformable to various types of bodies. This feature guarantees a secure fit and reliable signal acquisition. Sensors can also be incorporated into a variety of wearable form factors, including clothing, accessories, or patches, making them appropriate for various health problems and monitoring. These sensors' versatility enables customized and unique heath-monitoring solutions. Healthcare monitoring is made simple and flexible by wearable electrical sensing technologies such as piezoelectric, electrostatic, and thermoelectric sensors. They are useful tools for individualized and ongoing healthcare monitoring because of their capacity to measure many signals, versatility to various body types, and non-invasiveness. By facilitating early detection, personalized treatments, and enhanced general wellbeing, these devices have the potential to fundamentally alter our ability to manage and monitor our health [37][38][39][40].

## 2. Performance Comparison among Wearable Energy Harvesters

Piezoelectric wearable energy harvesters have the benefit of being able to produce high voltages, and their manufacturing processes could allow for further miniaturization. These devices are useful for a variety of applications, because they can effectively transform mechanical vibrations into electrical energy. They can be integrated into wearable devices due to their small size and high voltage output, which makes them suitable with many different electronic devices. Additionally, improvements in their manufacturing methods may result in PWHMSs that are even smaller and more effective. EWHMSs have a relatively simple fabrication method and allow flexibility with Micro-Electro-Mechanical Systems technology. They can produce large voltage levels and efficient low-frequency signal capture. Electrostatic harvesters need a small space between the plates to generate high power densities, however, this might cause the dielectric material to deteriorate with time. To begin energy generation, these devices need an initial voltage, which makes the system more complex. Despite these drawbacks, EWHMSs have demonstrated promise in absorbing energy from different kinds of motion. The integration of TWHMSs is quite simple. Depending on what temperature the device has, they can yield significant power densities. However, a method is needed to maintain this temperature difference, which would need the use of more power. Thermoelectric harvesters typically produce less energy and less voltage output than piezoelectric and electrostatic harvesters. However, they have the advantage of producing electricity from temperature gradients, making them appropriate for applications where there are substantial temperature changes.

As a result, piezoelectric WEHs have the potential for further miniaturization and offer high voltage outputs. Electrostatic WEHs require a small gap and starter voltage, but are easy to fabricate and are adaptable with MEMS technology. Thermoelectric EHs have a lower energy production and output voltage requirements, but they are simple to incorporate and can generate large power densities based on temperature changes. The choice is based on the application requirements and environmental factors, as each technology has advantages and disadvantages of its own.

## 3. Applications of Wearable Energy Harvesters

### 3.1. Heart Rate Monitoring

By picking up on the vibrations that the heartbeat causes, piezoelectric sensors can be used to determine heart rate. These sensors can be included in a wearable device, such as a wristband or chest strap, and used to continuously measure heart rate [41]. While piezoelectric sensors play an important role here, thermoelectric sensors can also be used in the same wearable devices for energy generation, which help in the monitoring of the heart rate for long periods, without the need to change the batteries, hence making them perfectly self-sustaining. This is great step, keeping in sight the concept of pacemakers that are used for abnormal heart monitoring. While this concept somewhat ancient and is in the implantable category, with the integration of piezoelectric and thermoelectric sensors, implantable heart-rate-monitoring technology can be shifted to self-sustaining wearable heart-rate-monitoring devices [42].

### 3.2. Respiration Monitoring

The movement of the chest or abdomen during breathing can be detected using piezoelectric sensors, which can then be used to estimate respiration rate. Monitoring breathing patterns and spotting changes that can point to respiratory issues can be performed using these data [43][44]. The pressure or piezoresistive have shown great potential in this field, in the form of smart chest belts and smart shirts. Now, smart chest belts and shirts are simple, comprising smart piezoresistive sensors that sense the deformity caused due to the movement of the chest that is the result of breathing, and then the difference in the form of smart belts shows us breathing patterns and respiratory results [45].

### 3.3. Movement Tracking

In a wearable device, piezoelectric sensors can be utilized to monitor movement and activity levels. These sensors, for instance, can pick up on limb movements during exercise or the vibration of footsteps [46]. An excellent example of such a principle are the insole devices used in shoes that use piezoelectric sensors, which sense changes in pressure through the steps of humans and can track simple human movements such as walking or running. Movement tracking is best for exercise purposes such as burning calories, through activities such as walking. The small and large deformations caused due to exercise provide the necessary data for health monitoring, which are collected by the pressure and strain sensors that are based on the piezoelectric principle [47].

### 3.4. Sleep Monitoring

Piezoelectric sensors can be used to track sleep patterns by spotting motions and vibrations at odd hours. Using these data, one may monitor their sleep patterns and spot issues such as sleep apnea [48][49].

### 3.5. Fall Detection

By monitoring the force with which a person’s body strikes the ground, piezoelectric sensors can be used to detect falls. In the event of a fall, this information can be used to contact the emergency services or carers. In addition, thermoelectric and electrostatic sensors are important here, because almost all physiological reactions of the human body result in heat and movements of different kinds, which can be sensed by different sensors based on the piezoelectric, electrostatic, and thermoelectric principles and cover the majority of the human body’s reactions. Based on the data collected by the sensors, an appropriate alert system and on-the-spot health measuring and monitoring can be performed, and the appropriate treatment methods can be prepared based on the same data compiled by the sensors’ monitoring.

### 3.6. Smart Bandages

A new type of smart bandage that uses electrostatic sensors may make treating wounds simpler, more efficient, and less expensive. Despite traditional dressings, which are made of multiple layers of a sponge-like substance, smart bandages are made of a resilient and stretchable material with integrated circuitry and medicine. Electrostatic sensors keep an eye out for chemicals such lactate or uric acid, as well as pH or temperature changes in the wound that could indicate a bacterial infection or inflammation, which are shown in **Figure 1**a,b [50]. As shown in **Figure 1**b, a SMART bandage with an oxygen sensor is placed on healthy skin. Because of the high oxygen content in the tissue, the detecting phosphor’s red emission is quenched. The fluorescent reference dye causes the entire film to radiate a green color. Similarly, an oxygen-sensing SMART bandage is applied on ischemic skin at the bottom of the figure. Because there is less oxygen in the tissue, the bright red emissions of the detecting phosphor outperform the reference dye’s green fluorescence. The entire bandage is red in color.

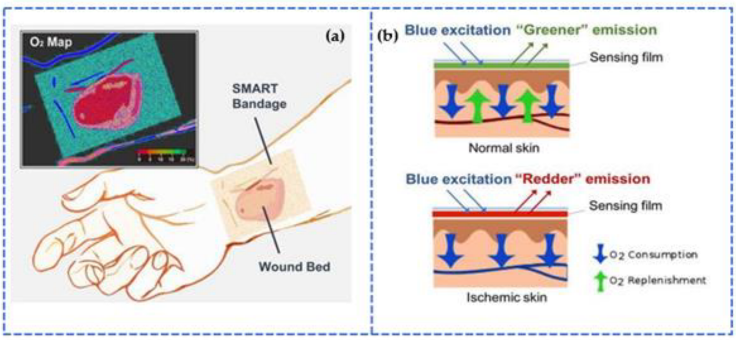

**Figure 1.** (**a**) O2 Map of Smart Bandage (**b**) Functionality of a Smart Bandage.

## References


1. Majumder, S.; Mondal, T.; Deen, M.J. Wearable Sensors for Remote Health Monitoring. Sensors 2017, 17, 130.
2. Wang, Y.; Yu, Y.; Wei, X.; Narita, F. Self-Powered Wearable Piezoelectric Monitoring of Human Motion and Physiological Signals for the Postpandemic Era: A Review. Adv. Mater. Technol. 2022, 7, 2200318.
3. Fan, Z.; Zhang, Y.; Pan, L.; Ouyang, J.; Zhang, Q. Recent developments in flexible thermoelectrics: From materials to devices. Renew. Sustain. Energy Rev. 2020, 137, 110448.
4. Mo, X.; Zhou, H.; Li, W.; Xu, Z.; Duan, J.; Huang, L.; Hu, B.; Zhou, J. Piezoelectrets for wearable energy harvesters and sensors. Nano Energy 2019, 65, 104033.
5. Dagdeviren, C.; Joe, P.; Tuzman, O.L.; Park, K.-I.; Lee, K.J.; Shi, Y.; Huang, Y.; Rogers, J.A. Recent progress in flexible and stretchable piezoelectric devices for mechanical energy harvesting, sensing and actuation. Extrem. Mech. Lett. 2016, 9, 269–281.
6. Seneviratne, S.; Hu, Y.; Nguyen, T.; Lan, G.; Khalifa, S.; Thilakarathna, K.; Hassan, M.; Seneviratne, A. A Survey of Wearable Devices and Challenges. IEEE Commun. Surv. Tutor. 2017, 19, 2573–2620.
7. Dassanayaka, D.G.; Alves, T.M.; Wanasekara, N.D.; Dharmasena, I.G.; Ventura, J. Recent Progresses in Wearable Triboelectric Nanogenerators. Adv. Funct. Mater. 2022, 32, 2205438.
8. Nasiri, S.; Khosravani, M.R. Progress and challenges in fabrication of wearable sensors for health monitoring. Sens. Actuators A Phys. 2020, 312, 112105.
9. Heikenfeld, J.; Jajack, A.; Rogers, J.; Gutruf, P.; Tian, L.; Pan, T.; Li, R.; Khine, M.; Kim, J.; Wang, J.; et al. Wearable sensors: Modalities, challenges, and prospects. Lab Chip 2018, 18, 217–248.
10. An, B.W.; Shin, J.H.; Kim, S.-Y.; Kim, J.; Ji, S.; Park, J.; Lee, Y.; Jang, J.; Park, Y.-G.; Cho, E.; et al. Smart Sensor Systems for Wearable Electronic Devices. Polymers 2017, 9, 303.
11. Zoui, M.A.; Bentouba, S.; Stocholm, J.G.; Bourouis, M. A Review on Thermoelectric Generators: Progress and Applications. Energies 2020, 13, 3606.
12. An, B.W.; Hyun, B.G.; Kim, S.-Y.; Minji, K.; Lee, M.-S.; Lee, K.; Koo, J.B.; Chu, H.Y.; Bae, B.-S.; Park, J.-U. Stretchable and transparent electrodes using hybrid structures of graphene-metal nanotrough networks with high performances and ultimate uniformity. Nano Lett. 2014, 14, 6322–6328.
13. Lee, M.S.; Lee, K.; Kim, S.Y.; Lee, H.; Park, J.; Choi, K.H.; Kim, H.K.; Kim, D.G.; Lee, D.Y.; Nam, S.; et al. High-performance, transparent, and stretchable electrodes using graphene-metal nanowire hybrid structures. Nano Lett. 2013, 13, 2814–2821.
14. Kim, J.; Lee, M.-S.; Jeon, S.; Kim, M.; Kim, S.; Kim, K.; Bien, F.; Hong, S.Y.; Park, J.-U. Highly Transparent and Stretchable Field-Effect Transistor Sensors Using Graphene-Nanowire Hybrid Nanostructures. Adv. Mater. 2015, 27, 3292–3297.
15. Lou, Z.; Wang, L.; Jiang, K.; Wei, Z.; Shen, G. Reviews of wearable healthcare systems: Materials, devices and system integration. Mater. Sci. Eng. R Rep. 2019, 140, 100523.
16. Osman, A.; Lu, J. 3D printing of polymer composites to fabricate wearable sensors: A comprehensive review. Mater. Sci. Eng. R Rep. 2023, 154, 100734.
17. Lu, Y.; Lou, Z.; Jiang, K.; Chen, D.; Shen, G. Recent progress of self-powered wearable monitoring systems integrated with microsupercapacitors. Mater. Today Nano 2019, 8, 100050.
18. Lim, H.; Kim, H.S.; Qazi, R.; Kwon, Y.; Jeong, J.; Yeo, W. Advanced Soft Materials, Sensor Integrations, and Applications of Wearable Flexible Hybrid Electronics in Healthcare, Energy, and Environment. Adv. Mater. 2019, 32, e1901924.
19. Lou, Z.; Wang, L.; Shen, G. Recent Advances in Smart Wearable Sensing Systems. Adv. Mater. Technol. 2018, 3, 1800444.
20. Li, Q.; Zhang, L.; Tao, X.; Ding, X. Review of Flexible Temperature Sensing Networks for Wearable Physiological Monitoring. Adv. Healthc. Mater. 2017, 6, 1601371.
21. Khalid, S.; Raouf, I.; Khan, A.; Kim, N.; Kim, H.S. A Review of Human-Powered Energy Harvesting for Smart Electronics: Recent Progress and Challenges. Int. J. Precis. Eng. Manuf. Technol. 2019, 6, 821–851.

22. Gowthaman, S.; Chidambaram, G.S.; Rao, D.B.G.; Subramya, H.V.; Chandrasekhar, U. A Review on Energy Harvesting Using 3D Printed Fabrics for Wearable Electronics. J. Inst. Eng. Ser. C 2016, 99, 435–447.
23. Rocha, J.G.; Goncalves, L.M.; Rocha, P.F.; Silva, M.P.; Lanceros-Mendez, S. Energy Harvesting From Piezoelectric Materials Fully Integrated in Footwear. IEEE Trans. Ind. Electron. 2009, 57, 813–819.
24. Alagumalai, A.; Shou, W.; Mahian, O.; Aghbashlo, M.; Tabatabaei, M.; Wongwises, S.; Liu, Y.; Zhan, J.; Torralba, A.; Chen, J.; et al. Self-powered sensing systems with learning capability. Joule 2022, 6, 1475–1500.
25. Lou, Z.; Li, L.; Wang, L.; Shen, G. Recent Progress of Self-Powered Sensing Systems for Wearable Electronics. Small 2017, 13, 1701791.
26. Yan, Y. Recent advances in electrostatic sensors and instruments for industrial measurement and monitoring. In Proceedings of the 2016 IEEE Student Conference on Research and Development (SCOReD), Kuala Lumpur, Malaysia, 13–14 December 2016; pp. 1–2.
27. Pu, X.; Zhang, C.; Wang, Z.L. Triboelectric nanogenerators as wearable power sources and self-powered sensors. Natl. Sci. Rev. 2022, 10, nwac170.
28. Li, Z.; Cui, Y.; Zhong, J. Recent advances in nanogenerators-based flexible electronics for electromechanical biomonitoring. Biosens. Bioelectron. 2021, 186, 113290.
29. Yan, Y.; Hu, Y.; Wang, L.; Qian, X.; Zhang, W.; Reda, K.; Wu, J.; Zheng, G. Electrostatic sensors—Their principles and applications. Measurement 2020, 169, 108506.
30. Romero, E.; Warrington, R.O.; Neuman, M.R. Energy scavenging sources for biomedical sensors. Physiol. Meas. 2009, 30, R35–R62.
31. Wang, W.; Yu, A.; Zhai, J.; Wang, Z.L. Recent Progress of Functional Fiber and Textile Triboelectric Nanogenerators: Towards Electricity Power Generation and Intelligent Sensing. Adv. Fiber Mater. 2021, 3, 394–412.
32. Gao, M.; Wang, P.; Jiang, L.; Wang, B.; Yao, Y.; Liu, S.; Chu, D.; Cheng, W.; Lu, Y. Power generation for wearable systems. Energy Environ. Sci. 2021, 14, 2114–2157.
33. Liu, R.; Zuo, H.; Sun, J.; Bei, S. A Review on Electrostatic Monitoring. In Proceedings of the 2017 International Conference on Sensing, Diagnostics, Prognostics, and Control, Shanghai, China, 16–18 August 2017; pp. 128–131.
34. Cadei, A.; Dionisi, A.; Sardini, E.; Serpelloni, M. Kinetic and thermal energy harvesters for implantable medical devices and biomedical autonomous sensors. Meas. Sci. Technol. 2013, 25, 012003.
35. Prasad, R.V.; Devasenapathy, S.; Rao, V.S.; Vazifehdan, J. Reincarnation in the Ambiance: Devices and Networks with Energy Harvesting. IEEE Commun. Surv. Tutor. 2013, 16, 195–213.
36. Xu, Y.; Hu, X.; Kundu, S.; Nag, A.; Afsarimanesh, N.; Sapra, S.; Mukhopadhyay, S.C.; Han, T. Silicon-Based Sensors for Biomedical Applications: A Review. Sensors 2019, 19, 2908.
37. Wu, Z.; Cheng, T.; Wang, Z.L. Self-Powered Sensors and Systems Based on Nanogenerators. Sensors 2020, 20, 2925.
38. Zou, Y.; Raveendran, V.; Chen, J. Wearable triboelectric nanogenerators for biomechanical energy harvesting. Nano Energy 2020, 77, 105303.
39. Yin, R.; Wang, D.; Zhao, S.; Lou, Z.; Shen, G. Wearable Sensors-Enabled Human–Machine Interaction Systems: From Design to Application. Adv. Funct. Mater. 2021, 31, 2008936.
40. Yao, S.; Swetha, P.; Zhu, Y. Nanomaterial-Enabled Wearable Sensors for Healthcare. Adv. Healthc. Mater. 2017, 7, 1700889.
41. Kakria, P.; Tripathi, N.K.; Kitipawang, P. A Real-Time Health Monitoring System for Remote Cardiac Patients Using Smartphone and Wearable Sensors. Int. J. Telemed. Appl. 2015, 2015, 373474.
42. Wood, M.A.; Ellenbogen, K.A. Cardiac Pacemakers from the Patient's Perspective. Circulation 2002, 105, 2136–2138.
43. Ali, A.; Pasha, R.A.; Sheeraz, M.A.; Butt, Z.; Elahi, H.; Khan, A.A. Investigation of Electrical Properties for Cantilever-Based Piezoelectric Energy Harvester. Adv. Sci. Technol. Res. J. 2019, 13, 76–85.
44. Park, S.W.; Das, P.S.; Chhetry, A.; Park, J.Y. A Flexible Capacitive Pressure Sensor for Wearable Respiration Monitoring System. IEEE Sens. J. 2017, 17, 6558–6564.
45. Dinh, T.; Nguyen, T.; Phan, H.-P.; Nguyen, N.-T.; Dao, D.V.; Bell, J.; Dinh, T.; Nguyen, T.; Phan, H.-P.; Nguyen, N.-T.; et al. Stretchable respiration sensors: Advanced designs and multifunctional platforms for wearable physiological monitoring. Biosens. Bioelectron. 2020, 166, 112460.
46. Liu, X.; Zhao, C.; Zheng, B.; Guo, Q.; Duan, X.; Wulamu, A.; Zhang, D. Wearable Devices for Gait Analysis in Intelligent Healthcare. Front. Comput. Sci. 2021, 3, 42.

47. Majumder, S.; Mondal, T.; Deen, M.J. A Simple, Low-Cost and Efficient Gait Analyzer for Wearable Healthcare Applications. IEEE Sens. J. 2018, 19, 2320–2329.
48. Shelgikar, A.V.; Anderson, P.F.; Stephens, M.R. Sleep Tracking, Wearable Technology, and Opportunities for Research and Clinical Care. Chest 2016, 150, 732–743.
49. Peng, M.; Ding, Z.; Wang, L.; Cheng, X. Detection of Sleep Biosignals Using an Intelligent Mattress Based on Piezoelectric Ceramic Sensors. Sensors 2019, 19, 3843.
50. Li, Z.; Marks, H.; Evans, C.L.; Apiou-Sbirlea, G. Sensing, monitoring, and release of therapeutics: The translational journey of next generation bandages. J. Biomed. Opt. 2018, 24, 021201.