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Self-powered sensing for health monitoring and robotics

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Abstract

Self-powered sensing technology plays a key role in autonomous and portable systems, with applications in health monitoring and robotics. These sensors, which do not rely on external power sources, offer stable, continuous data acquisition for real-time monitoring and complex interactions. For instance, triboelectric nanogenerators have enabled self-powered wearable sensors to monitor vital signs such as heart beat rate and respiration by converting body movement into electrical energy, eliminating the need for batteries. Despite their advantages, challenges remain in large-scale manufacturing, miniaturization, and multifunctional integration. Overcoming these challenges may require innovative advances in novel materials, intelligent algorithms, and multifunctional integration strategies. This perspective summarizes recent advances and existing challenges in self-powered sensing technologies for health monitoring and robotics applications, and provides an outlook on their future development.

Keywords: Self-powered sensing, real-time monitoring, intelligent algorithms, human-machine interaction

INTRODUCTION

With the rapid growth of wearables and Internet of Things (IoT) technologies, there is a growing need for miniaturized and energy-efficient devices[1-5]. The demand for sensors goes beyond basic performance such as high sensitivity and real-time response. It focuses more on device autonomy, light weight, and low power consumption. However, traditional sensors typically rely on external power sources or battery power. This makes it difficult to meet the needs of emerging applications due to the high battery replacement and maintenance costs. Additionally, there is an environmental impact during long-term use and large-scale deployment. Therefore, it is highly desirable to develop self-powered sensors. Self-powered sensors can convert mechanical, thermal, or optical energy into electrical energy through energy harvesting technologies such as piezoelectric, triboelectric, or chemical energy[6-10]. These sensors work by capturing ambient energy from the surrounding environment and converting it into usable electrical power. For example, piezoelectric materials generate electric charge when subjected to mechanical stress or vibration, while triboelectric materials generate energy through friction or contact with other surfaces. Thermoelectric materials, on the other hand, convert temperature gradients into electrical energy, powering the sensor's operation and eliminating the need for external power sources. They offer environmental benefits by reducing electronic waste from battery disposal and ensuring sustainable use in remote areas without external power supply. Although initial development may be costly, they become more cost-effective over time due to savings on battery replacements and maintenance. Additionally, they greatly improve the applicability of sensors in passive, distributed environments, making them an ideal solution for IoT and wearable devices. Advances in flexible electronics have provided the technological foundation for research into self-powered flexible sensors. These technologies include highly bendable electronic components and circuits that can be integrated into clothing, skin patches or other soft surfaces. Self-powered flexible sensors are particularly suitable for use in areas such as continuous health monitoring and human-machine interaction (HMI) due to their lightweight and wearable nature, enabling more efficient and continuous collection of monitoring data[7,11-15].

As the attention to health and preventive medicine grows, traditional medical equipment and monitoring methods have struggled to meet the demand for real-time, continuous, and convenient monitoring. The demand for long-term, non-invasive health monitoring is especially significant in an aging society and chronic disease management. In this regard, wearable devices for health monitoring are rapidly gaining popularity. However, traditional sensors rely on batteries or external power sources, making it difficult to ensure uninterrupted monitoring for long periods and creating inconvenience in charging or replacing batteries regularly. In contrast, self-powered flexible sensors, with their soft, lightweight, and self-powered characteristics, can continuously acquire physiological information about the human body, such as heart rate, blood pressure, respiratory rate, temperature, *etc*., which meets the demand for long-term autonomy in health monitoring devices[16-19]. As health monitoring systems are increasingly integrated with robotics, synergies between self-powered sensors for wearables and self-powered sensors for robots are becoming more apparent. For example, self-powered sensors can be used not only for continuous health tracking, but also for robotic-assisted healthcare, such as monitoring vital signs during surgery or patient rehabilitation, while robots can help enhance sensor deployment and monitoring in complex environments. This creates a feedback loop in which improved sensor technologies for health monitoring can directly inform and enhance the capabilities of robotic systems in healthcare environments. Moreover, robots are gradually expanding from the industrial field to various scenarios such as medical, industrial manufacturing, and agriculture, with increasing requirements for environment sensing and human-robot interaction. As a result, intelligent robots now require highly sensitive sensors to perform delicate tasks, such as detecting the shape and hardness of objects, or even recognizing the characteristics of the surrounding environment. Traditional rigid sensors are unsuitable for applications on flexible robot surfaces and fail to meet complex sensing needs, such as tactile and force feedback. Self-powered flexible sensors, however, are suitable for robotic e-skin, providing high sensitivity and low power consumption for tactile and pressure sensing. This allows robots to operate autonomously and interact with the environment in complex ways without an external power supply, thereby enhancing their performance in HMI and environmental adaptation[20-23].

APPLICATIONS OF SELF-POWERED SENSING

Self-powered sensing for health monitoring

As the quality of life continues to improve, there is an increasing demand for self-health management that not only focuses on daily physical health but also aims for early disease prevention and non-invasive monitoring. Liu *et al.* constructed a self-powered knee monitoring system based on a dual ratchet structure using 3D printing technology [Figure 1A and B][24]. The dual ratchet sensing system reduces the weight and cost of the device and can be customized for users with different leg shapes to improve the user's long-term wearing experience. Using pawl-triboelectric nanogenerators (P-TENGs) and electromagnetic generators, the negative work generated during walking is converted into electrical energy to power the wearable device, while simultaneously outputting rotation angle data for high-precision rotation sensing of the knee joint. Additionally, the device can charge a 220 μF capacitor to 5 V in 180 s. Combining the sensing system with algorithms enables stable and continuous accurate monitoring of leg status, providing a solution for early prevention of lower limb functional decline. The combination of sensing technology with algorithms such as machine learning and signal processing can further improve the data analysis accuracy and information processing capability[25-29]. Zhang *et al.* embedded textile-based triboelectric sensors into socks for gait monitoring [Figure 1C][30]. By analyzing the collected data through deep learning techniques, they achieved walking pattern recognition and gait sensing of human activities, enabling long-term monitoring of the user's physical state. Five different human activities were detected with an accuracy of 96.67%.

In conventional health monitoring, a single mode of data collection is usually difficult to fully reflect an individual's health status and may miss potentially other important physiological information, thus reducing the accuracy of diagnosis. As our understanding of health status deepens and technology advances, multimodal data acquisition has gradually become a new trend in health monitoring[31,32]. Chen *et al.* proposed a self-powered flexible wearable wireless sensing system for heat stroke prevention and health monitoring in outdoor work [Figure 1D][33]. The system can monitor temperature, heart rate and blood oxygen, and assess the potential risk of heat stroke based on a multilayer perceptron model, realizing heat stroke prevention and health monitoring for outdoor workers. Through multimodal data collection, it is possible to capture a wider range of physiological changes in an individual and identify health trends and potential risks more accurately. The addition of self-powered sensing technology further enhances the convenience and continuity of multimodal monitoring and promotes the advancement of health monitoring in the direction of intelligence and refinement.

Self-powered sensing for robotics

With the rapid development of emerging technologies and artificial intelligence, traditional tactile sensing functions can no longer meet the high-level needs of modern intelligent robots. The future development of robots requires not only the ability to perceive the surrounding environment but also human-like cognitive capabilities to execute more complex tasks and facilitate human-robot collaboration. Therefore, enhancing the perception and cognitive ability of robots has become the focus of robotics research, and the extension of tactile perception to cognitive functions has also attracted much attention. Zhang *et al.* monitor the process of a robotic hand grasping an object by combining triboelectric and piezoresistive sensors to detect dynamic and static pressure [Figure 2A][22]. When further combined with neural network models, the system can recognize the type of object upon contact. The triboelectric component can be powered by harvesting energy from the environment, thus reducing the reliance on traditional power sources and

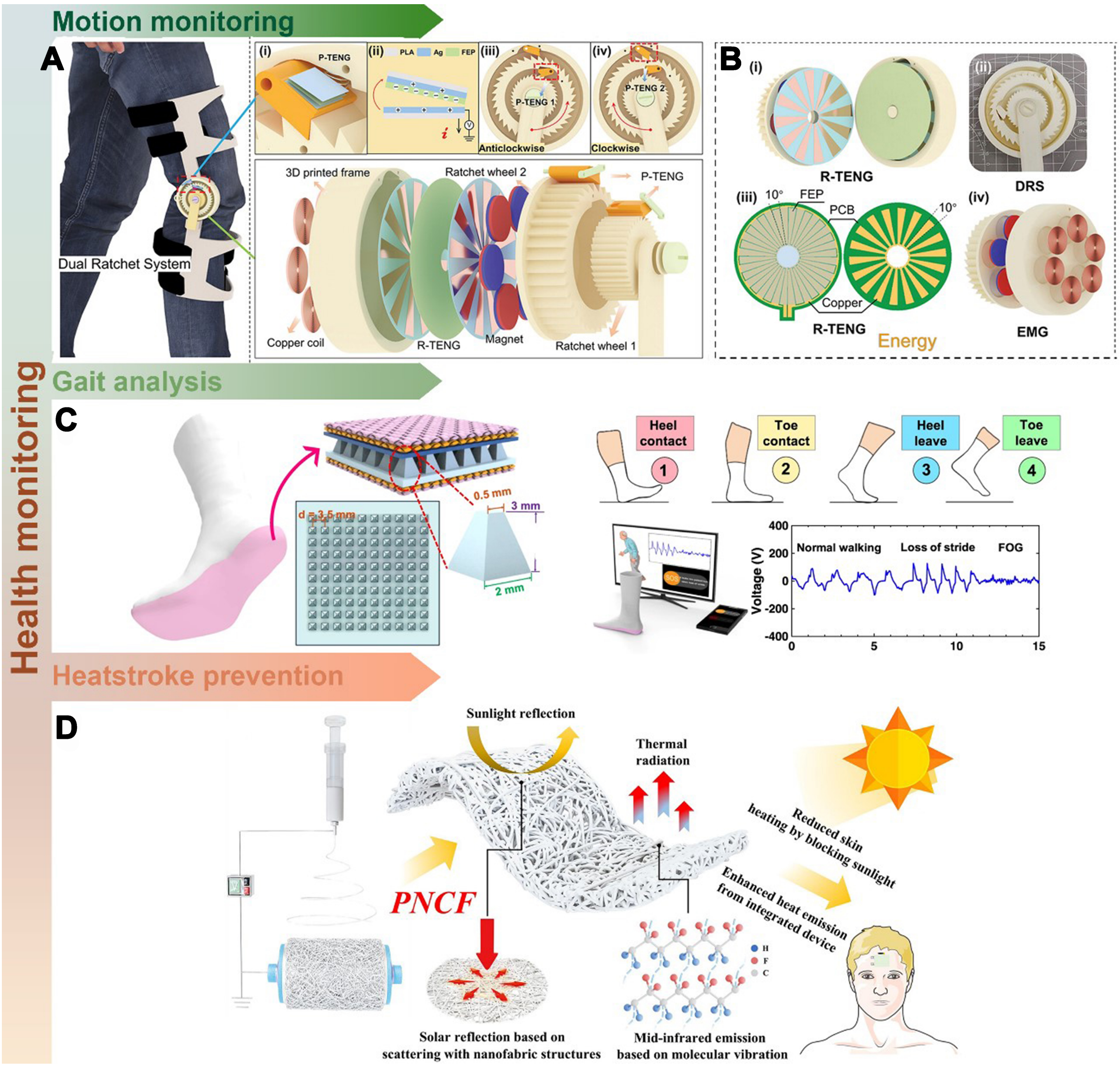

Figure 1. (A) Schematic diagram when wearing DRS system; (B) Photograph of DRS. Reproduced with permission[24]. Copyright 2024, Wiley-VCH; (C) Schematic diagram of smart sock. Reproduced with permission[30]. Copyright 2020, Springer Nature; (D) Schematic cooling mechanism of PVDF-HFD nanofibre cooling film and integrated devices. Reproduced with permission[33]. Copyright 2024, Elsevier. DRS: Dual ratchet sensing; PVDF-HFD: polyvinylidene fluoride-hexafluoropropylene copolymer.

further increasing the sustainability of the system. Meanwhile, the piezoresistive section exhibits a clear and stable current curve after about 4,500 consecutive shocks. This research provides a new direction for the further development of tactile sensing and cognitive functions in robots. The significance of self-powered sensors is that they reduce the power consumption of the measurement system. However, the complex processing and high transmission of sensed data often lead to high energy consumption in signal processing and wireless communication units. Notably, Wang *et al.* proposed an autonomous wake-up wireless sensing system [Figure 2B-D][34]. Due to the autonomous wake-up of the TENG, the average power consumption of the wireless transmitter can be as low as 4 mW. In this system, the TENG signal serves as a trigger to record the voltage amplitude of the piezoelectric nanogenerators (PENGs) as angle sensing data for wireless transmission. The wireless receiver receives the data from the wearable bending sensor and can control the robotic arm to bend to the same angle as the human finger. By reducing redundant data and generating

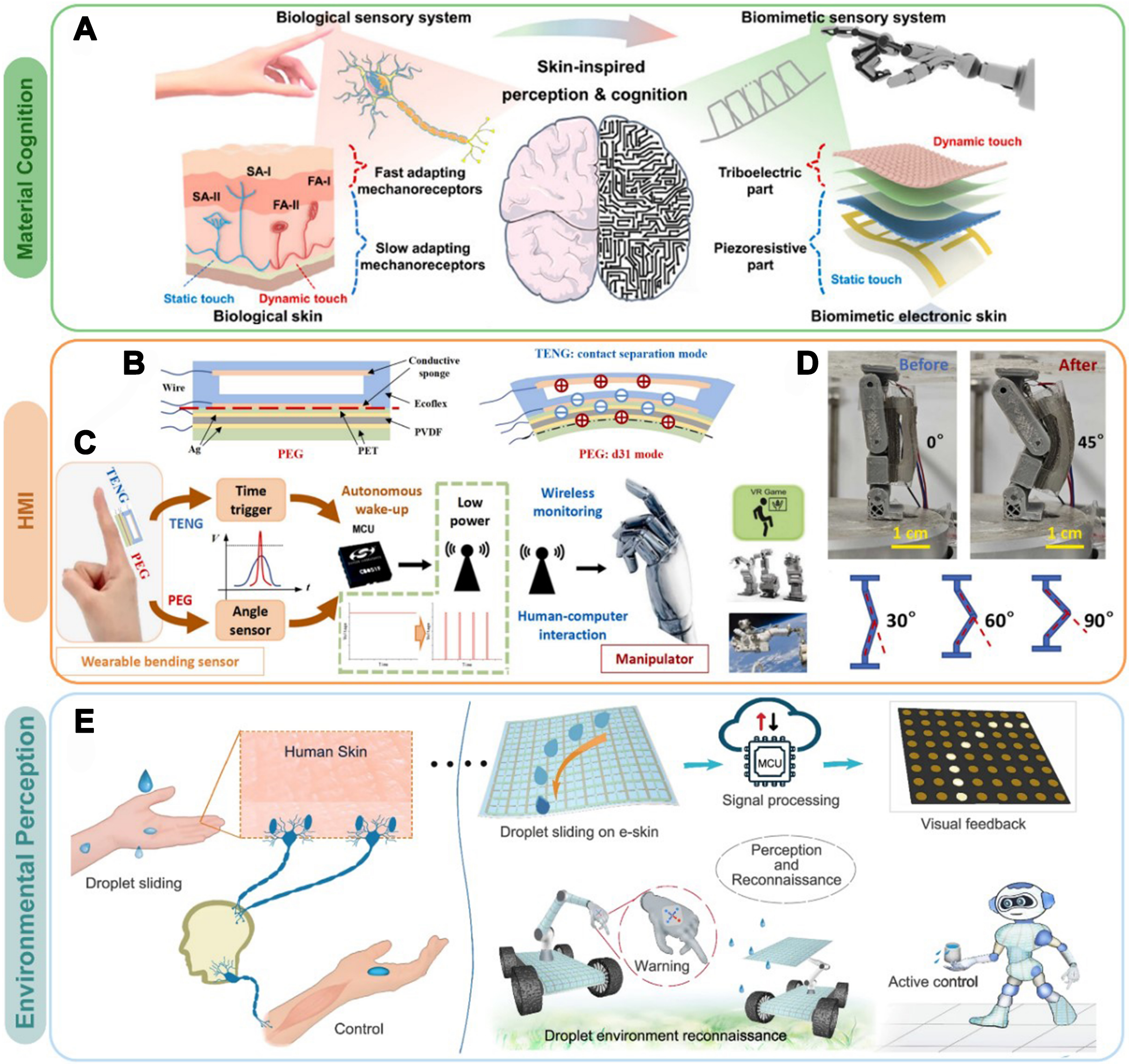

Figure 2. (A) Integration of triboelectric and piezoresistive components enables dynamic and static pressure sensing for cognitive processing. Reproduced with permission[22]. Copyright 2024, American Chemical Society; (B) Wearable hybrid nanogenerators; (C) Principles of robotic systems and application concepts; (D) Machine in a bent state. Reproduced with permission[34]. Copyright 2023, Elsevier; (E) Schematic diagram of the human tactile nervous system and the bionic droplet e-skin system. Reproduced with permission[35]. Copyright 2024, Springer Nature.

concise and accurate sensing information on the hardware side, the sensor effectively reduces the computational burden and power consumption for wireless transmission.

As an efficient aid to human work, robots provide effective support in diverse task scenarios and have become indispensable technological tools in modern industry and services. The basis for intelligent robots to acquire external information lies in their perception module, which consists of distributed sensor nodes and integrated bionic electronic skin. Bionic electronic skin senses various physical information of the surrounding environment by mimicking the unique functions of human skin. It offers significant advantages in flexibility and multimodal sensing, enhancing its potential for application in complex environment sensing and multitasking. Xu *et al.* proposed a self-powered bionic droplet electronic skin for droplet environment reconnaissance, which is based on triboelectricity to convert various dynamic droplet sliding behaviors to electrical signals, providing intelligent robots with comprehensive sensing of droplet sliding [Figure 2E][35]. The flexible bionic e-skin can be attached to non-planar surfaces of robotic devices to provide delicate feedback to external stimuli, realizing an intelligent flow warning system inspired by human neuromodulation and a droplet leakage closed-loop control system. By mimicking the complex functions of human skin, the bionic electronic skin significantly improves the tactile perception of the robot, bringing it closer to the level of human perception[36,37]. This allows the robot to have a more three-dimensional and comprehensive understanding of the surrounding environment, and promotes the development of the robot towards a more intelligent, flexible and adaptable to complex environments. Additionally, self-powered sensing technologies can provide continuous, real-time data for autonomous decision-making, thus enhancing the integration of artificial intelligence in robotics. By using visual, tactile or acoustic sensors, robots can collect continuous information about their environment, which artificial intelligence algorithms analyze to optimize behavior.

CONCLUSION AND FUTURE PERSPECTIVES

The development of self-powered sensing technology shows promising potential in health monitoring and robotics. By integrating energy harvesting and sensing functions, this technology eliminates the reliance of traditional sensors on external power sources, enabling wearables, non-invasive medical devices and smart robots to gain significant application flexibility. In health monitoring, self-powered sensors can continuously capture physiological signals such as heart rate, blood pressure and respiratory rate to support personalized medicine and remote diagnosis. In robotics, such sensors open up new possibilities for perception and adaptability in soft robots, autonomous devices, and human-robot interactions through energy self-supply and multifunctional design. Although considerable progress has been made with self-powered sensors, there are still some significant technical challenges [Figure 3].

(1) Miniaturization and integration: Self-powered sensors show great potential for miniaturization and integration, achieving breakthroughs in low-power consumption, multimodal sensing and high adaptability by integrating energy harvesting, sensing, signal processing and wireless communication into a compact system, bringing flexibility and intelligence to health monitoring and robotics. However, miniaturization poses serious challenges in terms of energy harvesting efficiency, signal quality and heat management. A high degree of integration increases the complexity of module compatibility and manufacturing processes. Nonetheless, with the deep integration of nanofabrication, flexible materials, and artificial intelligence, these issues are expected to be gradually resolved. By introducing nanoscale structures, such as nanowires, nanotubes, or nanoparticles, the surface area and mechanical properties of the material can be significantly increased, thus enhancing the energy harvesting efficiency.

(2) Hardware performance: Self-powered sensing technologies currently still have hardware performance limitations. Many advanced sensor technologies, such as high-precision tactile or multimodal sensing sensors, usually require high power consumption to maintain their sensing performance. The energy harvesting capabilities of existing self-powered systems usually cannot meet the demands of these high power consumption sensors, resulting in limited sensor performance. Despite the availability of multiple energy harvesting methods, the challenge remains in effectively storing the harvested energy and releasing it stably when needed. As flexible sensors are widely used in wearable devices and robotic systems, the development of flexible energy storage devices compatible with them has become an important research direction. For example, flexible thin-film batteries or supercapacitors can provide stable electrical energy to self-powered sensors while maintaining the flexibility and light weight of the devices. In the future, the development and optimization of multiple energy harvesting methods, research in energy storage

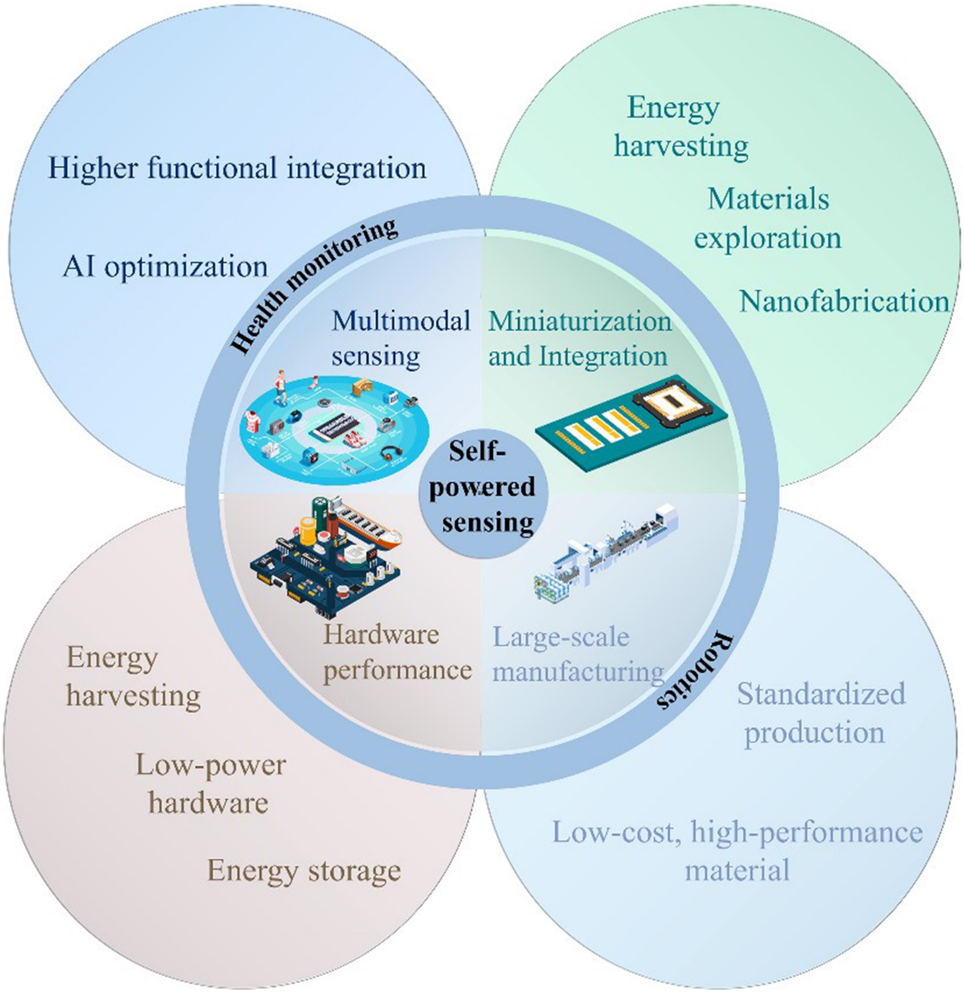

Figure 3. Challenge and future perspectives of self-powered sensing for health monitoring and robotics.

technologies, and improvements in low-power technologies will overcome the limitations of hardware performance.

(3) Large-scale manufacturing: Self-powered sensors face multiple challenges in large-scale manufacturing, including the preparation and consistency of high-performance materials, cost control of complex manufacturing processes, and balancing miniaturization, flexibility and reliability in large-scale production. In addition, the diverse needs for sensor performance and integration in different application scenarios also increase the difficulty of design and production. Utilizing conductive polymers, nanomaterials (e.g., graphene and carbon nanotubes), and other high-performance materials can improve the flexibility and electrical properties of sensors and ensure the consistency of the materials in mass production. Nevertheless, with the ongoing advancement of flexible electronics, printed manufacturing and 3D printing technologies, the technical bottleneck of mass production is gradually being overcome[38,39]. With standardized production processes and low-cost, high-performance material systems, self-powered sensors are expected to become widely available on a large scale, providing broader support for healthcare, robotics, and the IoT.

(4) Multimodal sensing: As the demand for multidimensional sensing grows in areas such as health monitoring, intelligent robotics and human-computer interaction, the limitations of single sensors have become particularly prominent, rendering them inadequate for complex application scenarios. This challenge has led to the rapid development of self-powered multimodal sensor technology, establishing it as a key solution for integrating multiple sensing capabilities[40]. Researchers have not only improved the efficiency of sensing multiple signals (including pressure, temperature, vibration, *etc.*), but have also achieved effective synergy and signal decoupling between different sensing mechanisms. However, multimodal sensing requires devices to monitor multiple types of data simultaneously, which not only increases energy demand, but also complicates sensor design and data synchronization. Additionally, space constraints and structural complexity pose challenges for practical applications. The employment of composites based on graphene, carbon nanotubes or other nanomaterials enables the integration of multiple sensing functions in the same sensor, reducing size and increasing integration. Hence, the development of efficient energy harvesting materials, smart sensing materials with higher functional integration, and the use of artificial intelligence to optimize the sensing and decoupling of multimodal signals will be the key directions to promote self-powered sensing technology for industrial applications.

In the development of self-powered sensors, the short-term goal is to improve the energy conversion efficiency and the sensitivity of the sensors, achievable through the optimization of material combinations and microstructure design. Long-term sustainability of self-powered sensors requires mass production and widespread adoption, especially in wearable devices and remote monitoring systems. Collaboration with industry and regulatory bodies is critical, as they provide the necessary technical support and guidance on standardization while ensuring product safety and reliability. Additionally, such partnerships can accelerate the marketing and adoption of new technologies, especially in meeting specific industry standards and regulatory requirements. Through these collaborations, it becomes possible to respond more effectively to market needs and drive technological innovation and commercialization.

DECLARATIONS

Authors' contributions

Wrote the original draft: Liu, S. Z.; Guo, W. T.
Supervised, reviewed, and revised the manuscript: Zhao, X. H.; Tang, X. G.; Sun, Q. J.

Availability of data and materials

Not applicable.

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Conflicts of interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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REFERENCES

1. Zhang, S.; Rana, S. S.; Bhatta, T.; et al. 3D printed smart glove with pyramidal MXene/Ecoflex composite-based toroidal triboelectric nanogenerators for wearable human-machine interaction applications. *Nano. Energy*. **2023**, *106*, 108110. DOI
2. Li, M.; Wan, Z.; Zou, T.; et al. Artificial intelligence enabled self-powered wireless sensing for smart industry. *Chem. Eng. J.* **2024**, *492*, 152417. DOI
3. Guo, W.; Lei, Y.; Zhao, X.; et al. Printed-scalable microstructure $BaTiO_3$/ecoflex nanocomposite for high-performance triboelectric nanogenerators and self-powered human-machine interaction. *Nano. Energy*. **2024**, *131*, 110324. DOI
4. Lu, B.; Xie, L.; Lei, H.; et al. Research progress in self-powered pressure sensors for internet of healthcare. *Adv. Mater. Technol.* **2024**, *9*, 2301480. DOI
5. Zhao, L.; Guo, X.; Pan, Y.; et al. Triboelectric gait sensing analysis system for self-powered IoT-based human motion monitoring. *InfoMat* **2024**, *6*, e12520. DOI
6. Liu, S. Z.; Guo, W. T.; Chen, H.; Yin, Z. X.; Tang, X. G.; Sun, Q. J. Recent progress on flexible self-powered tactile sensing platforms for health monitoring and robotics. *Small* **2024**, *20*, e2405520. DOI PubMed
7. Su, Y.; Chen, G.; Chen, C.; et al. Self-powered respiration monitoring enabled by a triboelectric nanogenerator. *Adv. Mater.* **2021**, *33*, e2101262. DOI
8. Zhu, J.; Zhou, C.; Zhang, M. Recent progress in flexible tactile sensor systems: from design to application. *Soft. Sci.* **2021**, *1*, 3. DOI
9. Zhu, H.; Liang, J.; Huang, J.; Chen, Z. Triboelectric haptic sensors based on fluorinated cellulose/PDMS composite porous films for monitoring joint flexion and smart writing. *Nano. Energy*. **2024**, *127*, 109735. DOI
10. Ren, M.; Guo, D.; Wang, Q.; et al. Recent advances in self-powered sensors based on nanogenerators: from material and structural design to cutting-edge sensing applications. *ACS. Appl. Electron. Mater*. **2024**, *6*, 3955-97. DOI
11. Kwak, W.; Yin, J.; Wang, S.; Chen, J. Advances in triboelectric nanogenerators for self-powered wearable respiratory monitoring. *FlexMat* **2024**, *1*, 5-22. DOI
12. Yeh, C.; Kao, F.; Wei, P.; et al. Bioinspired shark skin-based liquid metal triboelectric nanogenerator for self-powered gait analysis and long-term rehabilitation monitoring. *Nano. Energy*. **2022**, *104*, 107852. DOI
13. Liu, S.; Qing, W.; Zhang, D.; et al. Flexible staircase triboelectric nanogenerator for motion monitoring and gesture recognition. *Nano. Energy*. **2024**, *128*, 109849. DOI
14. Noor, A.; Sun, M.; Zhang, X.; et al. Recent advances in triboelectric tactile sensors for robot hand. *Mater. Today. Phys*. **2024**, *46*, 101496. DOI
15. Hao, D.; Gong, Y.; Wu, J.; et al. A self-sensing and self-powered wearable system based on multi-source human motion energy harvesting. *Small* **2024**, *20*, e2311036. DOI
16. Yang, X.; Chen, W.; Fan, Q.; et al. Electronic skin for health monitoring systems: properties, functions, and applications. *Adv. Mater.* **2024**, *36*, e2402542. DOI
17. Lai, Q. T.; Zhao, X. H.; Sun, Q. J.; Tang, Z.; Tang, X. G.; Roy, V. A. L. Emerging MXene-based flexible tactile sensors for health monitoring and haptic perception. *Small* **2023**, *19*, e2300283. DOI PubMed
18. Li, J.; Jia, H.; Zhou, J.; et al. Thin, soft, wearable system for continuous wireless monitoring of artery blood pressure. *Nat. Commun.* **2023**, *14*, 5009. DOI PubMed PMC
19. Meng, K.; Xiao, X.; Wei, W.; et al. Wearable pressure sensors for pulse wave monitoring. *Adv. Mater.* **2022**, *34*, e2109357. DOI PubMed
20. Qu, J.; Cui, G.; Li, Z.; et al. Advanced flexible sensing technologies for soft robots. *Adv. Funct. Mater.* **2024**, *34*, 2401311. DOI
21. Sun, Z.; Zhu, M.; Shan, X.; Lee, C. Augmented tactile-perception and haptic-feedback rings as human-machine interfaces aiming for immersive interactions. *Nat. Commun.* **2022**, *13*, 5224. DOI PubMed PMC
22. Zhang, H.; Li, H.; Li, Y. Biomimetic electronic skin for robots aiming at superior dynamic-static perception and material cognition based on triboelectric-piezoresistive effects. *Nano. Lett.* **2024**, *24*, 4002-11. DOI
23. Pang, Y.; Xu, X.; Chen, S.; et al. Skin-inspired textile-based tactile sensors enable multifunctional sensing of wearables and soft robots. *Nano. Energy*. **2022**, *96*, 107137. DOI
24. Liu, C.; Gu, R.; Yang, J.; et al. A self-powered dual ratchet angle sensing system for digital twins and smart healthcare. *Adv. Funct. Mater.* **2024**, *34*, 2405104. DOI
25. Zhang, Z.; Liu, X.; Zhou, H.; Xu, S.; Lee, C. Advances in machine-learning enhanced nanosensors: from cloud artificial intelligence toward future edge computing at chip level. *Small. Struct.* **2024**, *5*, 2300325. DOI
26. Lee, J. P.; Jang, H.; Jang, Y.; et al. Encoding of multi-modal emotional information via personalized skin-integrated wireless facial interface. *Nat. Commun.* **2024**, *15*, 530. DOI PubMed PMC
27. Jiang, Y.; An, J.; Liang, F.; et al. Knitted self-powered sensing textiles for machine learning-assisted sitting posture monitoring and correction. *Nano. Res.* **2022**, *15*, 8389-97. DOI
28. Wei, C.; Cheng, R.; Ning, C.; et al. A self-powered body motion sensing network integrated with multiple triboelectric fabrics for biometric gait recognition and auxiliary rehabilitation training. *Adv. Funct. Mater.* **2023**, *33*, 2303562. DOI

29. Zhang, M.; Yan, W.; Ma, W.; Deng, Y.; Song, W. Self-powered hybrid motion and health sensing system based on triboelectric nanogenerators. *Small* **2024**, *20*, e2402452. DOI
30. Zhang, Z.; He, T.; Zhu, M.; et al. Deep learning-enabled triboelectric smart socks for IoT-based gait analysis and VR applications. *npj. Flex. Electron.* **2020**, *4*, 92. DOI
31. Tu, J.; Wang, M.; Li, W.; et al. Electronic skins with multimodal sensing and perception. *Soft. Sci.* **2023**, *3*, 24. DOI
32. Liao, Y.; Xue, C.; Zhang, H. Self-powered wearable remote control system based on self-adhesive, self-healing, and tough hydrogels. *Nano. Energy.* **2024**, *131*, 110262. DOI
33. Chen, X.; Wan, Z.; Zhang, R.; Ma, L.; Yang, Z.; Xiao, X. Self-powered flexible wearable wireless sensing for outdoor work heatstroke prevention and health monitoring. *Chem. Eng. J.* **2024**, *499*, 156431. DOI
34. Wang, L.; Fei, Z.; Wu, Z.; et al. Wearable bending wireless sensing with autonomous wake-up by piezoelectric and triboelectric hybrid nanogenerator. *Nano. Energy.* **2023**, *112*, 108504. DOI
35. Xu, Y.; Sun, Z.; Bai, Z.; et al. Bionic e-skin with precise multi-directional droplet sliding sensing for enhanced robotic perception. *Nat. Commun.* **2024**, *15*, 6022. DOI PubMed PMC
36. Duan, S.; Zhang, H.; Liu, L.; et al. A comprehensive review on triboelectric sensors and AI-integrated systems. *Mater. Today.* **2024**, *80*, 450-80. DOI
37. Wen, F.; Wang, C.; Lee, C. Progress in self-powered sensors - moving toward artificial intelligent and neuromorphic system. *Nano. Res.* **2023**, *16*, 11801-21. DOI
38. Shao, B.; Lu, M. H.; Wu, T. C.; et al. Large-area, untethered, metamorphic, and omnidirectionally stretchable multiplexing self-powered triboelectric skins. *Nat. Commun.* **2024**, *15*, 1238. DOI PubMed PMC
39. Park, H.; Gbadam, G. S.; Niu, S.; Ryu, H.; Lee, J. Manufacturing strategies for highly sensitive and self-powered piezoelectric and triboelectric tactile sensors. *Int. J. Extrem. Manuf.* **2025**, *7*, 012006. DOI
40. Zhu, M.; Sun, Z.; Lee, C. Soft modular glove with multimodal sensing and augmented haptic feedback enabled by materials' multifunctionalities. *ACS. Nano.* **2022**, *16*, 14097-110. DOI PubMed