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Review on Multifunctional properties of self-powered electronic skin

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Abstract:

In recent years, with the rapid development of wearable devices, smart materials and flexible electronics, self-powered electronic skin has received widespread attention as a novel multifunctional sensor platform.. Self-powered electronic skin is mainly based on the piezoelectric effect (PE), thermoelectric effect (TE) and photoelectric effect (OE) and other physical mechanisms By converting mechanical, thermal and light energy in the environment into electrical energy, it can achieve self-sufficiency in energy supply. This paper will discuss the multifunctional characteristics of self-powered electronic skin, especially its application potential in health monitoring, environmental monitoring and smart wearable devices. Self-powered electronic skin is mainly based on the piezoelectric effect (PE), thermoelectric effect (TE) and photoelectric effect (OE) and other physical mechanisms, by converting mechanical, thermal and light energy in the environment into electrical energy, it can achieve self-sufficiency in energy supply. This technology not only shows important application value in the field of physiological signal monitoring and disease early warning, but also provides a new research direction for future personalized medicine, environmental protection and smart device design.

Keywords: Self-powered electronic skin; Wearable devices; Smart materials.

1. Introduction

Self-Powered Electronic Skin (SPEK) is bringing new opportunities and challenges to smart sensors, wearable devices and human-computer interaction technology. While traditional electronic devices often rely on external power sources for electricity, which limits their portability and adaptability, self-powered electronic skins achieve energy self-sufficiency through the integration of advanced self-powered mechanisms. This technology relies on energy-converting materials such as nanogenerators (NGs), which can effectively convert ambient energy (such as mechanical, thermal or light energy) into electricity, which can support the operation of a variety of functional sensors. In this context, self-powered e-skins demonstrate significant advantages in real-time monitoring of physiological parameters, envi-

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ronmental changes, and physical signals [1]. For example, a self-powered electronic skin based on the piezoelectric effect can automatically generate electricity to drive the sensor when sensing changes in touch or pressure, making it promising for a wide range of applications in the fields of health monitoring/power supply for implanted devices and smart medicine. Self-powered electronic skin (SPEK) is a cutting-edge research direction in the field of flexible electronics and biomedical engineering, which is basically defined as a smart surface material that can be self-powered, sense the environment and have some biological properties [2]. SPEK is usually composed of multiple functional layers, including a sensing layer, a power layer and a signal processing layer, which enables it to monitor physiological signals and environmental changes in real time. These functional layers achieve energy acquisition and application through active and passive mechanisms, especially through biodynamics or the energy conversion means of the external environment (such as temperature, humidity, pressure, etc.), making them self-powered.

As a new flexible electronic device, self-powered electronic skin has shown great potential in the fields of smart wearable devices, robot tactile perception and biomedical monitoring in recent years. According to a comprehensive literature analysis, current research hotspots of self-powered electronic skin focus on energy harvesting technology, sensor performance optimization and material innovation [3]. However, despite the remarkable progress, there are still significant differences in technology development and application in different countries and regions.

Globally, research progress shows clear geographical differences. In Asian, such as Japan and South Korea, researchers focus on the efficiency of energy harvesting and surplus utilization, taking advantage of the high conversion efficiency of “Piezoelectric Materials” and “Thermoelectric Materials”. They have successfully developed a variety of wearable self-powered systems. For example, high-performance polyelectrolyte materials are designed to increase the output power of piezoelectric devices, which can be further applied in health monitoring. The application of nanomaterials has enhanced energy storage capabilities, laying the foundation for the long-term use of electronic skin. In Europe and the United States, researchers are paying more attention to material innovation, especially the application of flexible and nanomaterials, to improve the sensitivity and durability of devices. These technological advances lay the foundation for a wide range of future applications in fields such as medical care, robotics and environmental monitoring.

This article will delve into the multifunctional properties of self-powered electronic skin and its application potential. First, the second part will introduce the basic definition of self-powered electronic skin and its development status. The third part will elaborate on its working principle, including the core mechanism of piezoelectric effect, thermoelectric effect and photoelectric effect. In the fourth part, the multifunctional characteristics and application prospects of self-powered electronic skin in environmental monitoring, health monitoring and wearable devices will be analyzed. Finally, in the fifth part, the future development trend of self-powered electronic skin will be summarized and prospected, pointing out the direction for further research and application.

2. The working principle of self-powered electronic skin

Self-powered electronic skin converts mechanical, thermal, and light energy into electricity through piezoelectric, thermoelectric, and photoelectric effects. Material innovations enhance energy conversion efficiency, driving the multifunctional development of this technology.

2.1 Piezoelectric effect

In the research of self-powered electronic skin, the piezoelectric effect is an important energy conversion mechanism. In general, nanogenerators (NG) can convert mechanical energy into electrical energy according to the piezoelectric effect (PENG) [4-6]. The basic principle is that some materials can generate electric charge when subjected to external pressure or mechanical deformation, so as to achieve electrical energy conversion of mechanical energy. This phenomenon provides an extremely important power source for the self-powered electronic skin, which in turn promotes the development of flexible electronic devices.

2.2 Thermoelectric effect

In the working principle of the self-powered electronic skin, the thermoelectric effect, as an important energy conversion mechanism, plays a crucial role in the construction and functional realization of the electronic skin. Thermoelectric Effect refers to the fact that when one end of the material is affected by the temperature difference, the electric potential difference will be generated at both ends, so as to realize the direct conversion of temperature gradient and electric energy. In recent years, ZnO, PZT, KNbO3 and PVDF have been widely used in the production of PyNG (Pyroelectric nanogenerators) [7-12]. Since PyNG does not experience mechanical deformation like piezoelectric nanogenerators (PENG) and triboelectric nanogenerators (TENG), it does not encounter difficulties in terms of the operational performance of the device.

2.3 Photoelectric effect

The self-powered electronic skin utilizes Photoelectric Effect to generate electric energy, which provides an important support for its multi-functional characteristics. In terms of optimizing the photoelectric conversion efficiency, there are a variety of innovative strategies, the implementation of which can significantly improve the overall performance of the system and have the potential for practical application.

In recent years, the rise of two-dimensional materials such as “transition metal sulfides (TMDs)” and “Graphene” have been widely used in optoelectronic components due to their excellent electrical conductivity, flexibility and feasibility of large area synthesis. Such materials have excellent performance in broad spectrum light absorption and high carrier mobility, which can effectively improve the photoelectric conversion efficiency. For example, some studies have shown that the photocurrent density can be improved by more than 30% by applying a “nitrogen-doped Graphene” to an optoelectronic conversion layer.

3. The multifunctional properties of self-powered e-skins

Fig. 1 shows the relationship between different energy sources and applications of self-powered multifunctional e-skin. It is divided into two parts in this article, including environmental monitoring and health monitoring two parts.

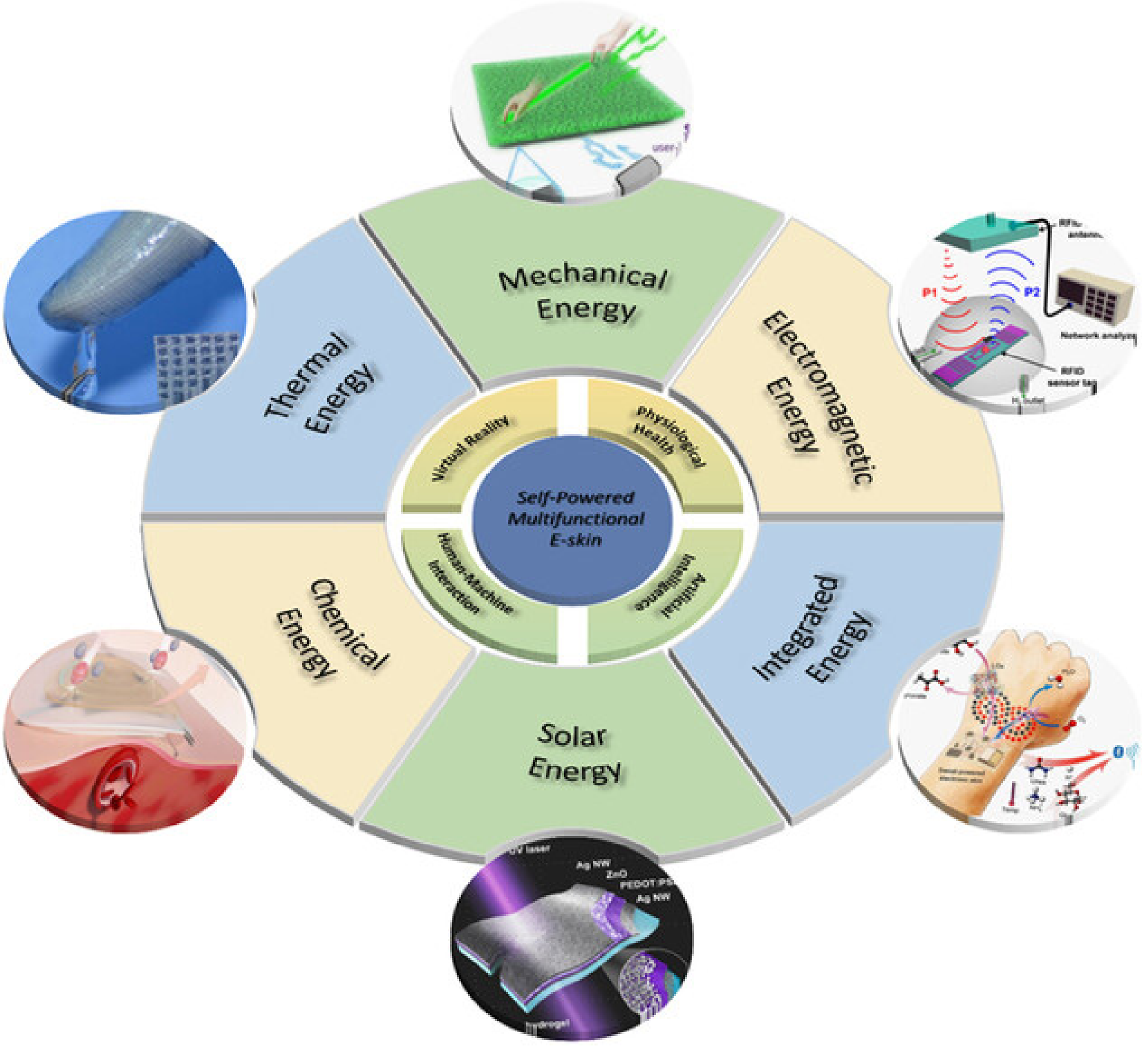

Fig. 1 Relationship between different energy sources and applications of self-powered multifunctional e-skin [13-18].

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3.1 Environmental monitoring

Self-powered electronic skin shows its excellent multi-functional characteristics in the field of temperature monitoring. This technology realizes efficient and real-time temperature monitoring in multiple application scenarios through innovative sensor design and energy harvesting mechanism [19]. Its core principle is to use the electrical signal output caused by temperature changes to achieve accurate measurement of the ambient temperature, and can realize remote real-time monitoring of data through wireless transmission technology (such as Bluetooth or Wi-Fi).

In terms of home security monitoring, the application of self-powered electronic skin can effectively monitor the indoor environmental temperature and warn family members of potential fire hazards in real time. For example, a number of household appliances will send abnormal signals in the state of high temperature, and the deployment of electronic skin with temperature sensors can give timely warning before the fire occurs, greatly improving the level of family security. Studies have shown that the response speed of the temperature sensor can reach the millisecond level, which lays a solid foundation for the establishment of a rapid response mechanism and helps realize the development and application of intelligent alarm systems.

Self-powered electronic skin has shown a wide range of application potential in the field of chemical pollutant detection, especially in the field of industrial and environmental science, and its multi-functional characteristics give it a significant advantage in real-time monitoring and feedback. The core of this emerging technology lies in its integrated self-powered system, which usually relies on self-powered mechanisms such as “piezoelectric effect (PE)” or “thermoelectric effect (TE)” to achieve independent operation without external power sources, providing feasibility for long-term environmental monitoring.

In the detection of chemical pollutants, the self-powered e-skin enhances its selectivity and sensitivity to target chemicals through functionalized sensitive membranes such as “nanomaterials (NM)” such as “graphene (G)” or “Gold nanoparticles (AuNP)”. For example, the use of functionalized graphene sensors can effectively identify “heavy metal ions (HMIs)” in water, and the high specific surface area and excellent conductivity of this material enable it to show high sensitivity at low concentrations. The miniaturization of the structure and the diversity of materials allow the e-skin to adapt to the needs of chemical detection in a variety of complex environments.

3.2 Health monitoring

As a cutting-edge technology, Self-powered Electronic Skin (SES) has gradually shown great application potential in many fields such as environmental monitoring, health monitoring and wearable devices with its unique multi-functional characteristics. The multi-functional characteristics of self-powered electronic skin are not only reflected in its sensitive response to changes in the external environment, but also in providing real-time data and wireless transmission capabilities to complement each other. These characteristics enable the self-powered electronic skin to play a role in a wider range of application scenarios and provide strong technical support for future intelligent systems [20].

In terms of environmental monitoring, self-powered electronic skin can achieve accurate detection of various environmental parameters [21]. Take temperature monitoring as an example. SES integrated temperature sensor converts temperature difference into electrical energy by Thermoelectric Effect, thus driving the sensor to achieve real-time monitoring of environmental temperature. Through the use of different types of sensing materials, SES is also able to effectively detect chemical pollutants, such as Volatile Organic Compounds (VOCs). These environmental monitoring capabilities not only help to improve the efficiency of ecological environment governance, but also contribute data base to the construction of smart cities.

In the field of health monitoring, self-powered electronic skin has shown significant application prospects. Using physiological sensors, self-powered electronic skin can monitor users’ physiological parameters in real time, such as Heart Rate and Blood Oxygen Saturation [22]. This monitoring method not only provides a new idea for disease prevention, but also can be used for exercise parameter monitoring, such as real-time feedback of exercise status and physical fitness, to help users adjust exercise plans. With the development of data processing technology, SES has more and more significant potential in disease prevention and diagnosis. Through data analysis and pattern recognition technology, SES can realize intelligent identification and early warning of early symptoms, and greatly improve the intelligent level of health management.

The application of self-powered electronic skin in wearable devices indicates the forward development of intelligent life [23]. Self-powered electronic skin can be widely used in Smart Clothing, Smartwatch and Wearable Bands, etc., to promote the intelligent human-computer interaction. For example, through SES integrated in smart clothing, users can obtain their own movement data in real time, and synchronize to the cloud for analysis and processing through intelligent terminals. At the same time, in the field of sports and fitness, SES can help athletes record and analyze data to optimize training results. In the application of medical rehabilitation equipment, SES can monitor the physiological indicators of patients in real time and promote the realization of personalized medicine.

Self-powered electronic skin not only relies on its superior perception ability, but also provides opportunities for applications in different fields with its versatility in external environment and health monitoring. By combining a variety of sensing technologies and energy conversion principles, the multi-dimensional characteristics of SES show great research value and application prospects, and lay a solid foundation for the future development of adaptive and intelligent technology.

The technological advancement of self-powered electronic skin shows its multi-functional properties in disease prevention and diagnosis [24]. This new type of e-skin usually consists of flexible sensors, self-supplying Energy systems and intelligent processing units. It relies on technologies such as “Sensor Networks” and “Energy Harvesting”. The core of this kind of e-skin is the ability to monitor human health in real time, In order to predict the occurrence of disease through data analysis.

For example, studies have shown that electronic skin can record physiological parameters, such as heart rate, body temperature, and electrical activity of the skin. The real-time monitoring of this data allows software algorithms, such as “Machine Learning” algorithms, to effectively analyse time series data and identify potential health risks, thereby warning of disease at an early stage. In the case of heart disease, studies have found that continuous monitoring of heart rate and electrodermal response can lead to interventions and treatments in the critical time window before a heart attack, greatly improving patient survival.

In recent years, with the rapid development of self-powered electronic skin technology, the application of motion parameter monitoring has attracted more and more attention from scientific research and industry [25]. The micro-sensor network and energy collection technology adopted by self-powered electronic skin make it have significant advantages in dynamic monitoring of motion parameters [26]. Studies have shown that using a hybrid energy harvesting mechanism based on “piezoelectric effect (PE)” and “thermoelectric effect (TE)”, not only can a lasting energy supply be obtained, but also a variety of motion parameters such as gait, heart rate and muscle activity can be monitored in real time.

In the practice of sports fitness and rehabilitation training, self-powered electronic skin can greatly improve training results by accurately capturing exercise data and providing personalized feedback and evaluation. For example, a sports data analysis tool based on “dynamic signal processing (DSP)” can efficiently extract information such as acceleration, angular velocity and displacement generated during exercise, providing a scientific basis for the optimization of athletes’ performance. Taking a high-level track and field athlete as an example, by implanting self-powered electronic skin on the surface of his lower limbs, relevant studies have shown that the athlete’s stride length and stride frequency have significantly increased by 14% and 10%, which indicates that accurate guidance can be achieved through scientific data monitoring [27].

4. Future application scenarios

4.1 Wearable devices

The rise of Self-Powered Electronic Skin (SPES) technology provides unprecedented opportunities for the design and application of smart clothing [28]. Through efficient energy collection and utilization mechanism, this kind of electronic skin can not only monitor physiological parameters in real time, but also enhance the user’s wearing experience and realize applications in a variety of scenarios. Its multi-functional characteristics are mainly reflected in three aspects: physiological signal monitoring, power feedback function and environmental perception ability.

SPES plays an important role in physiological signal monitoring. By integrating micro-sensors and Advanced Materials, electronic skin can accurately capture physiological data such as heart rate, skin temperature, and sweat composition [29]. The self-powered nature of the technology ensures stability over the long term. This ability to monitor in real time is especially important for tracking athletes’ training status and managing the health of the elderly, and can provide important data support for Personalized Medicine.

The application prospect of Self-powered Electronic Skin (SES) in smart watches and wristbands is particularly extensive and full of potential, mainly reflected in several core dimensions to improve the combination of comfort and functionality. The use of self-powered mechanisms such as “Piezoelectric Effect” and “Thermoelectric Effect” can effectively reduce the dependence on external batteries, thereby achieving lightweight design and extending the service time of the device. This self-powered capability enables the device to be competitive on environmental sustainability, further promoting market acceptance and improving user experience.

The self-powered electronic skin shows great potential in the field of sports and fitness due to its unique material properties and energy self-supply ability. This kind

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of electronic skin is based on “flexible electronics” and can withstand high strength stretching and deformation, so as to adapt to the wearing needs of various sports. Its integrated sensor network can monitor physiological parameters such as heart rate, muscle activity and body temperature in real time. With the help of high-frequency data acquisition and analysis, athletes can obtain accurate real-time feedback to optimize training results. For example, during high-intensity training, athletes can adjust their training load in time through physiological data monitoring to reduce sports injuries and improve training efficiency.

Self-powered electronic skin, with its unique multi-functional properties, provides a strong impetus for innovative applications of medical rehabilitation devices [30]. Especially in patient monitoring and rehabilitation progress tracking, its application value is becoming increasingly prominent. The electronic skin integrated sensor array can monitor physiological parameters in real time, such as heart rate (HR), body temperature (BT) and electrodermal response (GSR), and the continuous monitoring of these physiological indicators can significantly improve the dynamic control of patients’ recovery status. Relevant studies have shown that continuous physiological monitoring can help to quickly evaluate the rehabilitation effect, so as to adjust the treatment plan in time, which has demonstrated significant clinical benefits in clinical practice.

4.2 Implantable medical devices

Neural interface and signal transmission: Self-powered electronic skin can be used in neural interface devices to help repair or replace damaged nerve functions. By integrating with the nervous system, it can convert external signals into electrical signals that can be fed back to the central nervous system to help with sensory restoration. For example, implantable prosthetics use self-powered electronic skin to gain energy and perception, sending feedback signals to the brain to help patients have a more realistic tactile experience.

Minimally invasive implants and enhanced biocompatibility: Thanks to the ultra-thin flexible material, the self-powered electronic skin can be designed to be very thin and highly flexible, making it suitable for minimally invasive surgical implants. This design not only reduces the patient’s recovery time, but also reduces the risk of tissue rejection. In addition, with the development of materials science, more and more self-powered e-skins use biocompatible materials (such as graphene, conductive polymers), reducing post-implantation inflammation and adverse reactions.

Smart drug delivery: The self-powered e-skin can be integrated into the drug delivery system and autonomously regulate the amount of drug release based on real-time monitoring data. For example, it can sense changes in certain indicators in the patient’s body, such as inflammation or infection levels, and release antibiotics or anti-inflammatory drugs in time according to these changes, providing precise treatment and reducing side effects.

Highly sensitive in vivo diagnostics: The self-powered e-skin can integrate multiple sensors to detect a variety of biological molecules (such as glucose, lactic acid, urea, etc.) or physical changes (such as pressure, temperature, humidity, etc.). After implantation, these data can be continuously collected for continuous monitoring. Especially for patients with chronic diseases (such as diabetes, heart disease, etc.), such a system could detect potential lesions at an early stage, thus improving treatment effectiveness.

Personalized medicine and AI integration: In the future, self-powered electronic skin could be combined with AI technology to collect personalized patient data through implanted devices, perform data analysis and machine learning, and help doctors formulate treatment plans more precisely. In addition, the device can synchronize data with an external doctor or hospital via the network, enabling remote diagnosis and personalized treatment.

Energy management and recovery: With the development of self-powered technology, the future electronic skin may manage and recover energy through a variety of energy sources (such as biomechanical energy, heat energy, etc.), not only for its own power supply, but also for other implantable devices to provide energy support, forming an internal energy network, reducing the number of surgeries and maintenance frequency.

The self-powered electronic skin shows good promise in terms of adaptive feedback mechanism. By transmitting monitoring Data in real time to a mobile device or the cloud, doctors can use Data Mining technology for in-depth analysis. Some preliminary analysis results show that intelligent algorithms, supported by rich real-time data, can effectively predict the progress of a patient’s recovery, so that personalized rehabilitation plans can be formulated. Specifically, the method based on Machine Learning can provide more practical rehabilitation recommendations on the basis of accurate diagnosis and combined with the patient’s historical data.

5. Conclusion

SPEK not only represents an emerging technology trend, but also shows significant potential for applications in many fields. From environmental monitoring to health monitoring to the design of smart wearable devices, self-powered electronic skins are redefining the functions of traditional biomedical and electronic devices with their unique multi-functional properties. In environmental monitoring, SPEK is able to capture parameters such as temperature change and concentration of chemical pollutants in real time, which promotes the intellectualization of ecological environment governance and urban management; In the field of health monitoring, SES can not only continuously monitor physiological signals such as heart rate and body temperature, but also assist real-time disease early warning through data analysis, providing strong support for personalized medicine and rehabilitation, while meeting the high demand for health management in modern society. In the application of smart wearable devices, SPEK, as the core technology, can improve the user's wearing experience, optimize comfort and functionality, improve the appearance and performance of products, and expand its market application. Especially in the field of sports and fitness, self-powered electronic skin helps athletes accurately analyze their sports status and achieve scientific health management through portable monitoring solutions. The multi-functional properties of the self-powered e-skin, as well as its innovative applications in biocompatible materials, energy conversion mechanisms and intelligent data processing, indicate that the technology has broad prospects for future development.

In the future, with the continuous progress of technology and the deepening of interdisciplinary cooperation, SPEK will further promote the deep integration of health monitoring, environmental protection and intelligent hardware, showing its unique value and application potential. The research of self-powered electronic skin is not only a technological breakthrough, but also a reimagination of the future lifestyle, laying the foundation for the realization of smarter and more humanized science and technology development.

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