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| RESEARCH ARTICLE

Exploring the Development of Triboelectronic Nanogenerators in Wearable Devices

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| ABSTRACT

Given the growing demand for sustainable energy in the buildout of the Internet of Things (IoT) and the shortcomings of traditional energy generation methods for wearable electronic devices, this paper focuses on the application of triboelectric nanogenerators (TENGs) in the field of wearable devices. By utilizing the principle of interaction between contact electrification and electrostatic induction, we describe the various operating modes of TENGs in this paper, including the vertical contact separation mode, lateral sliding mode, single-electrode mode, and freestanding triboelectric-layer mode, and summarize the applications of TENGs in various fields. Wearable devices can be classified into fibre/yarn types, fabric types and patch types according to their morphology. For these categories, the progress made through material innovation and structural design, functional integration and performance optimization, as well as the enhancement of durability and comfort, are described in detail, while the effects of these approaches are discussed through specific application cases, including energy harvesting, flexible wearable and health monitoring aspects. Practical difficulties and challenges that hinder the development of TENGs in the wearable field are also discussed. Finally, future development trends and technological breakthroughs are proposed to provide new strategies and ideas for the development of TENGs.

| KEYWORDS

Triboelectric nanogenerator (TENG), wearable device, energy harvesting, wearable flexibility, healthcare monitoring.

| ARTICLE INFORMATION

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1. Introduction

A triboelectric nanogenerator (TENG) is a new type of energy harvesting device based on the coupled effect of friction initiation and electrostatic induction, which converts mechanical energy into electrical energy, and its core mechanism originates from the dynamic charge transport process driven by charge separation and spatial potential differences at the interfaces of two heterogeneous materials. TENG research has evolved from the early elucidation of the mechanism to the development of multiple modes of operation and enhancement of charge density, and more recently, applications have been extended to self-powered sensor networks, ocean energy harvesting, and other cutting-edge directions. The research methodology covers theoretical modelling, experimental verification, and numerical simulation. The current research focuses on improving the performance of TENGs and expanding their practical applications.

Traditional wearable electronic devices generally rely on chemical batteries for energy supply, which have inherent defects such as limited energy density, short cycle life, and heavy metal contaminants. In contrast, a wearable system powered by a TENG collects energy from the kinetic energy of human body movement, environmental vibration energy, etc., to realize a continuous self-supply of energy, which has the technical advantages of reducing the dependence on the external energy supply, increasing the compatibility of flexible devices with human body movement, and integrating pressure/strain sensing functions to support intelligent application scenarios such as medical monitoring. Therefore, this paper focuses on the application of friction nanogenerators in the field of wearable devices to carry out in-depth discussions, first, to analyse their working mechanism and mode of operation; second, to analyse their effectiveness in wearable device scenarios through specific cases; third, to explore the challenges and future development trends, aiming to comprehensively review the current status of the research in this field; and lastly, to provide references for subsequent research.

2. Concepts: basic principles and working mechanisms of triboelectric nanogenerators

2.1 Fundamental Principle

Triboelectric nanogenerators (TENGs) are based mainly on the coupling mechanism of contact electrification and electrostatic induction. Contact electrification provides a static polarized charge, whereas electrostatic induction converts mechanical energy into electrical energy. When two different materials (friction pairs) come into contact with each other, charge transfer occurs due to differences in the affinities of the material surfaces for electrons. After contact electrification generates charge, when the material undergoes relative motion, an induced potential difference is generated at the two ends of the electrode, which in turn drives the flow of charge in the external circuit, realizing the conversion of mechanical energy to electrical energy.

2.2 Operating mode

2.2.1 Vertical Contact Separation Mode

This is one of the most common TENG operating modes. In this mode, two friction electric materials periodically contact and separate in the vertical direction. When they are in contact, contact electrification occurs; when they are separated, electrostatic induction takes place. This mode has the advantages of high instantaneous power density and simple structural design, making it effective in capturing short-range periodic motions such as vibrations and periodic shocks.

2.2.2 Lateral Sliding Mode

The lateral sliding mode has the same device structure as the vertical contact separation mode. Two friction electrical materials slide relative to each other in a direction parallel to the contact surface. During the sliding process, electrical energy is generated. Since the charge contact-separation process can be performed several times during the sliding process, the charge transfer in this mode is more efficient and contributes to a higher power output. Recent theoretical studies on the lateral sliding mode have focused on understanding the basic model and grid structure of TENGs.

2.2.3 Single-Electrode Mode

A TENG in single-electrode mode uses only one electrode, and the other electrode usually uses the Earth or the surrounding environment as the reference electrode. When the friction electric material and the surrounding environment have relative motion, an induced charge is generated on the single electrode, which in turn outputs electrical energy. The advantage of this mode is that the charged object is not limited to movement, and the relative motion between the friction electric layer and the electrode is not limited to one mode, making it particularly suitable for self-powered active sensors on shoes or other moving objects.

2.2.4 Freestanding Triboelectric-Layer Mode

The freestanding triboelectric-layer mode is a relatively new mode of TENG operation, which is characterized by the ability of the triboelectric layer to move or vibrate freely. The friction layer generates relative displacement with the fixed electrodes, thus generating electrical energy. This mode avoids the shielding effect of the single-electrode mode, and the electrostatic-induced electron transfer is more effective. Since the friction layer does not need to remain in contact with the electrode layer during the sliding process, noncontact sliding operation becomes possible, which avoids direct friction between the two surfaces and greatly improves the energy conversion efficiency and long-term stability of the motor.

3. Basic Research Process

In 2012, Zhonglin Wang's team first proposed the concept of TENGs[4]], which utilize the contact-separation modes of polyester (PET) and Kapton films to realize the conversion of mechanical energy to electrical energy through contact electrification and electrostatic induction coupling, opening a new pathway for the conversion of environmental mechanical energy. The four basic working modes of TENGs—vertical contact separation (CS), lateral sliding (LS), single-electrode (SE), and freestanding triboelectric-layer (FT) modes—were further clarified by the research team in a subsequent study. They also developed a mathematical model of the output current and voltage using the capacitance framework and the theory of displacement current. Zi et al. proposed a performance quality factor index for standardized performance evaluation in 2015. In 2017, an important theoretical breakthrough in which the physical mechanism of TENGs was traced back to the polarization contribution of Maxwell's displacement currents; moreover, Maxwell's displacement currents are still the theoretical basis of all refined electrical models. In 2018, Xu et al. verified through high-temperature experiments that electron transfer is the dominant mechanism for contact electrification and proposed the “electron cloud-potential well” model[25]]. From 2016–2018, the performance of TENGs was optimized, the charge density was significantly increased by various methods, and progress has been made in power management technology, with significant improvements in energy storage efficiency. In terms of applications, from 2014 to the present, TENGs have been widely used in a variety of fields, such as micro/nanopower supplies, self-powered sensing, and blue energy applications.

3.1 Critical influencing factors

Material properties are critical to TENG performance. The charge affinity of the material pairs in the friction electric sequence directly affects the output, e.g., PTFE is negatively charged, and nylon is positively charged. Early research focused on common polymer materials such as polytetrafluoroethylene (PTFE) and silicone rubber. As research has progressed, a variety of new materials have emerged. While flexible and long-lasting materials such as silicone are appropriate for wearable technology, high dielectric constant elements such as BaTiO3 and SrTiO3 as fillers can improve charge trapping. In terms of structural design, operating modes are adapted to different forms of mechanical excitation, surface micro/nanostructures can increase the effective contact area, and integrated structures such as fibrous, 3D braided, and spherical-shell structures enable wearable integration and optimize wave energy harvesting, respectively. Among the environmental factors, temperature affects the charge stability and material dielectric properties, humidity, and air pressure also play significant roles in TENGs, and a high vacuum environment prevents air breakdown and enhances the charge density. In terms of power management, the conversion of high-voltage and low-current outputs and improvements in energy transfer efficiency are achieved via impedance matching circuits and optimized charging and discharging cycles. Multidisciplinary crossover provides a strong impetus for the development of TENGs, with materials science developing new composite materials, mechanical engineering improving the structure to enhance the low-frequency response, and electronics promoting the integration of TENGs with the Internet of Things (IoT) to facilitate the development of passive systems.

4. **Applications of triboelectric nanogenerators in various fields**

4.1 Medical monitoring and sports tracking

Friction nanogenerators (TENGs) have promising applications in medical monitoring. For pulse and blood pressure monitoring, the flexible woven structure self-powered sensor (WCSPS) by K. Meng's team (2018), made of PTFE, PET, and ITO, has high sensitivity (45.7 mV Pa^{-1}) and a short response time (<5 ms)[12] and is capable of calculating a variety of cardiovascular physiological parameters, including K (degree of vascular sclerosis), AC (arterial compliance) and TPR (total peripheral resistance), on the basis of pulse waveforms. For respiratory monitoring, Zhao’s textile TENG generates friction electricity through changes in the yarn contact area and fixes the chest through a nonelastic cotton chest strap[34]. The TENG responds to human respiration by generating electrical signals, and information such as the respiratory rate and respiratory depth can be obtained through data processing. In the field of exercise tracking, TENGs have unique advantages. Yu's team utilized the high sensitivity and flexibility of TENGs to develop a sensor that can accurately sense the movement state of the human body. This sensor can monitor joint movement, muscle activity, etc., in real time, which provides an effective means for monitoring athletes' training and rehabilitation. Moreover, the electronic skin made of TENGs can fit human skin to achieve precise capture of minute movements, which is of great value for the analysis and optimization of sports postures, helping to improve the training effect of athletes and reduce sports injuries.

Compared with nontextile-based sensors, textile-based sensors have obvious advantages; on the one hand, their soft, lightweight, and breathable features prevent the wearer from feeling uncomfortable or even allergic; on the other hand, nontextile-based sensors need to be fixed to the human body with the aid of adhesive tapes or band aids, which is both inconvenient and unsuitable for long-term use. Notably, despite the fruitful results of TENGs in the field of medical monitoring and motion tracking, they still face the challenges of improving energy conversion efficiency, enhancing stability and optimizing biocompatibility, which need to be explored in further research.

4.2 Smart Textiles: Energy Harvesting and Haptic Feedback

Friction nanogenerators (TENGs) have shown great potential in the field of smart textiles, and numerous research teams have carried out related work. TENGs can be integrated into apparel products to power wearable electronic devices. Zhang et al. prepared a high-performance wearable t-TENG by constructing a novel structure[29] with tilted microroding arrays with a maximum peak power density of 211.7 $\mu W/cm^{-3}$, which can be worn on the elbow and continuously harvest energy from human movement to provide sustainable power for wearable electronic devices. Moreover, Seung et al. integrated t-TENGs into automobile tires[15] and used nylon and polydimethylsiloxane (PDMS) as positive and negative friction electric materials to harvest mechanical energy from tire rolling, which provides a potential framework for future self-powered in-vehicle energy systems. Ye et al. developed hydrophobic and breathable all-textile TENGs[28], which contain friction electric nanoparticles on the surface to efficiently harvest energy from raindrops, with output voltages of up to 22 V, and can be integrated into wearable electronic devices for energy harvesting.

TENGs also play an important role in haptic feedback, as they can be used as pressure and strain sensors for tactile sensing. For example, Wen et al. prepared an advanced glove based on friction electrotextile sensors that can control the virtual/augmented reality interface by sensing pressure or tensile stress**Error! Reference source not found.**. In a virtual shooting scenario, the glove allows the virtual hand to follow the movement of the real hand to grasp a gun. The thumb presses the sensor to initiate the bullet-loading action, whereas the index finger bends to initiate the shooting action. Additionally, Shi et al. created an ET, a self-powered, high-sensitivity skin-mounted device based on a TENG that can create a noncontact virtual haptic experience**Error! Reference source not found.**. The participants in the augmented haptic VR experience test were able to identify various patterns via the system, which indicates that the TENG is highly valuable in enhancing the realism and immersion of virtual interaction.

4.3 Blue Energy:

Friction nanogenerators (TENGs) show great potential for blue energy applications. Chen's team proposed that the TENG network (TENG-NW) can be used for large-scale harvesting of ocean wave energy[2]. TENG-NWs rely on the surface charging effect between a conventional polymer and a thin layer of metal electrode and are able to convert slow, random, and high-force oscillatory wave energy into electrical energy. The average power output of TENG-NW is estimated to be 1.15 MW for 1 square kilometer. Yi Xi's team developed a multifunctional TENG to simultaneously harvest water waves, water currents, and wind energy[23]. The device consists of a rotating part (r-TENG) and a vertical cylindrical part (c-TENG). The r-TENG is used to collect wind and water current energy, and the c-TENG is used to collect water wave energy. The two TENGs produce outputs of 490 V, 24 μA and ≈100 V, 2.7 μA at a rotational frequency of 200 rpm and a kinematic frequency of 3 Hz. These research results show that TENGs are valuable in the development and utilization of blue energy and provide new methods for solving energy problems.

4.4 Human–Computer Interaction: Gesture Recognition and VR Augmentation

The TENG monitors the human body's movement intentions and action changes in real time. When the human body moves, the TENG generates corresponding electrical signals, which are transmitted to the wearable robot system to precisely control the robot's movements. In industrial production, workers wearing smart gloves integrated with TENGs can synchronize their hand movements to the wearable robot in real time, and the robot can accurately mimic the worker's movements to complete complex, dangerous, or high-precision operational tasks, greatly improving productivity and safety. In the meantime, wearable robots in medical rehabilitation, which utilize TENG and VR technology, offer customized rehabilitation training programs based on the patient's motor abilities and rehabilitation requirements, assisting the patient in better regaining limb function.

5. State of the Research: Progress of TENGs in Wearable Devices

5.1 Classification of wearable TENGs

5.1.1 Fibre/Yarn-Type TENGs

Fibre/yarn TENGs usually have a one-dimensional structure, with flexible fibres formed by weaving or twisting, and this structure allows them to be easily integrated into clothing. This fibre/yarn TENG is lightweight, does not overburden clothing, and has good washability for everyday use. Moreover, it is highly compatible with textile processes and can be mass produced by existing textile technologies, facilitating its widespread use.

5.1.2 Textile TENGs

Textile TENGs present a two- or three-dimensional structure, forming a friction interface with breathability through weaving, knitting, or lamination. In three-dimensional spacer fabrics, the upper and lower layers of friction materials are kept at a certain distance through the spacer structure, which increases the contact and separation efficiency between the friction layers, thus improving the energy conversion efficiency. In the field of smart clothing, textile TENGs are widely used. When the human body moves, smart garments integrated with textile TENGs generate friction electrical signals along with the body's movements, and through the analysis of these signals, the human body's movement status and physiological information can be obtained, providing data support for health monitoring and movement analysis.

5.1.3 Patch-type TENGs

Patch-type TENGs have good fit and flexibility; they are usually in the form of elastic patches that attach directly to the skin or joints and are used to capture the energy generated by small movements, such as pulsing. When used to capture pulse energy, it can accurately sense the subtle pulsations of blood vessels. Because of this characteristic, patch-type TENGs are promising for use in the wearable medical device industry. It is anticipated that these devices will provide wearable medical devices with a reliable energy source so that they can achieve continuous and long-term health monitoring.

5.2 Material innovation and structural design

5.2.1 Options for Flexible Substrates

In the field of wearable devices, the choice of flexible substrate for friction nanogenerators (TENGs) is crucial. The use of textiles as substrates is an effective way to achieve good breathability and wearability. Combining nylon and polyester fibres with conductive silver fibres, this combination not only possesses the soft properties of textiles but also achieves good electrical conductivity due to the presence of conductive silver fibres. Among these, conductive silver fibres serve as the charge transfer pathway, whereas nylon or polyester fibres act as the substrate. The TENG created by combining the two methods can efficiently increase the contact area and friction charge while guaranteeing wearability, washability, and breathability.

Elastic materials play an essential role in adapting to the dynamic deformation of the human body. Elastic materials such as silicone rubber and PDMS are extensively used for energy harvesting in joint movements. The high elasticity of silicone rubber enables it to deform according to the bending and stretching of the joints, during which the mechanical energy is efficiently captured and converted into electrical energy. This characteristic makes silicone rubber-based TENGs especially suitable for application in joint parts, such as knees and elbows, which provides a reliable guarantee for the energy supply of wearable devices in the dynamic environment of the human body.

5.2.2 Surface Functionality

The enhancement of frictional charge density through the construction of nanoporous structures or microstructures is an important means of improving the performance of TENGs. Kong reported that the structure of mesoporous silica loaded with perfluorooctane ethanol could significantly enhance the output performance of TENGs**Error! Reference source not found.**. The mesoporous silica provided a high specific surface area and increased the frictional contact area, whereas perfluorooctane ethanol optimized the surface charge generation and transport through its chemical properties, and the synergistic effect resulted in a significant increase in the frictional charge density, which in turn enhanced the overall performance of the TENG.

In terms of composite material development, optimizing friction electric sequence matching by doping conductive or dielectric materials is also a popular research topic. Doping conductive materials such as carbon nanotubes and graphene into materials can change the electrical properties of the materials and optimize the friction electric sequence. Carbon nanotubes and graphene have excellent electrical conductivity and a high specific surface area, which can promote charge transfer and accumulation, thus improving the output performance of TENGs. Moreover, doping with PVDF, PTFE and other dielectric materials can also adjust the dielectric constants of the materials to further optimize the friction electric properties and improve the performance of TENGs in various application scenarios.

5.3 Functional integration and performance optimization

5.3.1 Self-powered sensing system

In the field of wearable devices, the integration of TENGs with multiple functions is an important development trend. Numerous studies have been devoted to combining TENGs with multimodal sensing functions such as pressure, strain, and temperature to realize more intelligent and comprehensive monitoring. The logical design of a TENG allows it to sense temperature, strain, and changes in pressure. When used for gesture recognition, TENGs output specific electrical signals according to the differences in pressure and strain generated by different gesture movements, thus realizing accurate recognition; in terms of health monitoring, they can monitor human health in real time by sensing changes in the temperature of the human skin surface, as well as tiny pressure fluctuations caused by breathing and heartbeats. This integration of multimodal sensing functions considerably expands the application scope of TENGs in wearable devices and provides users with more comprehensive services.
To achieve continuous and stable operation of wearable devices, the integration of TENGs with energy storage devices is crucial. Wang integrated TENGs with supercapacitors to construct a self-sustainable energy system**Error! Reference source not found.**. In this system, the TENG is responsible for collecting mechanical energy from the environment and converting it into electrical energy, whereas the supercapacitor stores this electrical energy to power the device when needed. This integration solves the problem of unstable power output from the TENG and ensures a stable energy supply for the wearable device in all situations, improving the device's practicality and reliability.

5.3.2 Improved durability and comfort

The durability and comfort of wearable TENGs are key factors affecting their practical applications. Antiwear coatings and self-repairing materials play important roles in enhancing durability. Kong used a mesoporous silica-encapsulated repair agent as an antiwear coating to effectively extend the service life of TENGs**Error! Reference source not found.**. The mesoporous silica coating can create a protective layer on the surface of a TENG to decrease friction and environmental damage because of its strong chemical stability and wear resistance. Moreover, some TENGs are made of self-repairing materials, which can automatically repair the internal structure and maintain stable performance when the materials are damaged, ensuring the reliability of the TENGs during long-term use.

Breathability must be prioritized in TENG design to improve comfort. The preservation of textile porosity and prevention of pore blockage by polymer coatings have been the focus of numerous investigations. Peng et al. developed an e-skin made of silver nanowires sandwiched between polylactic acid-hydroxyacetic acid copolymer (PLGA) and polyvinyl alcohol (PVA) [14]. This material has a multistage porous structure with good comfort, environmental friendliness, and antimicrobial activity.

Another example is Xiong et al., who designed a skin-triggered sandwich structure fabric, a TENG, using silver sheets and a PDMS binder as stretchable and breathable electrodes and waterproofing it with cellulose-derived hydrophobic nanoparticles (HCOENPs)[24]. This coating does not affect the porous structure of the fabric, maintaining breathability and comfort. In addition, the HCOENP encapsulation layer provided protection for black phosphorus (BP) and inhibited charge loss, thereby greatly improving the output performance.

By optimizing the coating process and material selection in the above study, the original pore structure of the fabric was preserved to the maximum extent while achieving TENG function. In this way, the breathability of the fabric is maintained, and the wearer will not feel uncomfortable due to the stuffy feeling during use, making the wearable TENG more in line with the needs of daily use.

6. Applications analysis: Specific examples and effects

6.1 Case for Energy Harvesting Efficiency

To address the issue of the separation between energy generation and storage modules in wearable energy harvesting systems, researchers have developed a composite fibre system that integrates a friction electric nanogenerator (TENG) and a microsupercapacitor to achieve the synergistic function of autonomous energy harvesting and storage. Wang's team presented the first self-charging fibre architecture in 2015[19]: carbon fibres were used as a conductive substrate, loaded with ruthenium oxide hydrate (RuO_2-xH_2O) by electrochemical deposition to form a pseudocapacitive layer, and subsequently coated with polydimethylsiloxane (PDMS) and polytetrafluoroethylene (PTFE) to form a friction electric bielectrode layer. The fibre supercapacitor exhibited a volume-specific capacitance of 83.5 F/cm^3, corresponding to a linear specific capacitance of 3.2 mF/cm and an area-specific capacitance of 146 mF/cm^2. The integration of power generation equipment and energy storage equipment through the braiding process realizes the continuous conversion of mechanical energy, electrical energy, and chemical energy.

In 2017, Dong’s team further texturized the device[3]: three single yarns composed of stainless steel and polyester fibres were tightly coupled by a twisting process and coated with silicone rubber, and the yarns were sequentially woven in the lateral (weft) direction to form a TENG fabric, which was cowoven with supercapacitors to form a self-powered textile. The system generates an instantaneous power density of 85 mW/m^2, which can illuminate approximately 124 light-emitting diodes (LEDs) and power devices such as wearable calculators and temperature and humidity sensors.

Yang's team made a breakthrough in 2018[27] to realize the structural innovation of integrating a friction electric nanogenerator (TENG) and a supercapacitor (SC) on a single fibre. The integrated structural design of the fibres adopts a composite configuration: carbon fibre yarn as the electrode material, a silicone rubber friction power generation layer, and the encapsulation of PDMS to achieve electrical isolation and mechanical protection, forming an axially integrated structure of “energy storage core - power generation layer - encapsulation shell”. This structural breakthrough sets a new standard for the seamless integration of wearable electrical devices. Experiments demonstrate that the technology overcomes the space constraints of traditional discrete architecture and offers a dependable option for the development of self-powered smart textiles.

6.2 Self-repairing coating TENG

Xiang Kong et al. prepared a new type of coated friction nanogenerator (TENG) with wear-resistant and self-repairing functions[9]. The team first prepared mesoporous silica by NH3-catalyzed hydrolysis of tetraethyl orthosilicate (TEOS) with cetyltrimethylammonium bromide (CTAB) as a template; 1H,1H,2H,2H - perfluoro-1-decanol was loaded into the mesoporous silica to obtain F-SiO2; a certain mass fraction of F-SiO2 was then dispersed ultrasonically by mixing it with dimethylformamide (DMF) solution and then mixed with acrylate coating, which was spun-coated with the nylon 11 solution on a Cu/PET film, and then combined with the nylon film to form the TENG after drying. Short-circuit currents (Isc) of 10 μA and output voltages of up to 220 V were measured during the performance characterization session, while the coefficient of friction of the new coating was reduced from 0.11 to 0.04, with a reduction in the wear volume of approximately 89%. Compared with those of pure acrylate materials, the short-circuit current and output voltage are increased by a factor of 4--5, and the friction reduction and wear resistance are also significantly improved.

This result provides a solution to the practical application limitations of TENGs. It can be widely used in the fields of energy harvesting and self-powered and self-driven sensors, such as by spraying it on walls and door handles to make single-electrode TENGs, which can be used for energy harvesting and lighting in daily life and has broad application prospects in the future.

6.3 Case for flexible wearable devices

To address the technical bottleneck of traditional fabric-based TENGs with limited air permeability, Tan's team has realized the synergistic optimization of air permeability and power generation performance by designing a composite coating porosity and dielectric enhancement strategy. They used polydimethylsiloxane (PDMS), silicone oil, and sodium chloride (NaCl) particles to construct a three-phase composite system, and at the same time, to further enhance the dielectric performance, polyvinylidene fluoride (PVDF) was introduced into the system, forming a uniform slurry through mechanical blending, which was then coated on the substrate via a squeege coating process. A thick coating was formed on the surface of the substrate fabric via a scraper coating process. The porous film was washed to remove the NaCl pore-forming agent and finally dried to obtain the porous film. After performance characterization, the air permeability of the porous coated fabric reached 73 mm/s, generating an open-circuit voltage of 600 V, a short-circuit current of 15 μA, and a power density of 5.67 W/m² per unit area on a 4×4 cm² sample, which breaks through the inverse relationship of "high output-low air permeability" of traditional power generation fabrics**Error! Reference source not found.**.

6.4 Healthcare monitoring cases

6.4.1 Cardiovascular health surveillance

Cardiovascular health monitoring is crucial for disease prevention and diagnosis. Traditional detection methods have limitations such as low pressure sensitivity and high detection limits. Bai et al reported a membrane-based TENG capable of detecting heartbeats, which represents a new opportunity in this field**Error! Reference source not found.**. The human heartbeat process causes small air pressure fluctuations in the thoracic cavity, and the membrane-based TENG sensor is able to acutely sense air pressure changes and convert them into electrical signals. The sensors have excellent sensitivity to micropressure changes caused by chest movements: a positive pressure response threshold of 0.34 Pa and a negative pressure detection accuracy of 0.16 Pa. In practice, the sensors are simply placed against the chest, and the heartbeat-induced rise and fall of the chest trigger the sensors to generate an electrical signal, allowing for the accurate recording of each heartbeat.

6.4.2 Pulse detection

Traditional pulse diagnosis relies heavily on herbalists' professional knowledge, and the pulse waveform at the wrist is extraordinarily complicated, making it challenging for a single sensor to record all of its nuances. Ouyang et al. reported a TENG sensor that consists of two layers of friction materials (e.g., n-polyimide and n-copper electrodes), spacer layers, and elastic encapsulation materials[13]. When the sensor was propped against a 24-year-old male's radial artery (i.e., wrist pulse), a voltage waveform corresponding to the "second derivative" of the pulse signal was immediately produced, eliminating the need for sophisticated mathematical computations or extra hardware. A voltage of 1.52 V, a current of 5.4 nA, and a charge of 1.08 nC were recorded. To address the challenge of multidimensional interpretation of radial pulse signals, the team proposed a dual-mode TENG sensing solution: the simultaneous use of two TENG sensors enables the measurement of pulse wave conduction velocity to determine the degree of atherosclerosis. In general, the faster the pulse wave conduction velocity is, the less elastic the blood vessel is.

These sensors are extraordinarily sensitive, detecting faint physiological signals that conventional equipment would normally miss. Their straightforward form makes them simple to include in wearable devices (e.g., smart wristbands) or medical monitoring systems. They offer a useful, noninvasive screening method for cardiovascular illnesses (such as atherosclerosis), which can aid in early identification and treatment.

7. Existing issues and challenges

Despite the remarkable progress in friction nanogenerators (TENGs) in the field of wearable devices, their development still faces many technical limitations and application bottlenecks. These issues not only hinder the further improvement of TENG performance but also limit its large-scale commercialization.

7.1 Output power limitation

Despite the progress in wearable TENGs, their power density is still low in most cases, limiting their application in more energy-intensive devices. At present, wearable TENGs still have much room for improvement in terms of energy conversion efficiency. In low-frequency mechanical energy conversion scenarios, such as the slow movement of the human body in daily life, the energy conversion efficiency of TENGs is insufficient, resulting in limited output power. This is because the working principle of TENGs is that the friction-generated electricity and electrostatic induction processes are not sufficient to generate enough electricity during low-frequency movements.

Textile-based friction nanogenerators (TENGs) are particularly problematic. The experimental data show that the textile-based TENG face power density only ranges from 22.5 nW/m^2 to 8.9 W/m^2, whereas conventional nontextile-based TENGs can consistently output face power densities greater than 500 W/m^2. Ryan Walden suggested that this difference in performance stems from a difference in the contact area: even with conventional Cu-PET interfaces (nontextile), the effective contact area is only 0.25% at 16 kPa contact pressure; only when the pressure is raised to as high as 1.12 MPa can the contact area rate increase to 82% [18]. This pressure dependence severely limits the effectiveness of wearable scenarios, as wearable devices are unable to provide sufficient normal contact force to press surfaces together in application scenarios. Optimizing the frictional charge density through surface modification methods is critical for enhancing the output power of flexible TENGs.

7.2 Environmental adaptability

Humidity and temperature changes can significantly affect the friction electrical performance of TENGs. In high-humidity environments, moisture is adsorbed on the surface of the friction material of the TENG, forming a water film, which interferes with charge generation and transfer, leading to a decrease in the output performance of the TENG. In environments with large temperature variations, the physical and chemical properties of the material change, affecting friction electrical sequence matching and the charge transfer process, which in turn reduces the performance of the TENG. Therefore, improving the stability of TENGs in different humidity and temperature environments is one of the keys to enabling their wide application. For example, Lai used an ethylene vinyl acetate (EVA) film as a waterproof layer and encapsulated the conductive fabric between the EVA layers through a lamination process to form a waterproof barrier, whose microporous structure can block the penetration of liquid water while maintaining air permeability[10].

TENGs have demonstrated good power generation performance in a laboratory setting, but the output in real-world applications may be much lower. Laboratories are usually able to provide TENGs with optimal surface contact, fixed frequency, and optimized amplitude for friction power generation, resulting in desirable power generation data. The driving force that the TENG is exposed to in real-world application circumstances, however, may be multidirectional and unpredictable, making it impossible to guarantee that every contact is as accurate and consistent as mechanical operation in the laboratory. Such irregular movements can significantly affect the power generation performance of the microgenerator; there is also a risk of corrosion and wear on the components of the TENG, and factors such as humidity, acidity, and alkalinity in the environment may accelerate this process, which in turn affects the output performance and service life of the microgenerator. Therefore, to ensure its reliability and stability in practical applications, long-term field tests need to be carried out in different seasons and scenarios.

7.3 Large-scale manufacturing

The compatibility between the textile process and micro/nanoprocessing technology is a challenge for the scale manufacturing of wearable TENGs. The textile process focuses on large-scale and high-efficiency production, while micro/nanoprocessing technology is usually used to prepare high-precision and small devices, and there are large differences between the two methods in terms of process parameters and equipment requirements. When applying TENG micro/nanostructure preparation technology to textile production, ensuring the consistency and stability of the products is difficult. In addition, large-scale production also needs to consider the issue of cost control, and ensuring the performance of TENGs under the premise of reducing production costs to achieve efficient and low-cost large-scale manufacturing is key to promoting the commercialization of wearable TENGs. At present, although some studies are trying to solve the compatibility problem by improving the textile process or adjusting the micro/nanoprocessing technology, a completely effective solution has not yet been found, which limits the large-scale popularization and application of wearable TENGs.

8. Future development trends and technological breakthroughs

8.1 Material innovation

The development of new friction electric materials offers new possibilities for TENGs. MXenes, novel two-dimensional nanomaterials with highly electronegative surfaces, are ideal friction electric materials for friction nanogenerators (TENGs). Jiang et al. introduced MXene into PDMS by mixing an aqueous solution of MXene with a solution of polydimethylsiloxane (PDMS)[6]. After the mixed solution was spin-coated onto glass and cured, a flexible film was obtained, which had a relatively high friction electronegativity. As a result, the output of the TENG increased significantly with increasing MXene concentration, and when 31 mg of MXene was added, the output was seven times greater than that of the pure PDMS-based TENG.

The integrated design of self-powered and self-healing devices is an important direction for future development. Self-powered materials with self-repair functions can enable TENGs to repair themselves and maintain energy harvesting functions when suffering from external damage. Guan's research team innovatively developed a self-repairing TENG device based on the near-infrared (NIR) response mechanism, which demonstrated the potential for application in the field of implantable electronics[5]. The core repair mechanism originates from the chemical reorganization property of dynamic disulfide bonds: when carbon nanotubes convert the absorbed NIR radiation energy into thermal energy, they activate the dynamic disulfide bonds in the epoxy resin matrix through heat conduction, thus triggering self-repair of the material structure.

8.2 Structural optimization

The bionic structure design provides a new idea for enhancing the performance of TENGs. On the basis of the structural bionic principle of the biological eardrum, Yang's research team successfully developed a self-supplied bionic membrane sensor (BMS) with cardiovascular feature detection and speech recognition ability[26]. The device adopts an elliptical configuration to mimic the broadband response of the human tympanic membrane, and its core structure consists of three parts: a nylon film modified with indium tin oxide electrodes laminated with a PET substrate, a miniature PET bump structure in the center of the nylon film loaded with PTFE vibrating membranes, and a tapered cavity structure formed through precision assembly for the contact separation effect. The experimental data show that the bionic sensor achieves a sensitivity of 51 mV/Pa and a detection limit of 2.5 Pa in the low-pressure range of <1.2 kPa while extending the effective frequency response range to 0.1--3.2 kHz.

While the design approach based on a sequence of friction electric materials provides an important theoretical framework for the construction of friction nanogenerators (TENGs), the inherent properties of the sequence also lead to the existence of a theoretical upper limit on the surface charge density of the device, which serves as a bottleneck that restricts the enhancement of its efficiency (in terms of the ratio of the energy harvested to the energy available). To address this limitation, an innovative strategy of coupling an electromagnetic-based generator with a friction electric generator is proposed, which uses the mechanical energy conversion advantage of the former to compensate for the energy capture blindness of the TENG in specific motion modes. Notably, the technology of integrating polarized piezoelectric materials into TENGs has made successive advances in recent years, with the mechanism originating from the coupling effect of piezoelectric nanogenerators (PENGs) with the electric field charge separation process of TENGs. Among many polymers with piezoelectric properties, poly(vinylidene fluoride) (PVDF) has become the material of choice for hybrid PE-TENGs because of its flexible features, which are particularly suitable for the construction of flexible electronic systems such as wearable sensors. In PE-TENG motion sensors, PVDF fibres can already be used as the only piezoelectric layer or as both a piezoelectric layer and a friction electrical contact surface, whereas vibration sensors and nanogenerators made of polarized PVDF films and PVDF nanoparticles have emerged, providing a continuous and stable power supply to wearable devices in different environments.

8.3 System integration

8.3.1 Seamless connectivity with the Internet of Things (IoT)

The seamless connection between TENGs and the Internet of Things (IoT) allows wearable devices powered by them to become smart nodes of the IoT, collect and transmit data in real time, and provide smarter and more convenient services to users. Zhang's team proposed textile-based TENG socks consisting of a silicone rubber film, a nitrile film, and conductive textiles as a negative friction electric layer, positive friction electric layer, and output electrodes[33]. The sock was integrated into a smart sock for gait monitoring with a pressure sensitivity of up to 0.4 V kPa-1 and a sensing range of more than 200 kPa. In addition to achieving 93.54% recognition accuracy for 13 participants, the optimized four-layer one-dimensional convolutional neural network (CNN) model demonstrated 96.67% accuracy in detecting five distinct human activities. It was also utilized in a virtual reality fitness game.

In special working scenarios such as industrial production and laboratories, ensuring personnel safety and real-time monitoring of personnel status are crucial. Ma et al designed a smart protective lab coat based on a PTFE yarn fabric TENG with the following four advantages: PTFE yarn, which is used to knit the smart protective lab coat, has strong resistance to acids and alkalis and is more resistant to chemical erosion than regular fabrics**Error! Reference source not found.**; the laboratory coat has a self-powered chemical leakage monitoring function. When a chemical droplet comes into contact with a hydrophobic yarn with a core–shell structure, it triggers frictional electricity and electrostatic induction, generating an obvious signal to realize timely detection and early warning of chemical leakage; intelligent laboratory coats can also provide vital signs and motion monitoring functions and real-time detection of the operator's status in the hazardous working environment. Information such as heart rate, movement amplitude, and frequency are obtained through TENG sensors to detect possible dangerous conditions of the operator on time; by tapping the single electrode TENG yarn on the protective clothing, real-time remote alarms can be realized, providing the possibility of timely rescue.

8.3.2 Convergence of artificial intelligence and TENGs

Artificial intelligence technology has powerful sensor signal processing and application expansion capabilities. On the one hand, it can help sensors detect more complex and diverse signals. On the other hand, with the powerful feature extraction capabilities of machine learning, specific features representing relationships within the dataset can be automatically extracted from the sensor signals. Machine learning can leverage more comprehensive and detailed sensing information to enable diverse applications, such as gesture/posture estimation, speech recognition, and object recognition. These applications serve more advanced human–machine interaction (HMI) systems, making them more suitable for constructing smart sensors in the Internet of Things (IoT) and promoting the intelligent development of the IoT.

A TENG can collect the mechanical energy generated by human movement and convert it into electrical signals, which can be combined with machine learning algorithms to realize a variety of intelligent interaction and identification functions. For example, Zhang et al. proposed a multilingual handwriting self-powered recognition system[30], which uses a TENG to record handwriting process signals, combined it with support vector machine decision tree (SVMDT) algorithms, and achieved 100% accuracy in recognizing the test data of the English word "nano". Wu et al. developed a TENG-based Smart Keyboard; by monitoring electrical signals during key presses and certified them via principal component analysis and a multiclass SVM classifier, the recognition accuracy reached 98.7%, demonstrating the feasibility of using this method for network security authentication[22].

TENG wearables can also be useful in health monitoring and rehabilitation assistance. For example, the TENG pressure sensor integrated into a smart toilet seat**Error! Reference source not found.**, combined with a deep learning approach, can recognize the biometric information of six users with 90% accuracy for use in an integrated health monitoring system. A textile-based friction electrical sensing system developed by Zhang's team for gait analysis and lumbar motion capture is integrated into a lower-limb rehabilitation robot for user identification, motion monitoring robot manipulation, and game-enhanced training**Error! Reference source not found.**.

8.4 Standardized testing

It is necessary to establish a comprehensive and practical performance evaluation system for wearable TENGs. At present, the performance testing standards for TENGs are not yet unified, and different research teams have adopted different testing methods and indicators. Theoretically, a unified performance evaluation system should cover key indicators such as energy conversion efficiency, output power, durability, and environmental adaptability. It should also incorporate relevant factors such as ergonomics and the user experience to ensure a comprehensive and accurate evaluation of the performance of wearable TENGs. For example, to assess the wearing comfort, stability, and impact on human activities of TENGs in different human movement states, a combination of subjective evaluation and objective measurements should be used to collect user feedback and quantify indicators such as comfort and convenience. The performance difference between actual conditions and laboratory conditions should also be considered when long-term testing standards are established under practical application scenarios. In practice, reference can be made to the relevant international standard framework already in place, and refinement and improvement can be made by combining the characteristics of wearable TENGs. Professional testing laboratories and certification bodies should be established to ensure the standardization and fairness of the testing process and provide strong support for the commercialization and promotion of TENGs.

9. Conclusion

Owing to their unique working principles and many advantages, friction nanogenerators show great potential in the field of wearable devices. This paper summarizes the working principle and research process of TENGs based on various working modes. TENGs have been optimized from conceptualization to theoretical deepening, their performance has been continuously optimized, and their application fields have been continuously expanded. In the field of wearable devices, TENGs have made remarkable progress. In terms of material innovation and structural design, the performance of TENGs has been improved by choosing suitable flexible substrates and surface functionalization. In terms of morphology classification, fibre/yarn-type, textile-type, and patch-type TENGs satisfy different application requirements. In terms of functional integration and performance optimization, TENGs have been integrated with multimodal sensing functions, energy storage devices, and other devices, as well as increasing durability and comfort, increasing their application in wearable devices. Specific cases have also demonstrated the promising results of TENGs in energy harvesting, flexible wearable devices, and medical health monitoring. However, its current development still faces many challenges, such as power, environmental adaptability, scale-up manufacturing, reliability, and stability.

In response to these challenges, the future development of TENGs in the field of wearable devices presents several important trends. In terms of material innovation, research and development of new friction electric materials as well as self-powered and self-repairing integrated materials; structural optimization strategies, such as bionic structural design and coupled electromagnetic generators; and system integration, the realization of seamless connectivity with the Internet of Things (IoT), fusion with artificial intelligence, and the establishment of standardized testing systems to ensure comprehensive and accurate assessment of their performance. In the future, the development of TENGs requires synergistic innovations in materials, structures, and systems to achieve greater breakthroughs in the field of wearable devices, realize large-scale commercial applications, and provide strong support for sustainable energy supply and smart life.

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References

[1] Bai P., Zhu G., Jing Q., Yang J., Chen J., Su Y., Ma J., Zhang G., and Wang Z. L., (2014). Adv. Funct. Mater., 24, 5807.

[2] Chen J, Yang J and Li Z, et al. (2015). Networks of triboelectric nanogenerators for harvesting water wave energy: a potential approach toward blue energy[J]. ACS nano, 9(3): 3324-3331.

[3] Dong K, Wang YC, and Deng J, et al. (2017). A highly stretch able and washable all-yarn-based self-charging knit ting power textile composed of fiber triboelectric nanogenerators and supercapacitors. ACS Nano. 2017;11(9):9490–9499.

[4] Fan F.-R., Tian Z.-Q. and Wang Z. L., (2012). Nano Energy 2012, 1, 328.

[5] Guan Q, Dai Y, Yang Y, Bi X, Wen Z, and Pan Y. (2018). Near-infrared irradiation induced remote and efficient self-healable triboelectric nanogenerator for potential implantable electronics. Nano Energy. 2018;51:333-339. https://doi.org/10.1016/j. nanoen.2018.06.060.

[6] Jiang C, Wu C and Li X, et al. (2019) All-electrospun flexible triboelectric nanogenerator based on metallic MXene nanosheets. Nano Energy. 2019;59:268-276. https://doi.org/10.1016/j.nanoen. 2019.02.052.

[7] Kong X, Liu Y and Liu Y, et al. (2020). New coating TENG with antiwear and healing functions for energy harvesting[J]. ACS Applied Materials & Interfaces, 2020, 12(8): 9387-9394.

[8] Kong X, Liu Y and Liu Y, et al. (2020). New coating TENG with antiwear and healing functions for energy harvesting[J]. ACS Applied Materials & Interfaces, 2020, 12(8): 9387-9394.

[9] Kong X, Liu Y and Liu Y, et al. (2020). New coating TENG with antiwear and healing functions for energy harvesting[J]. ACS Applied Materials & Interfaces, 2020, 12(8): 9387-9394.

[10] Lai Y C, Hsiao Y C, Wu H M, et al. (2019). Waterproof fabric-based multifunctional triboelectric nanogenerator for universally harvesting energy from raindrops, wind, and human motions and as self-powered sensors[J]. Advanced Science, 6(5): 1801883.

[11] Ma L, Wu R, and Patil A, et al. (2021). Acid and alkali-resistant textile triboelectric nanogenerator as a smart protective suit for liquid energy harvesting and self-powered monitoring in high-risk environments[J]. Advanced Functional Materials, 2021, 31(35): 2102963.

[12] Meng K, Chen J., Li X., Wu Y., Fan W., Zhou Z.,. He Q, Wang X., Fan X., Zhang Y., Yang J., Wang Z. L (2018) Adv. Funct. Mater, 29, 1806388.

[13] Ouyang H., Tian J., Sun G., Zou Y., Liu Z., Li H., Zhao L., Shi B., Fan Y., Fan Y., Wang Z. L. and Li Z. (2017) Adv. Mater. 2017, 29, 1703456.

[14] Peng X, Dong K and Ye C, et al. (2020). A breathable, biodegradable, antibacterial, and self-powered electronic skin based on all-nanofiber triboelectric nanogenerators[J]. Science Advances, 2020, 6(26): eaba9624.

[15] Seung W., Yoon H. J., Kim T. Y., Kang M., Kim J., Kim H., Kim S. M. and Kim S. W., (2020) Adv. Funct. Mater. 2020, 30, 2002401.

[16] Shi Y., Wang F., Tian J., Li S., Fu E., Nie J., Lei R., Ding Y., Chen X. and Wang Z.L, (2021) Self-powered electro-tactile system for virtual tactile experiences, Sci. Adv. 7 (2021) eabe2943, https://doi.org/10.1126/sciadv.abe2943.

[17] Tan D, Xu B and Gao Y, et al. (2022) Breathable fabric-based triboelectric nanogenerators with open-porous architected polydimethylsiloxane coating for wearable applications[J]. Nano Energy, 2022, 104: 107873.

[18] Walden R, Kumar C, Mulvihill D M, et al. (2022). Opportunities and challenges in triboelectric nanogenerator (TENG) based sustainable energy generation technologies: a mini-review[J]. *Chemical Engineering Journal Advances,* 2022, 9: 100237.

[19] Wang J, Li X and Zi Y, et al. (2015) A flexible fiber-based supercapacitor-triboelectric-nanogenerator power system for wearable electronics. Adv Mater. 2015;27 (33):4830–4836.

[20] Wen F, Sun Z, and He T, et al. (2020). Machine learning glove using self-powered conductive superhydrophobic triboelectric textile for gesture recognition in VR/AR applications[J]. Advanced science, 2020, 7(14): 2000261.

[21] Wen Z, Yeh M H and Guo H, et al. (2016) Self-powered textile for wearable electronics by hybridizing fiber-shaped nanogenerators, solar cells, and supercapacitors[J]. Science advances, 2016, 2(10): e1600097.

[22] Wu C., Ding W., Liu R., Wang J., Wang A.C. et al. (2018) Keystroke dynamics enabled authentication and identification using triboelectric nanogenerator array. Mater. Today 21, 216–222 (2018). https://doi.org/10.1016/j.mattod.2018.01.006

[23] Xi Y, Guo H and Zi Y, et al. (2017) Multifunctional TENG for blue energy scavenging and self-powered wind-speed sensor[J]. Advanced Energy Materials, 2017, 7(12): 1602397.

[24] Xiong J, Cui P and Chen X, et al. (2018) Skin-touch-actuated textile based triboelectric nanogenerator with black phosphorus for durable biomechanical energy harvesting. Nat Commun. 2018;9(1):1-9. https://doi.org/10.1038/s41467-018-06759-0.

[25] Xu C., Zi Y., Wang A. C., Zou H., Dai Y., He X., Wang P., Wang Y.-C., Feng P., Li D. and Wang Z. L., (2018) Adv. Mater. 2018, 30, 1706790.

[26] Yang J., Chen J., Su Y., Jing Q., Li Z., Yi F., Wen X., Wang Z., and Wang Z.L. (2015). Eardrum- inspired active sensors for self-powered cardiovascular system characterization and throat-attached anti-interference voice recognition, Adv. Mater. 27 (2015) 1316–1326.

[27] Yang Y, Xie L and Wen Z, et al. (2018) Coaxial triboelectric nanogenerator and supercapacitor fiber based self-charging power fabric. ACS Appl Mater Interfaces. 2018;10(49):42356–42362.

[28] Ye C., Liu D., Peng X., Jiang Y., Cheng R., Ning C., Sheng F., Zhang Y., Dong K. and Wang Z. L. (2021) ACS Nano 2021, 15, 18172.

[29] Zhang L. , Su C., Cheng L., Cui N., Gu L., Qin Y., Yang R., and Zhou F., (2019) ACS Appl. Mater. Interfaces 2019, 11, 26824.

[30] Zhang Q., Jin T., Cai J., Xu L., and He T. et al., (2022) Wearable triboelectric sensors enabled gait analysis and waist motion capture for IoT-based smart healthcare applications. Adv. Sci. 9, e2103694 (2022). https://doi.org/10.1002/advs.202103694

[31] Zhang W., Deng L., Yang L., Yang P., and Diao D. et al., (2020) Multilanguage-handwriting self-powered recognition based on triboelectric nanogenerator enabled machine learning. Nano Energy 77, 105174 (2020). https:// doi. org/ 10. 1016/j. nanoen.2020.105174
[32] Zhang Z, Shi Q, and He T, et al. (2021) Artificial intelligence of toilet (AI-Toilet) for an integrated health monitoring system (IHMS) using smart triboelectric pressure sensors and image sensor[J]. Nano Energy, 2021, 90: 106517.
[33] Zhang Z., He T., Zhu M., Sun Z., Shi Q. et al., (2020) Deep learning-enabled triboelectric smart socks for IoT-based gait analysis and VR applications. NPG Flex. Electron. 4, 29 (2020). https://doi.org/10.1038/s41528-020-00092-7
[34] Zhao Z., Yan C., Liu Z., Fu X., Peng L.-M., Hu Y., Zheng Z., (2016) Adv. Mater. 2016, 28, 10267.