Application of Triboelectric Nanogenerators for Biophysical Sensing System

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Triboelectric nanogenerators (TENGs) can not only collect mechanical energy around or inside the human body and convert it into electricity but also help monitor our body and the world by providing interpretable electrical signals during energy conversion, thus emerging as an innovative medical solution for both daily health monitoring and clinical treatment and bringing great convenience.

pulses TENG circuit

1. Introduction

Since the first invention by Wang et al. in 2012, sensors that are based on triboelectric nanogenerators (TENGs) have attracted strong attention because they can dynamically monitor the physiological condition of our body and environmental stimuli with high sensitivity at the triboelectric interface while converting environmental mechanical energy into electric energy [1]. Due to the advantages of high compatibility, customization, and portability, TENG-based self-powered systems have shown great potential in the ever-growing intelligent device market, and their application is rapidly extending to various fields, including artificial intelligence [2], Internet of things, energy conversion from ocean waves [3], biomedicine [4], disability assistance, and so on, where the TENG is either a power source, a self-powered sensor, or in most cases, both [5].

In principle, materials selection is always the basis for enhancing the performance of TENGs. Currently, many two-dimensional nanomaterials have been proven to be ideal candidates as triboelectric materials, including TMDs, graphene, MXenes, layered MOFs, GO, BP, layered COFs, layered metals, and h-BN [6]. These materials are characterized by ultra-high surface area, adaptability for modification, outstanding electrical conductivity, and optical properties. At the same time, among the many ways to improve the TENG output and sensing performance, 3D fabric structure provides a more efficient, scalable, simple and controllable strategy. The 3D fabric increases the fiber distribution in and out of the plane direction and improves dimensional stability and structural integrity, thereby creating more space for contact separation, which effectively increases the TENG power output density [7]. The 3D fabric structure achieves the asymptotic contact response between fibers and improves the response speed and sensitivity of the TENG [8]. Furthermore, a new type of 4D printed TENG can be designed using spraying technology and fused deposition modelling (FDM) printers. This 4D printing technology is a powerful technique for manufacturing TENGs with self-powered human motion sensors and capturing mechanical energy [9], which is in great demand for accurate robotic sensing and control.

In recent years, with the increasing demand for health, the design and development of TENG-based wearable biosensors in human health monitoring and personalized medicine have garnered significant attention [10]. At the same time, biomechanical energy is one of the most used energy sources. This energy is provided by human joint movement, eyelid movement, respiration, heartbeat, muscle contraction, blood flow, etc. and can be collected by TENGs to generate high-quality electrical signals [11]. As a result, adaptive designs have been intensively developed to integrate TENG-based sensors with the human body in patches, gloves, clothing, and implants to harvest biomechanical energy while fulfilling the wearing requirements of tensile strength and flexibility to provide real-time measurement of physical parameters such as pulse, heart rate, temperature, and blood pressure [12]. With the support of Internet and wireless network technology, sustainable and personalized physiological monitoring of the human body can be carried out, where mobile or portable devices are used to detect, record, and calculate data in vivo to ensure two-way feedback between doctors and patients [13]. In these applications, TENGs can not only quantify various biochemical markers (such as saliva, sweat, skin, and tears) in human body fluids noninvasively, but also be implanted into the human body and provide personalized physiological parameters [14]. At present, TENG-based therapeutic tools, such as a pacemakers, brain nerve stimulators, cardiac defibrillators, and metabolic state monitoring systems, have been developed for clinical treatment [15]. Such innovative designs have shown excellent performance in tissue repair, cell proliferation, and nerve prosthesis [16] with additional advantages in biocompatibility and biodegradability, which also help to reduce the risk of secondary surgery and improve the life quality of patients [17].

Meanwhile, in the field of biomedicine and healthcare, the power supply of traditional biomedical equipment is limited by a short life span, complex recovery process and large volume [18]. The TENG-based sensor provides the possibility to solve these problems by harvesting the mechanical energy from the motion of internal organs, thus operating in a self-powered mode and reducing the risk of secondary surgery for replacing the power source [19]. With the characteristics of long-term stability, high output performance, wear resistance, and high energy efficiency [20], a TENG-based self-powered system can accurately identify the health status of the body and treat chronic diseases with a flexible plan through continuous feedback of data [21][22]. With innovation and advances in materials science and development in mechanical engineering and wireless communication technologies, the intelligence and mobility of TENG-based self-powered systems have been further optimized for providing customized medical services and personalized medical solutions in drug delivery, wound healing, nerve regulation, respiratory sensing, and so on.

2. Cardiac Pacemaker

Ryu et al. [23] reported an I-TENG with an output power of 4.9 μW/cm^3, showing excellent performance in recharging lithium-ion batteries. The I-TENG relies on Bluetooth to monitor the output voltage data in real time and convert mechanical energy into electricity in the body. In addition, the self-charging pacemaker system is integrated with the pacemaker to demonstrate the pacemaker in sensing mode. The device has successfully realized the technological innovation of using biomechanical energy to drive the internal energy collector, which provides the power for the implantable medical device encapsulated in titanium.

Niu et al. [24] developed TENGs based on silk nanoribbon (SNR), which utilized regenerative silk fibroin membrane (RSFF) and nascent SNR membrane (SNRF). RSFF and SNRF have different working capacities and microstructure, and SNRs with a thickness of 0.38 nm are directly exfoliated from natural silk to maintain the original medium/nanostructure. The device has a maximum current, maximum voltage, and power density of 0.5 μA, 41.64 V, and 86.7 mW/m^2, respectively. It not only can generate high output energy through human pulse alone but also has high sensitivity. Moreover, the TENG has excellent biodegradability, biocompatibility, and a controllable lifetime composed only of silk and magnesium. Magnesium and silk, as raw materials for TENG, can achieve complete biocompatibility and biodegradation in vitro. Its service life is determined by the post-processing of the RSFF package. This TENG avoids inflammation and second surgery and has excellent performance in output, biodegradability, biocompatibility, and degradation rate, making it very attractive in implant devices and pacemakers.

3. Neural Prosthesis

One of the most common causes of permanent disability is peripheral nerve damage, and therapeutic electrical stimulation can help regenerate nerves. Some studies have shown that the application of neural prostheses combined with neural cuff implantation has a promising future. However, current electrical stimulation programs cannot complete nerve repair, and there is a lack of research on implantable TENGs. Therefore, Zhou et al. [25] designed an implantable self-regulating sciatic nerve stimulation system, which is composed of contact separation TENGs and nerve cuff electrodes. The injured sciatic nerve can be stimulated by electrical signals generated by the nerve cuff electrodes, and biphasic electrical pulses can be spontaneously generated in response to movement in rats. With tested biological safety, biocompatibility, and system stability, the output amplitude did not decrease significantly, the skin around the incision was benigngrowth, and the liver and kidney were not deformed. There was no abnormal lymphocyte infiltration and no inflammation, and the body was always in a stable state. Compared with the repair effect of chronic therapeutic electrical stimulation, the upregulation of growth-associated protein may serve as a novel strategy, and the recovery of neurological function can be observed by histological analysis and gait.

Shlomy et al. [26] demonstrated a self-powered integrated tactile TENG. After the device is implanted into the skin, it is transmitted to the sensory neurons through the cuff electrode, which can convert tactile pressure into electric potential, thus stimulating the nerve to simulate tactile sensation. It not only has good output performance but also is relatively simple, sensitive, flexible, and biocompatible. The demonstration results in rats show that the device provides tactile perception, in which the distal tibial nerve transection blocks the rat's hindfoot perception. In addition, the tactile pressure exerted on the device determines the degree of electrical activity of induced sensory neurons in vitro. The treatment of tactile loss due to soft tissue injury or traumatic peripheral nerve injury is extremely limited. This research creates a theoretical basis for implantable self-powered TENG in the field of tactile restoration, which is the direction of development prospects.

4. Cell Maturation

Cardiomyocyte–based therapy is often chosen for the treatment of myocardial injury, but its prognostic ability is limited due to the immaturity of cardiomyocytes. Zhao et al. [27] proposed a TENG-based implantable electrical stimulation device that can be self-powered. Cardiomyocytes were induced to mature by the electric field generated by the cross-electrode of the device. The cardiomyocytes of newborn rats were significantly promoted to mature in vitro by the addition of c-troponin T, connexin 43, and α-actinin to the device. In addition, the peak Ca^{2+} amplitude in the cardiomyocytes, Ca^{2+} levels, and Ca^{2+} transient rates are significantly improved by electrical stimulation that optimizes fracture formation and sarcomere tissue. Both the heartbeat of rabbits and the breathing movement of rats can be used as the energy drive of TENG, which is an important technical support for the treatment of myocardial injury.

Guang et al. [28] developed an implantable electrostimulation fracture device consisting of a self-powered TENG with a pair of dressing electrodes that can apply electrostimulations directly toward a fracture. Devices attached to the surfaces of different tissues display biphasic electrical pulses based on surrounding internal movements. The output performance of the device is improved. After electric field optimization, growth factors are activated to regulate the bone microenvironment, promote bone formation and remodeling, and accelerate bone regeneration and maturation. The flexural strength and mineral density increased by 83% and 27%, respectively, compared with the control group, and the fracture healing effect that took more than 10 weeks in the control group was achieved in only 6 weeks. The high output, battery-free, self-responsive, and bioabsorbable device provides a reliable implantable biological device for the medical treatment of fractures.

5. Other Implantable Applications

Cheng et al. [29] reported a new type of mechanical asymmetry TENG (ATNG), which not only exhibits excellent output performance but also is ultrasensitive. It can even monitor the micro-weak intestinal motion of about 0.3 Hz and can accurately output signals in real time. The physiological states of the gastrointestinal system after glucose absorption at different times have been successfully monitored, despite the presence of multiple noises and disturbances in vivo. This research demonstrates the potential application of TENG for long-term, accurate, and real-time monitoring of weak in vivo microscales.

The injury of articular cartilage often causes long-term pain or even disability and is irreversible. In modern medicine, artificial prostheses are usually used to replace diseased joints for relief. Liu et al. [30] designed a self-powered TENG-based artificial joint device to detect wear debris. The device is made by thermo-compression, consists of polyethylene film and a steel ball, and could in-situ detect wear debris. The simulation test of the fabricated sensor on the worn joint site shows that it not only has good output performance but also can monitor wear debris in real time. In addition, the influence of the size and number of particles on the electronic output signal is also studied. The results show that the voltage decreases gradually with the increase of the number and size of particles. This research overcomes limitations of the aseptic loosening of wear fragments and promotes the development of TENG in the replacement of diseased joints with artificial prostheses, contributing to the combination of intelligent medicine and biomedical sensors.

Since implantable magnesium alloys are prone to corrosion, Wu et al. [31] designed a TENG (irTENG) in which the open circuit voltage reaches up to 175 V and the short circuit current reaches up to 14 μA. It is confirmed that irTENG can slow down the corrosion rate of Mg-3Zn-0.2Ca alloy in a short-term test. In addition to excellent output performance, irTENG also has excellent antibacterial activity in experimentation on antibacterial properties of TENG materials. On this basis, the irTENG corrosion protection system was implanted into two-month-developed SD rats. In the long-term implantation experiment on SD rats, it was found that gram-negative and positive bacteria could be effectively eliminated by the Ag electrode. With excellent anti-inflammatory and antibacterial effects in vivo and in vitro, the new bone was obviously better in the process of surgical recovery after implantation, indicating its biocompatibility and potential in vivo application.

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